Livelihood security of pastoralists in semi-arid rangelands under global change

A social-ecological modelling study

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Abstract

More than two billion people inhabit global drylands where animal husbandry is the most important source of income for pastoral livelihoods. Consequences of climate and land use change accompanied by human population growth cause an accelerating degradation of natural resources. These trends endanger sustainable range management for livestock and consequentially pastoral livelihood security. Drylands are characterized by low and spatio-temporally variable precipitation. It follows, that sustainable range management is dependent on adaptive mobility to make use of the highly variable availability of forage resources. Intensive research on such strategies is mainly focused either on ecological or economic aspects of sustainable resource use. However, the feedbacks between the natural and the social system are currently not well understood so far. It is still an open question how the diverse set of drivers interacts and translates into vulnerability for pastoral livelihoods.

We aim to analyze the consequences of climate and land use change on pastoral livelihood security. This is exemplified by a case study on nomadic herdsmen in the High Atlas Mountains of Southern Morocco. The challenge is to evaluate diverse aspects of pastoralism and their combined impact on pastoral households. To achieve this goal, we develop an ecological-economic simulation model on spatially heterogeneous rangelands. The resulting herd size dynamics are then evaluated by means of an innovative risk assessment, to identify the constraints under which income for households is not sufficient anymore in three different model applications.

First, consequences of projected climate change for drylands are investigated in terms of increased precipitation variability and decreased mean annual precipitation. Interestingly, increasing precipitation variability has a smaller effect on the sustenance of the herd size than for example a decreased mobility. Especially the negative effects of extremely high precipitation variability were not confirmed by this study. This can be partly explained by the traits of perennial vegetation. Mediterranean shrubs are able to conserve reserves that buffer effects of variable precipitation and production of forage. But even more important is the adaptive strategy of mobile and frequently destocked herds, which allows sufficient pasture resting and thereby a sufficient performance of vegetation and herd size.

The second model application tests the effect of drought events on pastoral livelihood security. Surprisingly, meteorological droughts are only in rare cases the single cause for the vulnerability of pastoral households since several effects overlap. This is proved by a hypothetical reference simulation under constant precipitation, where a considerably high variation of vegetation and herd size can be observed. This is evidence for a tightly coupled vegetation-herbivore system which already poses a challenge for pastoral livelihoods. The innovative characterization of diverse socio-economic household types reveals the major influence of socio-economic factors compared to single drought events on the livelihood of mobile pastoralists.

The third model application uses a newly developed operationalization of the concept of *key resources* to evaluate the relative importance of different pasture types for

local herds in the High Atlas Mountains of Morocco. These pastures are characterized by specific vegetation traits due to the climatic gradient and different tenure regimes. Particularly, the communal winter pastures can be identified as essential for the long term sustenance of livestock. Besides vegetation production, the ability to conserve reserves plays an important role. This applied example helps to review and refine the concept of *key resources*.

The different applications of our newly developed model help to find options and constraints of sustainable range management related to the combined effect of natural and socio-economic impacts. Model analyses enable us to compare climate and socio-economic change in their consequences on pastoral livelihood security. Notably, it seems that climate change affects adaptive herd management less then previously expected. This underlines the importance of typical traits of adaptive pastoralism for sustainable resource use. A major risk for livelihoods is posed by socio-economic change such as increasing income needs or reduced mobility resulting from land use change. This could partly be compensated by increasingly diversified income from non-pastoral activities but it remains an open question how effective this strategy is in the long-term.

The general principles of sustainable range management can be further demonstrated by the development of a strategic board game. In it, three to five players take the role of nomadic herdsmen to raise their herd of sheep. During the game, players can experience typical events in the environment of pastoral households and are confronted with complex decisions. The board game supports the communication and education about various aspects of sustainable range management, such as mobility and resting times for pastures. Beyond that, it facilitates learning about natural resource use and livelihood security in a broadly understandable way.

Finally, the problem-oriented modelling approach of this work contributes to the integration of natural and social sciences in research on range management in drylands. The interdisciplinary perspective supports mutual understanding on principles of sustainable land use which could be transfered to wider regions.

Kurzzusammenfassung

Über zwei Milliarden Menschen leben weltweit in Trockengebieten, in denen Weidetierhaltung die zentrale Wirtschaftsform und Haupteinkommensquelle ist. Klima- und Landnutzungswandel verursachen gemeinsam mit dem rasanten Bevölkerungswachstum eine zunehmende Zerstörung (Degradation) der Naturressourcen. Dies gefährdet die nachhaltige Versorgung von Weidetieren mit Futter und somit die Existenz der lokalen Nutzer. Trockengebiete sind durch niedrige und zeitlich wie räumlich stark variierende Niederschläge gekennzeichnet. Die Haltung größerer Viehherden ist meistens nur dann möglich, wenn die stark schwankende Verfügbarkeit von Futter durch angepasste Mobilität strategisch genutzt wird. Umfangreiche Forschungen zu solchen Beweidungsstrategien hatte bisher einen Schwerpunkt in den ökologischen oder ökonomischen Aspekten der Nachhaltigkeit. Vernachlässigt wurden dabei die Rückkopplungen zwischen natürlichem und sozialem System, sowie die komplexen Einflüsse verschiedener zeitgleicher Wandelprozesse und deren Übersetzung in Risiken für Landnutzer.

In dieser Arbeit werden die Auswirkungen von Klima- und Landnutzungswandel auf die Existenzsicherung am Beispiel der Berbernomaden im Hohen Atlasgebirge von Marokko analysiert. Um verschiedene Einflussgrößen und ihre kombinierten Auswirkungen auf die pastoralen Haushalte gemeinsam analysieren zu können, wird ein ökologisch-ökonomisches Simulationsmodell entwickelt. Mittels einer neuartigen Risikoanalyse wird ausgewertet, unter welchen Bedingungen die jährlich schwankende Anzahl von Tieren ein existenzsicherndes Einkommen für die Nomadenhaushalte ermöglicht. Dazu werden im Folgenden drei Modellanwendungen vorgestellt.

Die Ergebnisse der ersten Modellauswertung zeigen, dass Auswirkungen des Klimawandels, wie eine für Trockengebiete vorhergesagte erhöhte Niederschlagsvariabilität, geringere Auswirkungen auf die Herdendynamiken haben als eine reduzierte Mobilität. Dies lässt sich durch spezifische Eigenschaften der mehrjährigen Vegetation erklären. Die für den mediterranen Raum typischen Sträucher und Zwergsträucher können auf Reservestoffe zurückgreifen, wodurch die Effekte schwankender Niederschläge auf Primärproduktion und stehende Biomasse zum Teil abgepuffert werden.

In einer weiteren Modellanwendung zur Gefährdung durch Dürren wird gezeigt, dass Dürren nur in seltenen Fällen ausschlaggebend für die pastorale Existenzsicherung sind, weil sich hier mehrere Effekte überlagern. Als Nachweis dient ein hypothetisch konstanter Niederschlag als Referenzfall, der bereits einen Großteil der beobachteten Variabilität von Vegetation und Herden zeigt. In einem eng gekoppelten Weidesystem stellen diese (einer Räuber-Beute-Beziehung entsprechenden) Dynamiken daher bereits eine große Herausforderung für die Existenzsicherung dar. Durch die neuartige Charakterisierung der Haushaltstypen in einer Vulnerabilitätsanalyse wird gezeigt, dass sozio-ökonomische Faktoren einen größeren Einfluss als einzelne Dürreereignisse auf die Existenz der mobilen Haushalte haben.

In der dritten Modellanwendung wird unter Anwendung des *key-resource*-Konzepts

untersucht welche relative Bedeutung die verschiedenen Weidetypen im Atlasgebirge von Marokko, gekennzeichnet durch spezifische Vegetationseigenschaften, für die regionale Nutzung durch die Viehherden der Berbernomaden haben. Es zeigt sich, dass besonders die gemeinschaftlich genutzten Winterweiden essenziell für die langfristige Aufrechterhaltung der Bestände sind. Neben der Produktivität spielt die Fähigkeit Reserven zu speichern eine wesentliche Rolle. An diesem Praxisbeispiel kann das Konzept der *key-resources* überprüft und verfeinert werden.

Mit Hilfe des in dieser Arbeit entwickelten Modells können in einem ganzheitlichen Ansatz die Grenzen und Möglichkeiten des nachhaltigen Weidemanagements aus dem Zusammenspiel vielfältiger Einflussfaktoren identifiziert werden. Daraus lassen sich die relative Bedeutung von Klimawandel und sozio-ökonomischem Wandel für die Existenzsicherung von nomadischen Hirten ableiten. Bemerkenswert ist, dass der Klimawandel gegenüber einer angepassten (adaptiven) Wirtschaftsweise weniger negative Auswirkungen zu haben scheint als bisher angenommen, was die Bedeutung dieser Wirtschaftsweise noch einmal unterstreicht. Ein größerer Risikofaktor für die Existenzsicherung ist der sozio-ökonomische Wandel, wie erhöhte Einkommensansprüche und verringerte Mobilität in Folge von veränderter Landnutzung. Dies geht einher mit einer Diversifizierung von Einkommensquellen in anderen Sektoren, wobei offen ist ob diese Strategie auch langfristig eine nachhaltige Weidetierhaltung aufrechterhalten kann.

Um die Prinzipien nachhaltiger Weidewirtschaft auch einem breiteren Publikum zu verdeutlichen, wird die Entwicklung von einem strategischen Brettspiel beschrieben. Darin können drei bis fünf Spieler in der Rolle eines Hirtennomaden eine Schafherde züchten und werden gleichzeitig durch Ereignisse in komplexe Entscheidungen verwickelt. Mit Hilfe des Spiels werden Grundprinzipien von nachhaltiger Weidewirtschaft vermittelt, zum Beispiel Mobilität und lohnende Schonung von Weiden, aber auch alltägliche Umstände der nomadischen Lebenswelt. So können Zusammenhänge der natürlichen Ressourcennutzung und Existenzsicherung auf besonders verständliche Weise näher gebracht werden.

Durch den problemorientierten Modellieransatz trägt diese Arbeit im besonderen Maße zur Integration von natur- und sozialwissenchaftlichen Ansätzen bei der Erforschung von Weidewirtschaft in Trockengebieten bei. Diese interdisziplinäre Ausrichtung unterstützt ein gegenseitiges Verständnis von Prinzipien der nachhaltigen Landnutzung, die auf weite Regionen der Erde übertragbar ist.

Part I

Introduction

1 Background and Objectives

1.1 The relevance of pastoralism

Sustainable use of natural resources challenges humankind. Pastoralism in drylands is one example of a natural resource use system that is highly dynamic and uncertain. Depending on the environment, pastoralists have developed different strategies to manage livestock and the rangeland and to make a living from it. However, they are facing tremendous climate and land use change affecting both their resource base and livelihood. This involves a complex interplay of the natural and the social system where it is often unclear which factors constitute the driving forces for change. Consequentially, the assessment of risk for pastoral livelihoods becomes a challenging task. One starting point, from where we might develop a comprehensive view of the most important natural and social factors of pastoralism, is the pasture. The state of a pasture reflects climate impacts and at the same time the type and the magnitude of usage by herbivores. Using innovative modelling tools accompanied by a new risk assessment, this thesis aims to investigate pastoral livelihood security which is based on semi-arid and heterogeneous rangelands.

1.1.1 Background of research on animal husbandry in drylands

Many disciplines contributed to the investigation of sustainable animal husbandry, particularly in drylands with its characteristic variability of climate and vegetation. Drylands take up more than 40% of the world's land surface and they are inhabited by 2.1 billion people (MEA, 2005; Neely et al., 2009). Drylands support 50% of the world's livestock, which is the dominant landuse and most important source of income (UNCCD, 2010; Walker and Janssen, 2002). Livestock grazing is often the only option to use arid lands since the dry environment is too harsh for cropping and the infrastructure for irrigated agriculture too costly.

Among other, major disciplines working on pastoralism are ecology, economy, and anthropology but also intermediary ones such as social geography (see for example Galvin, 2009). Regarding range management, ecologists mainly focus on the dynamics in the plant-herbivore system differentiated by the type of ecosystem and the spatio-temporal scale under study (Asner et al., 2004; Campbell and Stafford Smith, 2000). While former ecological studies emphasized a coupling between plant and animal dynamics that tend to reach a carrying capacity (Le Houérou, 1984; Abel, 1993), approaches during the 90's underline the stochastic nature of plant-livestock relations as a non-equilibrium system (Niamir-Fuller and Turner, 1999; Illius and O'Connor, 1999).

Using insights from the ecological perspective, range utilization strategies were economically evaluated often under the heading of support for marginalized households, communities or regions (Fafchamps et al., 1998; McPeak, 2004; Lybbert and McPeak, 2012). The concept of a carrying capacity was often related to an optimal stocking regime despite the uncertain and highly variable nature of vegetation resources. Thus, various range utilization strategies exist, varying from extensive use such as mobile pastoralism to intensive use such as commercial farming practices (FAO, Mountain Partnership Secretariat, UNCCD, SDC, CDE, 2011). However, the economic valuation of mobile pastoralism acknowledges large contributions to the global market, particularly in Africa, where extensive pastoralism surpasses intensive production systems (Davies and Hatfield, 2007).

In contrast to the mainly quantitative perspective by ecologists and economists, studies in anthropology and social geography have focused on the socio-economic system of pastoral livelihoods (for example Niamir-Fuller and Turner, 1999). They identified the value of the local knowledge of pastoral nomads and their adaptive strategies, particularly within the context of globalization and social change (Folke, 2004; Davis, 2005; Fernandez-Gimenez and Le Febre, 2006; Breuer, 2007; Angassa and Oba, 2008; Eisold, 2009; Galvin, 2009).

In summary, research on pastoralism is an interdisciplinary field in which problem-oriented approaches aim to link the single households to a global view or vice versa.

1.1.2 Livelihood security of pastoral nomadic households

Extensive range management varies by the extent to which pastoral households move during the course of the year from highly nomadic through transhumant to agropastoral. The United Nations Development Programme (UNDP) estimated that 100–200 million people rely on strict nomadic or transhumant pastoralism (FAO, Mountain Partnership Secretariat, UNCCD, SDC, CDE, 2011). Nomadism is not fixed to a certain area as movement routes are flexible and mainly related to unpredictable resource availability (Niamir-Fuller and Turner, 1999). Transhumant pastoralism is characterized by seasonal movement between two different regions, such as between high or low altitude ranges (Scoones, 1999). Agropastoralists are partly sedentary, growing crops in the main growing season and moving with their herds in the rest of the year. These classifications are largely simplified and, in fact, pastoralists change between each form in a gradual way as they have the need and options to do so (FAO, Agriculture and Consumer Protection, 2009).

While mobility is one aspect to differentiate between strategies of range management, the reason why people move is another. Herd movements are mostly related to the household-specific basis for livelihood and seldom practiced only for traditional reasons (FAO, Mountain Partnership Secretariat, UNCCD, SDC, CDE, 2011). Pastoral livelihoods differ in the level of subsistence as this is related to the type and size of the herd, forage density, proximity to water and last but not least to the alternative options to make a living from the land. While agropastoralists have diverse income sources and thereby a distributed risk between cropping and herding, nomadic pastoralist need herds large enough to build their complete livelihood from income from pastoral activities (Breuer, 2007). Which strategies can be realized is largely dependent on governmental constraints and regulating institutions (Niamir-Fuller and Turner, 1999; Goodhue and McCarthy, 2009).

Collaborative resource management is an important feature of nomadic communities (Niamir-Fuller and Turner, 1999; FAO, Mountain Partnership Secretariat, UNCCD, SDC, CDE, 2011). Since the demand and scarcity of communal resources, such as forage and water, needs clear regulations, a well-defined membership, kinship networks and social control are an important asset (Murphree, 1997). By mutual aid and collective control, communities face and withstand severe environmental constraints (Argumedo and Pimbert, 2005). Their endurance can often be explained by precise local ecological knowledge on social and ecological interactions (Argumedo and Pimbert, 2005; Eisold, 2009). These assets of manifold social networks are often aggregated with the term of *social capital* (see for example Dougill et al., 2010). Despite this comprehensive set of options for the use of variable resources, pastoralists today are often marginalized due to the loss of rangelands (Hassen, 2008).

1.2 Research questions and methods

From the current state of threats to pastoral livelihoods in drylands, we identify two major challenges and gaps for research. First, pastoralism is a complex social-ecological system with interactions between the natural and the social system that often cause non-linear (unexpected) behavior (Walker et al., 2002). Second, many single aspects of pastoralism have been investigated so far, but their combined effect is unclear. Major issues of interest include consequences of climate change and events of drought (Lybbert et al., 2009; Dougill et al., 2010). Further, the vulnerability towards drought relates to the type of ecosystem and management (Scoones, 1992). The studies presented in this thesis aim to translate observed trends such as climate and land use change to the vulnerability of pastoral livelihoods on a household level. The following questions introduce the particular chapters:

1. How much climate change can be tolerated by pastoral households? (Chapter 4) Our purpose is to identify changes in rainfall regimes that can be coped with by pastoral households, and changes which pose a threat to pastoral livelihood security. We hypothesize that decreasing mean annual precipitation accompanied by increasing variability leads to smaller herd sizes and consequently to increased risks for pastoral livelihoods.

2. When does a drought endanger pastoral livelihoods? (Chapter 5) In this study,

we aim to evaluate how droughts are transmitted by the rangeland ecosystem and when these effects endanger pastoral livelihoods. Households are characterized by their socio-economic background and we expect to differentiate household types by their vulnerability towards droughts.

3. What key traits of dryland vegetation sustain livestock? (Chapter 6) Here we investigate a heterogeneous rangeland system to identify the bottleneck therein that determines the livestock population size.

Since rangeland management and pastoralism are complex social-ecological systems (Walker et al., 2002), we investigate the interdisciplinary set of questions by first developing and then applying an ecological-economic model. This method and its conceptual background is presented in the following.

1.2.1 Complex system analyses using social-ecological models

One promising approach to analyze the social-ecological system is to use an abstract simulation model. The main purpose of this kind of model is to support decision making on resource management questions for example in the context of fisheries, hunting, pastoralism, or small-scale farming (Schlüter et al., 2012a). Model analyses allow a mechanistic understanding (in terms of causal relationships) of the complex system to identify factors that are responsible for the provisioning of ecosystem services (ES). Therefore, factors from both the natural and the social system are included. Figure 1.1 presents an overview of modelling approaches that are closely related to social-ecological models. Pure ecological models focus on the dynamics within the ecosystem with optional feedback relationships between modeled plant or animal species. Herein, the human factor is reduced to an external force which is not subject to change driven by the ecosystem. In contrast, bioeconomic models investigate exactly the feedback between a natural resource and its user who can be a farmer, pastoralist or land manager (termed social planner in Figure 1.1). However, this type of model often neglects the structure and dynamics within the natural resource. Complex social-ecological models combine these different systems and their specific inner structure including a feedback between the social and the natural system, which is an additional level of complexity compared to the former model types. Currently, only few models exists that include the mentioned structures and processes from above at the same time (for example Le et al., 2012). However, this perspective provides a holistic view upon the possible integration of the most important ecological and social drivers in the specific system under study.

Current rangeland models

Rangeland management systems are one example of social-ecological systems (Walker et al., 2002). In general, simulation models provide an opportunity to test basic principles of sustainable management under different socio-economic settings (Müller et al.,

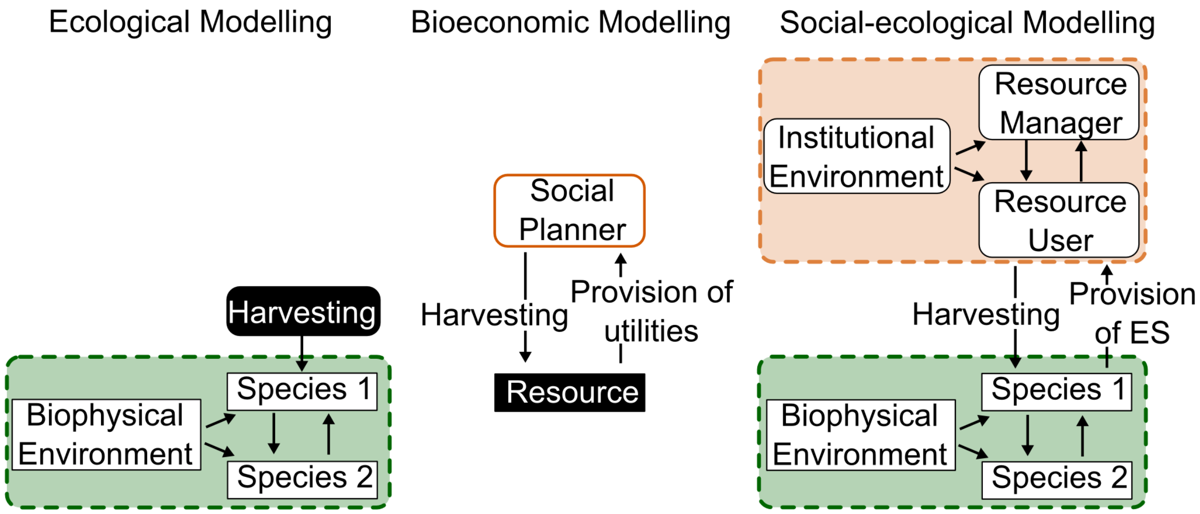


Figure 1.1: The structural elements and included processes of three general modelling approaches. Rectangles denote stocks, boxes with black background denote very simplified factors without internal structure. Social-ecological models aim at a full integration of feedback processes within and between the natural and the social system. Redrawn after Schlüter et al. (2012a) with permission to reprint.

2007b). Specifically, abstract models are suitable for supporting system understanding by generating testable hypotheses rather than making predictions (Epstein, 2008). Many ecologic-economic models were developed to investigate semi-arid rangelands with a focus on economic evaluations (Janssen et al., 2000; Milner-Gulland et al., 2006; Higgins et al., 2007; Quaas et al., 2007; McAllister et al., 2009; Freier et al., 2011). However, only few models assess the effects of changing climatic conditions on pastures and livestock dynamics (for an exception see Köchy et al., 2008) and aim at a generic understanding of rangeland systems (see critical review in Tietjen and Jeltsch, 2007). Moreover, only few studies consider intraseasonal variability (but see Gross et al., 2006; Jakoby, 2011), as most of the ecological-economic models run on an annual timescale.

1.2.2 Structure of this thesis

This introduction is accompanied by a more detailed description of case studies on mobile pastoralism in Southern Morocco (Chapter 2). It is followed by the documentation of the developed rangeland model (Chapter 3), which is the methodological starting point for the subsequent applications. After that, three separate studies build the center piece of this work as they are different applications of the rangeland model. They investigate the three research questions from above and deal with climate change, social change and the identification of key pastures respectively. Chapter 7 uses a different approach than simulation modelling and demonstrates principles of sustainable pastoralism by developing and evaluating a strategic board game. Finally, a synthesis of this thesis and an outlook for further research is provided.

2 Nomadic herdsmen in the High Atlas Mountains, Morocco

The motivation for this investigation and the developed model structure originates from studies conducted on mobile pastoralism and range management in the High Atlas Mountains of Southern Morocco. We present the background of nomadic herdsmen and their livelihoods from a multi-disciplinary perspective. Our aim was to select ecological and economic data on those circumstances under which nomadic herdsmen can maintain their livelihood. Therefore, we review sources for the data on climate, vegetation, and livestock development as well as statements by herdsmen on pasture preferences and utilization strategies. After that, we discuss observed trends in the regions such as climate and land use change to sharpen the focus for our further investigation.

2.1 The environment of nomadic herdsmen in the High Atlas Mountains

Pastoral production has a long tradition in Morocco but it is undergoing dramatic changes during the last decades. Confined to different regions and environments people make use of different strategies to make a living of their land (Barrow and Hicham, 2000).

Moroccos climate can be characterized as subtropical divided by the High Atlas mountain chain into a north-western maritime part and a south-eastern continental part. Regional climates range from moderate at the coast, over subhumid at the mountains to desert climates at the northern boundary of the Sahara. The climate has important implications for the type of agriculture practiced. While in the northern part rainfed and irrigated agriculture is possible, this is restricted to small oases in the southern part. More than 90% of the area is used as extensive grazing area for several kinds of livestock such as cattle, small ruminants and dromedaries.

In the following, we will summarize available data sources that describe the environment used by nomadic pastoralists. Major parts of the study were coordinated by the GLOWA project IMPETUS[1] between 2000–2009 with the objective to analyze, quantify and simulate scarce water resources in the Moroccan catchment of the Wadi Drâa. This is located south of the central High Atlas mountain chain. The working group "Effects of land use and climate change on the resilience of vegetation", where I was part from, investigated plant growth in an area utilized by mobile herdsmen. Several Berber fractions inhabit the Southern slopes of the High Atlas Mountains side by side (Akasbi et al., 2012). We will focus on Ait Toumert nomads in the following.

2.1.1 People and livelihoods

Livestock husbandry is the dominating land use in the Drâa valley and coexists beside crop production in oases which are heavily dependent on irrigation (Kuhn et al., 2010).

[1]http://www.impetus.uni-koeln.de/

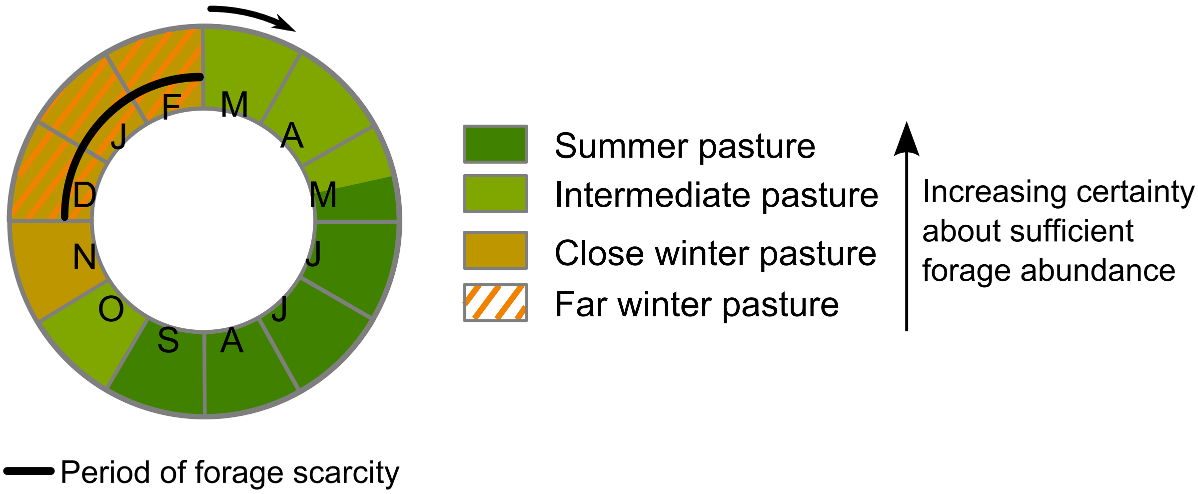


Figure 2.1: The normative transhumance cycle by Ait Toumert nomads. In fact, households often deviate from this cycle leaving out far winter pastures particularly in scarce times. Redrawn from Linstädter et al. (2010)

Although labor migration and tourism increasingly help to diversify income sources, pastoral households mainly depend on income generation from livestock. Extensive pastoral production of sheep and goats is based on transhumance. In an annual mobility pattern Ait Toumert nomads use areas at high altitudes during the summer season and move with their complete households to lower altitudes during winter (see Figure 2.1). In the following, we term the pastures by the season when it is used during the transhumance cycle. While summer pastures are exclusively used by Ait Toumert, they share the winter pastures with neighboring fractions (Rössler et al., 2010), see Figure 2.2. The winter season is characterized by a large uncertainty due to precipitation variability and usage by other pastoralists. In fact, movement decisions differ largely between households dependent on their specific socio-economic background. Some households have alternative income sources from wage labor and can afford supplementary feeding or far distant travel with trucks (Kuhn et al., 2010). For poorer households it depends mostly on their social networks whether they or their herd can move to distant areas or not. Although movement decisions differ, range utilization by Ait Toumert nomads is based on a complex set of management strategies. The exclusively used summer pasture can only be accessed during fixed opening an closing dates which were determined by the community of Ait Toumert (Ilahiane, 1999). A pasture managed in this way is called Agdal, a very common institution throughout the High Atlas region (Gilles et al., 1992). Agreements are possible to transport animals by trucks to distant grazing areas during scarce times (see Table 2.1). Beside mobility, households use a diversity in livestock breeds, feed supplementation or non-pastoral income sources to secure their livelihood.

Summarizing, the Ait Toumert nomads have a very diverse set of strategies (in sensu Fratkin and Mearns, 2003; Fernandez-Gimenez and Le Febre, 2006), including mo-

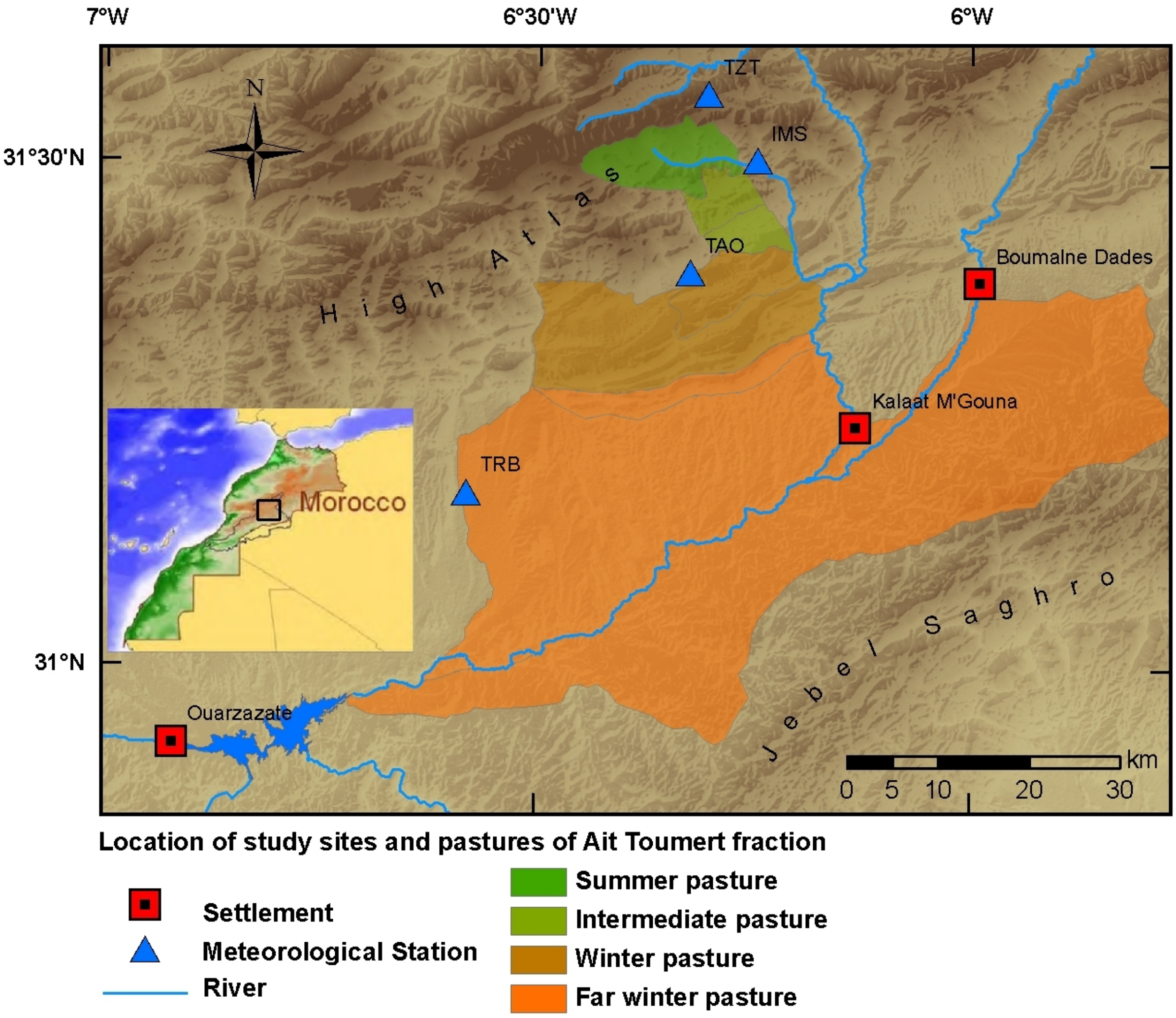


Figure 2.2: Map of study area in Southern Morocco with seasonal pastures utilized by Ait Toumert nomads (from mental maps derived and described by Birgit Kemmerling (Rössler et al., 2010)).

Table 2.1: Pasture areas of the Ait Toumert from north to south (Rössler et al., 2010), classified by their seasonal usage in the transhumance cycle (Linstädter et al., 2010). Area sizes were calculated using the area borders and the digital elevation model. See also the corresponding map in Figure 2.2.

Area name	**Area size (km^2)**	**Classification**	**Area size (ha)**
Awjgal	100.6	Summer pasture	10060.0
Asselda	37.7	Intermediate pasture	7053.5
Imaun	32.8		
Alatagh	77.4	Winter pasture	34889.7
Timassinine	271.5		
Azweg	76.8		
Imlil	818.6	Far winter pasture	116328.5
Sargho	1163.3		

bility, diversity, flexibility and resting, that ensure survival of animals and secure pastoral livelihoods in an arid land. To understand the relation of pastoral strategies to their natural resource base, we take a closer look at the specific constraints by the local climate and vegetation.

2.1.2 Climate and geography

Starting in 2001, climate data was collected from thirteen climate stations along the altitudinal gradient in the Middle and Upper Drâa basin (see Schulz (2008), Figure 2.4). Mean annual precipitation ranges from 150 mm in the basin of Ouarzazate to 800 mm in the mountains.

The climatic gradient can mainly be characterized by an increase in mean annual precipitation (MAP) and decrease in temperature correlating with the altitude. Further, also the intraannual pattern of precipitation differs. While the upper station reported an unimodal course of the year of precipitation, the three lower stations show a bimodal course with maximum peaks in spring and autumn (Schulz, 2007), (see Figure 2.3).

2.1.3 Vegetation and landscape

Different types of vegetation evolved along the rainfall and temperature gradient with other factors such as soil composition (Finckh and Poete, 2008; Finckh and Goldbach, 2010). At the lower altitudes between 1200 m a.s.l and 2000 m a.s.l., the *Hammada*

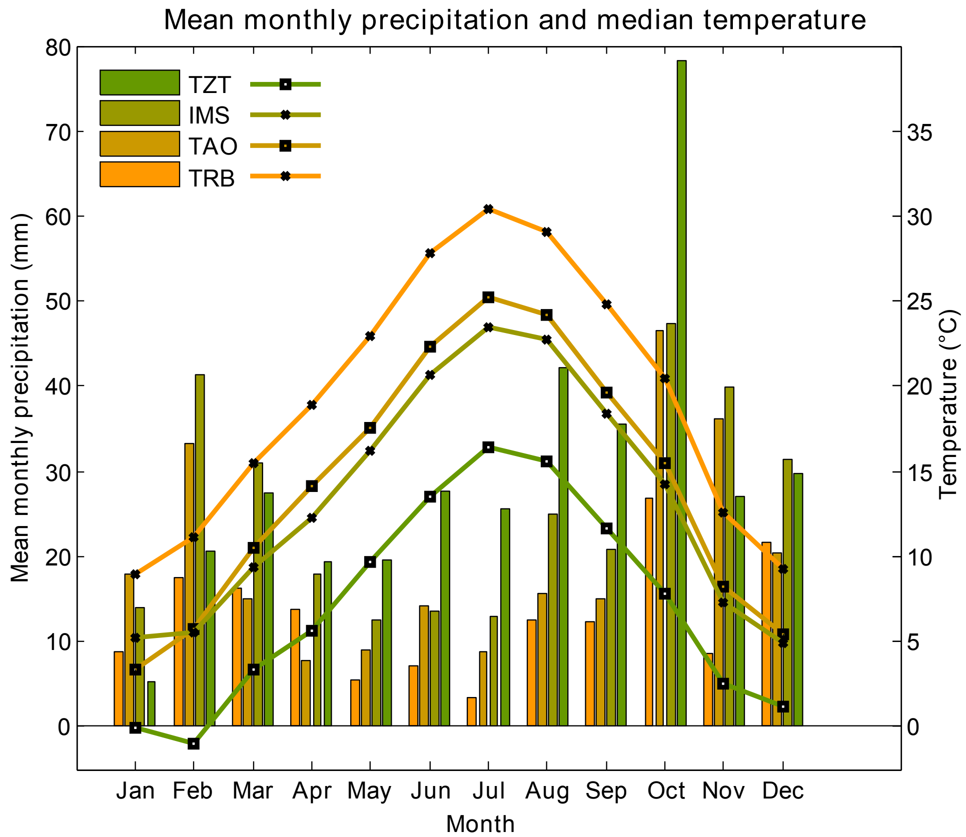


Figure 2.3: Climograph for four climate stations with the mean monthly precipitation calculated from data on daily basis measured between September 2001-August 2008. The median temperature per month is based on mean daily temperatures (Schulz, 2008; Schulz et al., 2010).

and *Artemisia* steppe receive less than 200 mm rainfall per year and are dominated by dwarf shrubs, *Hammada scoparia* and *Artemisia herba-alba* respectively, growing very sparse (see Figure 2.5, left). The presence of several annual grasses and herbs varies due to rainfall. The *Artemisia* steppe is traditionally appreciated as a grazing area (Roth, 2010). Especially close to villages, perennial forbs and grasses with high forage value become rare (Baumann, 2009).

Figure 2.4: Climate station in Taoujgalt, Southern Morocco.

Roughly between 2000 m a.s.l. and 2500 m a.s.l., the landscape is dominated by *Juniper* woodsteppes. These are open sclerophyllous forests of *Juniperus phoenicea* and *Juniperus thurifera* accompanied by several chamaephytes. This zone is characterized by steep slopes and shallow soils so that plant growth is dependent on slope exposition where erosion by wind and rain is a little less intense.

In the area utilized by Ait Toumert nomads, four climate stations are located along the altitudinal and aridity gradient (Table 2.2). Close to the climate stations were grazing exclosures installed where plant productivity was measured.

At the highest level above 2500 m a.s.l., the oromediterranean shrubland can be found. Facing extreme abiotic conditions with a very short growing season, tree growth is not possible. The vegetation is dominated by xerophytic and often thorny shrubs, associated with dwarf shrubs or perennial grasses (see Figure 2.5-right, and Baumann (2009) for more details.).

Table 2.2: Climatic variables from study sites along the altitudinal gradient of the southern High Atlas slopes. Mean annual precipitation (MAP) and temperature was measured on a daily basis between September 2001 and August 2008 (Schulz, 2008; Schulz et al., 2010)

Station	**Altitude m a.s.l.**	**MAP** (mm)	**Temperature min, max (°C)**
Tizi-N-Tounza (TZT)	2960	358	-10.5, 18.8
Imeskar (IMS)	2250	317	-4.2, 25.5
Taojgalt (TAO)	1870	240	-1.4, 27.5
Trab Labied (TRB)	1380	152	3, 32.6

Figure 2.5: Left: Winter pasture, Right: Summer pasture (Photos: G. Baumann)

Within the IMPETUS work group for rangeland ecology, vegetation productivity was measured in order to derive indicators of grazing impact. Therefore, exclosures starting in 2001 and in 2007 were build on four study sites along the altitudinal gradient. Plant growth was measured in 2008 (Table 2.3). The ANOVA evaluation for standing crop and aboveground net primary productivity (ANPP) has shown a strong effect along the altitude, but no effect comparing the recovery between short-term and long-term exclosures (Baumann, 2009).

Our further aim was to identify the growth rate for each pasture's vegetation on a per area basis independently from the current precipitation and standing biomass. By this normalization, productivity would be comparable along the rainfall gradient and between pasture types with different vegetation density. The normalization by precipitation is termed rain-use efficiency (RUE) and was initially introduced as an indicator of grazing impact by Le Houérou (1984). Thus, a linear relationship between rainfall and production (= constant rain-use efficiency) is not realistic but often implemented (Ruppert et al., in press 2012). The normalization by standing biomass results in a relative growth rate which was evaluated as functional plant trait before (see e.g. Poorter and Garnier, 2007; Garnier and Navas, 2012). The combination of both normalizations, vegetation growth related to precipitation and precedent biomass, was evaluated to test its usability as indicator for degradation of pastures (Baumann, 2009; Steinschulte, 2011). RUE_{rel} was found to decrease with altitude which was probably related to soil effects (Baumann, 2009).

Table 2.3: Vegetation characteristics from study sites along the altitudinal gradient of the southern High Atlas slopes (2007 to 2008). Standing crop was measured on long-term exclosure plots (LTE) (Baumann, 2009, Tab. 5.3). The aboveground net primary production (ANPP) was provided for shrub vegetation (Linstädter and Baumann, 2013, Fig. 5), and the relative rain use efficiency (RUE_{rel}) (Baumann (2009), see detailed explanation in the text).

Station	**Standing crop LTE** ($kg \cdot ha^{-1}$)	$\mathbf{ANPP}_{rel}$ ($kg \cdot (kg \cdot \textit{growth period})^{-1}$)	$\mathbf{RUE}_{rel}$ ($kg \cdot (kg \cdot \textit{growth period} \cdot mm)^{-1}$)
TZT	5249	0.36	0.0007
IMS	2518	0.54	0.0014
TAO	2146	0.45	0.003
TRB	437	0.14	0.004

2.1.4 Sheep and goats

Sheep and goats are usually mixed in one herd where the proportion management is one strategy to adapt to available forage resources. Due to their specific dietary preferences, co-grazing of sheep and goats has the advantage to make use of a diverse vegetation (Animut and Goetsch, 2008). However, nomadic herds in Morocco compete for forage and water resources with sedentary herds close to villages.

Supplementary feeding is a very usual strategy and pastoralists would only reduce feeding in years with forage availability above average (Kemmerling, 2008). In years of drought, also mass selling or far distant truck transport is practiced (Kuhn et al., 2010). Liable data on livestock numbers in the Drâa valley is very rare. Interviews with herdsmen resulted in estimations of herd sizes between 150 and 1000 head, but the average herd size of Ait Toumert households was roughly 200 heads (pers. comm. Birgit Kemmerling, 2008). This results in a rough estimate of about 0.5 sheep per ha assuming that Ait Toumert nomads use the same area size during winter on the communal pastures as on their exclusively used summer pastures. Very recent studies report an average herd size of 600 animals per household (Akasbi et al., 2012), but this estimation probably includes accompanying herds from relative sedentary families.

2.2 Current changes that endanger pastoral livelihoods

Pastoralism in southern Morocco is representative for many pastoral systems in dryland areas around the world such as in Spain (Olea and Mateo-Tomás, 2009), Pakistan (Omer et al., 2006), Kazakhstan (Milner-Gulland et al., 2006), and Mongolia (Zemmrich et al., 2010). Most of these drylands face decreasing precipitation and increasing

Table 2.4: Observed trends in agricultural development in the High Atlas Mountains.

	Issue	Possible causes
1.	Rainfall (Decreasing MAP, increasing variability)	Climate change (Paeth et al., 2009; Linstädter et al., 2010)
2.	Degradation	Climate and landuse change, population growth (Barrow and Hicham, 2000; Johnson, 1996)
3.	Pasture division	Privatization, state encroachment (Barrow and Hicham, 2000; FAO, Mountain Partnership Secretariat, UNCCD, SDC, CDE, 2011)
4.	Increased demands	Population growth, market (Barrow and Hicham, 2000)
5.	Diversification of income	Unreliability of pastoralism (Breuer, 2007; Kuhn et al., 2010)

precipitation variability due to climate change. Western Africa is likely to face a reduction of precipitation by 10–30% during the 21st century (Paeth et al., 2009).

Besides climate change, several changes in land use, social networks and economic constraints were observed (see Table 2.4). Areas close to growing settlements become degraded due to mainly immobile livestock grazing. However, a general trend of degradation of nomadic pastures is very debatable since mostly, the assertion that nomads would degrade their land cannot be confirmed (Davis, 2005). This is more likely a local phenomenon which can be caused by fragmentation and particularly an increased pressure due to reduced access to remaining rangelands (Galvin, 2009). Partly sedentary or former mobile pastoralists diversify their livelihoods by growing crops in irrigated areas or by sending family members to cities for wage labor (Breuer, 2007). Given the set of climatic and socio-economic changes, the future development of pastoralism in Morocco is very uncertain.

2.3 Preprocessing of available data

To use general characteristics from Morocco for the calibration in our simulation model, I reexamined collected climate and vegetation data.

2.3.1 Precipitation series

Daily precipitation was aggregated for hydrological years starting in September and running till August. Since the original time series consists of only seven years (September 2001 - August 2008), it is not reasonable to derive a long-term probility distribu-

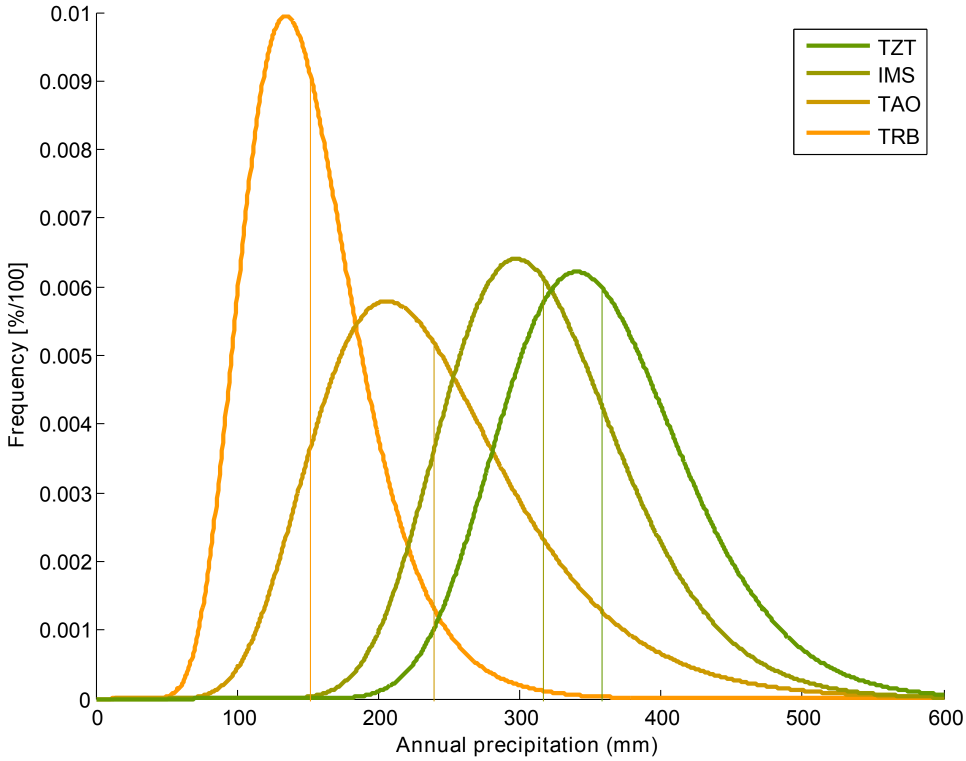


Figure 2.6: Log-normal probability distribution functions of annual precipitation at case study stations. Mean annual precipitation at each station is denoted by a vertical line.

tion. However, for dryland areas the log-normal distribution has been frequently used to describe dryland ecosystem models before due to its skew to the right (e.g. Sandford, 1982; Williams and Albertson, 2006). The log-normal distribution captures interannual precipitation variability with years of below-average precipitation being typically more frequent than years with above-average rainfall. Therefore, we parameterized the log-normal distribution with the mean annual precipitation and its variability for each station (see Table 2.2). Log-normal distributions were visualized by their probability distribution function (Figure 2.6).

2.3.2 Vegetation types and productivity

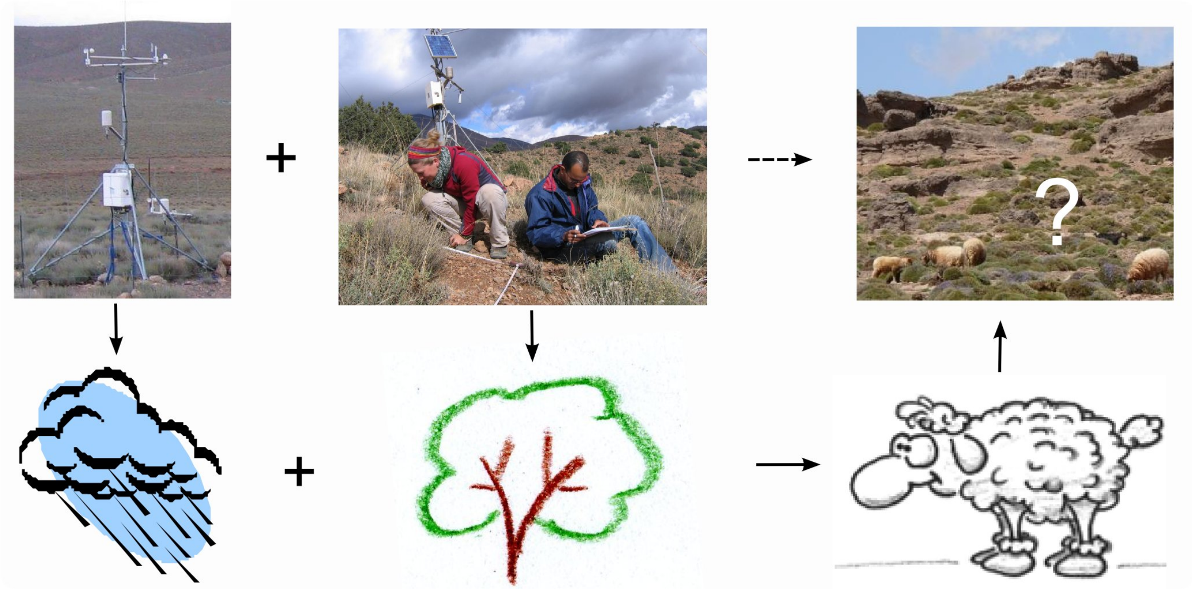
The vegetation on pastures along the altitudinal gradient can be characterized by their amount of standing crop, the relative growth rate and an average forage plant type Table 2.5. For the matter of qualitative comparison instead of quantitative precision, we rounded the values for the estimated maximum of standing crop. By doing so, we increased the value for the second station slightly (IMS), since this site was under heavy use by livestock from the close-by village (pers. communication G.Baumann,

Table 2.5: Vegetation characteristics estimated from study sites, High Atlas (2007 to 2008). Standing crop from longterm-exclosure plots (LTE) rounded upwards, the percentage of perennial plants within the amount of standing crop is provided (Baumann, 2009, Tab. 5.3). The relation of herbaceous to ligneous biomass was adapted for one station (measured value in brackets, see text for explanation).

Station	**Standing crop LTE (**kg · ha^{-1}**)**	**% perennials on STE**	**her/lig biomass**
TZT	5000	100	0.35
IMS	3000	100	0.4 (0.27)
TAO	2000	95.3	0.84
TRB	500	49.8	0.96

2008). For the same reason, we increased the ratio of herbaceous to ligneous biomass. We used this ratio as a very rough estimate of an average plant type.

3 Development of the rangeland model



In this chapter, we explain how abstract rule-based models can be helpful in tackling complex system analyses in general. My purpose is to introduce general ideas about toy models regarding their application and development requirements. This perspective aids to use model representations as thinking tools that lead to open up 'black boxes' in science. Something like a 'guided tour into model development and scrutiny' is described by a recent model documentation format (Schmolke et al., 2010).

In specific, we apply this format to provide perspectives on the rangeland model development beyond its static architecture and aim to integrate the reasons for design, links to calibration data and testing procedures. Finally, the overview of model versions and scenarios provides an entry point to the studies developed in this thesis for investigating mobile pastoralism.

3.1 A rationality for 'toy models' – options for application

The term 'toy model' denotes a type of abstract computational models which is mostly used for the purpose of general system understanding (Schlüter et al., 2012b). Users seek to examine and to discuss model behavior qualitatively rather than to make exact numerical predictions. The rules and the structure of the model enable to generate hypotheses about the behavior of certain variables of interest. Classification of model types can be based on the properties or the purpose. Levins (1966) identified three model properties that relate in a trade off to each other, namely reality, generality, and precision. While optimizing two traits, the third is sacrificed, which is illustrated via a triangle denoting the diverging relationship.

In our case, we developed a toy model to investigate how the dynamics of a livestock population is affected by stochastic precipitation mediated by forage production. Rather than seeking a certain number of heads, we want to identify whether the herd size is generally increasing, oscillating or collapsing under different environmental constraints. To achieve this, we develop a model which includes the structural links between precipitation, vegetation and herbivores. Mathematical functions provide the rules which can be calculated in a computer program. Some parameters of the utilized functions can be measured in the system under study, others remain unknown in their specific value. For the latter case, we vary parameter values and check for the response in the variable of interest. When the response is more intensive than the change in the parameter value, the response is identified as sensitive towards the tested parameter.

Another approach to determine meaningful parameter ranges in a qualitative way is called pattern-oriented modelling (Grimm et al., 2005). First, this is done by specifying feasible modes of model behavior that are expected in the real system (see for an example Jakoby, 2011). In our case, we expect that the simulated rangeland shows a more or less stable level of biomass and herd size under a stable rainfall regime rather than to degrade. The second step is to test a range of parameter values that allow simulations of stable rangelands without degradation which is exemplified in Section 3.2.1.

The results of model simulations can be viewed as best guesses or estimations of 'what happens if'-typed questions until there is a more detailed model specification. Thus for example, model results can be used to refine field studies so that hypotheses can be confronted with data. Often models can be used for experiments that are impossible or too costly to conduct in the real system.

3.2 Model documentation via TRACE

In order to make computational models more transparent and accessible to the research community, several standards for model descriptions were developed. One standard protocol for individual-based models, namely ODD (short for overview, design and details), was introduced by Grimm et al. (2006) and updated on the basis of an extensive review on models using ODD (Grimm et al., 2010). One drawback of this protocol is that several steps of the model development process are omitted which would be helpful for model application in environmental decision making contexts. Typically, one develops and uses several versions of one model in an iterative process to find out at which level of complexity results are meaningful and comparable. If models are confronted with question related to complex social-ecological systems, also non-modellers need a feasible access to the model to address their questions and to interpret results in a scientifically sound way. Therefore, a standard format was developed for documenting models in the context of environmental decision making (Schmolke et al., 2010). This format comprehends the main model development steps and fosters their documentation on a level of 'good modelling practice'. Therefore, it is advisable to maintain the documentation in a modelling notebook as it is commonly done in laboratories with lab notebooks. The following sections present an extract from the notebook documentation on the rangeland model. As natural language descriptions of computer programs still may be unintentional misleading (Ince et al., 2012), access to the digital code can be requested from the author.

3.2.1 Development

This section covers roughly two thirds of the modelling cycle described by Schmolke et al. (2010) which includes sections for the analysis and the application of the model. Model development steps start with the formulation of the problem followed by the formal model design. This is followed by details on the implementation and the parameter calibration, which is important to link the designed model to a specific case study.

Problem formulation

The formulation of problems is mainly referring to the specific research questions at the beginning of each study (Section 1.2). We aim to test precipitation scenarios, which are subject to climate change, in their effects on vegetation, livestock and pastoral households (Figure 3.1). Therefore, a mechanistic representation of processes between the vegetation, which is dependent on precipitation, and livestock is necessary. Depending on different optional mobility strategies, smallstock dynamics result from the simulation. Finally, hed sizes can be evaluated related to different household demand levels in terms of the minimum required herdsize.

Model design and formulation

Pastoralism can be represented as social-ecological system including households as actors that decide on the management of their livestock in the bio-physical environment (Section 1.1.1). We focus on the dynamic interactions of vegetation and livestock driven by precipitation rather on the decision process by pastoralists (Figure 3.2). Different management strategies are integrated through comparative scenario evaluations. In the following, single parts of the model are described in detail, namely the vegetation model and the livestock model.

Vegetation model The purpose of our vegetation model is to simulate annual forage production in a semi-arid rangeland under the impact of grazing and variable precipitation (similar to Müller et al., 2007b). We focus on perennial plants and their ability to provide forage resources since the vegetation from our case study in Morocco is dominated by shrubs and perennial grasses (Baumann, 2009; Linstädter and Baumann, 2013). There, we found four different vegetation types situated along an altitudinal gradient, ranging from the *Hammada* semidesert, *Artemisia* steppe, *Juniperus* woodsteppe, to an Oromediterranean shrubland.

Functional comparable, mainly mountainous, ecosystems with the utilization form of mobile pastoralism can be found in Spain (Olea and Mateo-Tomás, 2009), Pakistan (Omer et al., 2006), Kazakhstan (Milner-Gulland et al., 2006), and Mongolia (Zemmrich et al., 2010). For the simulation of precipitation we used a log-normal distribution to capture interannual precipitation variability with years of below-average precipitation being typically more frequent than years with above-average rainfall. Due to its skew to the right, the log-normal distribution has been frequently used in dryland ecosystem models before (e.g. Sandford, 1982; Williams and Albertson, 2006).

Perennial vegetation was simulated on the basis of two functionally complementary parts, namely green (G - photosynthetically active) biomass and reserve (R - woody) biomass (Noy-Meir, 1982). The reserve biomass quantifies storage of nutrients (Owen-Smith, 2008), which is not only influenced by rainfall but also by grazing history (O'Connor and Everson, 1998). This is congruent with previous models (Müller et al., 2007a; Jakoby, 2011). In contrast to previous models, we assumed that shrubs may carry over green biomass to the next year and that parts of reserve biomass are palatable. We considered this to be more realistic for shrub individuals found in Morocco as opposed to perennial grasses for which the concept of reserve biomass was originally

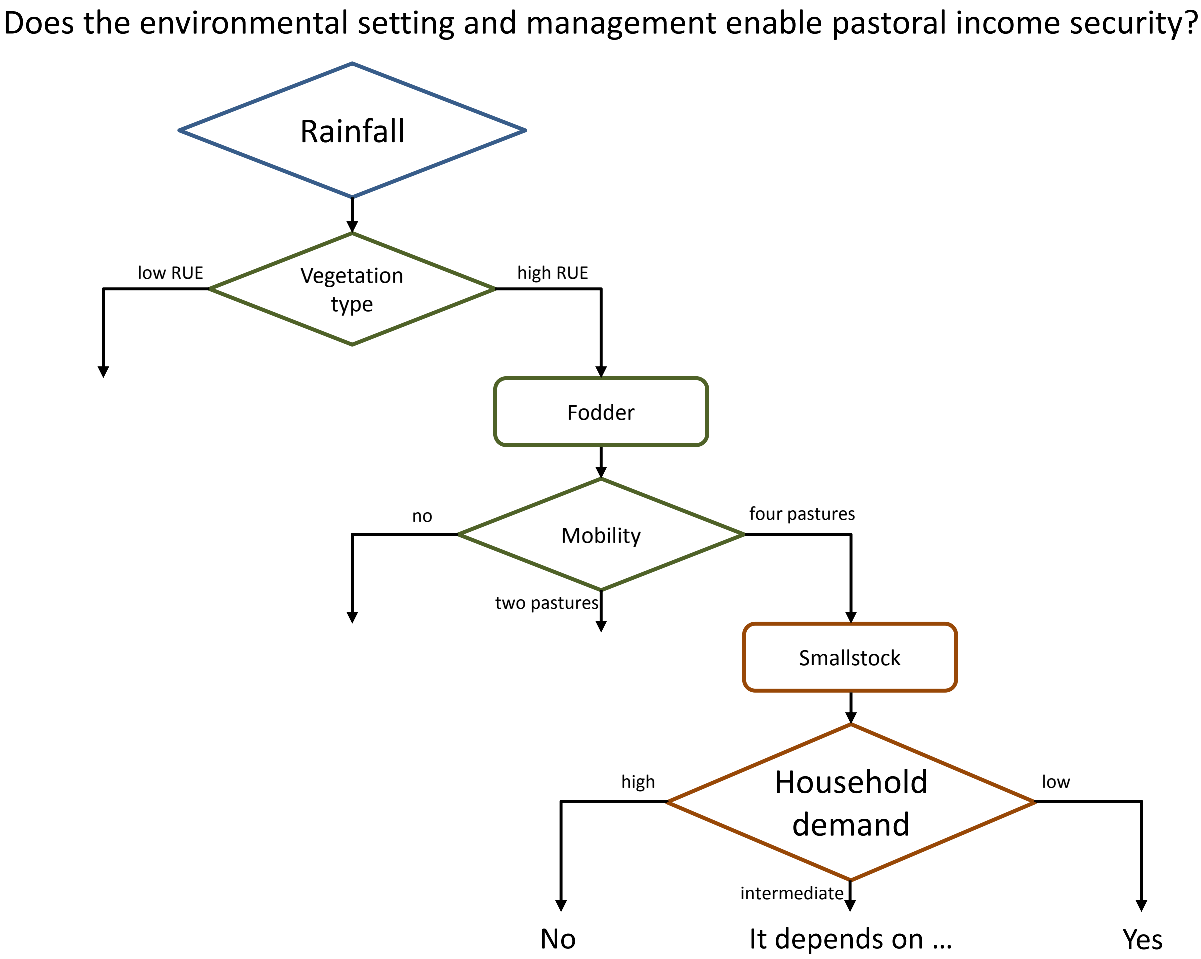


Figure 3.1: One simplified optional storyline from the question to answers through model evaluation and assessment. Diamonds represent several aspects that differentiate the consequences in the following calculation step (scenarios). Several stocks (rectangle) such as fodder and the herd size of smallstock are monitored to compared between different scenarios.

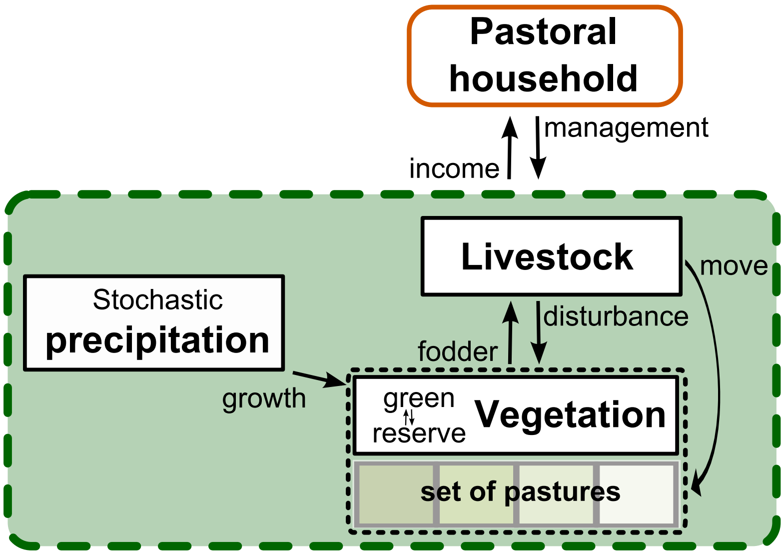


Figure 3.2: The structure and processes represented by our spatial-explicit rangeland model.

developed (Müller et al., 2007a).

Equation 3.1 describes the calculation of green biomass (G) in the beginning of the simulation year *t* including a term for growth and a term of mortality.

$$G_t\ [\text{kg/ha}] = G_{t-1} + \text{rain}_t(mean, CV) \cdot \text{RUE}_{R\to G} \cdot R_t - m_G \cdot G_{t-1} \quad (\text{with } G_t/R_t \leq \lambda) \tag{3.1}$$

where G_{t-1} denotes the carry over from last year, $\text{RUE}_{R\to G}$ the specific rain use efficiency for green biomass from reserve biomass in units of mm^{-1}, R_t the currently standing reserve biomass, and m_G denotes the fractional mortality of green biomass. The threshold λ (G/R) denotes a capacity of how much green biomass may grow from reserve biomass. Values of $\lambda < 1$ describe shrub-like vegetation and values > 1 perennial grasses. For simplicity, we assume that the amount of green biomass growth per year is equally distributed over the seasons. While we assume no density dependence in green biomass growth, growth of reserve biomass is density dependent (Equation 3.2).

$$R_{t+1}\ [\text{kg/ha}] = R_t + \underbrace{w \cdot \big(p \cdot gr_1 + (1-p)\big) \cdot G_t \cdot d \cdot R_t}_{\text{growth}} - \underbrace{(m_R + gr_2) \cdot R_t}_{\text{reduction}} \tag{3.2}$$

with w denoting the recovery rate, p the portion of the grazed pasture, gr_1 the harshness of grazing which impacts the recovery of reserve biomass (values ranging from 0 to 1, where 0 denotes a strong impact by grazing and thereby low regeneration), G_t the complete green biomass before grazing, d the density dependent factor ($1/R_{max}$), m_R the mortality rate of reserve biomass (values ranging from 0 to 1), and gr_2 the fraction of grazed reserve biomass (value ranging from 0 to p_R which denotes the maximum part of palatable reserve biomass). The fraction p of the grazed pasture is calculated using the amount of grazed forage related to the previously available forage. Vegetation processes are computed separately for each pasture. Parameter values can vary between the pastures for specific evaluations see Table 3.1.

Via the concept of reserve biomass, our model implements a feedback mechanism between vegetation state and grazing. High grazing pressure leads to a decreased ability of perennial plants to refill their storage, and thus to a reduction of reserve biomass. Grazing pressure thus had an indirect effect on the growth of green biomass in the following year. In contrast, specific rain use efficiency was set constant for a certain vegetation type and used to compare grazing effects on different pasture types with intrinsically different abilities to produce green biomass. This approach is in agreement with empirical data from our case study showing that specific rain use efficiency changed considerably between pasture types arranged along an altitudinal gradient (Linstädter and Baumann, 2013).

Livestock model We simulated the mobility and browsing of a smallstock herd consisting of sheep and goats. We assumed that no supplementary feed was provided. Thus, smallstock population dynamics were assumed to be solely dependent on available forage from local pastures. In each season animals move to the pasture with the highest abundance of green biomass (see Figure 3.3). We compare three resource

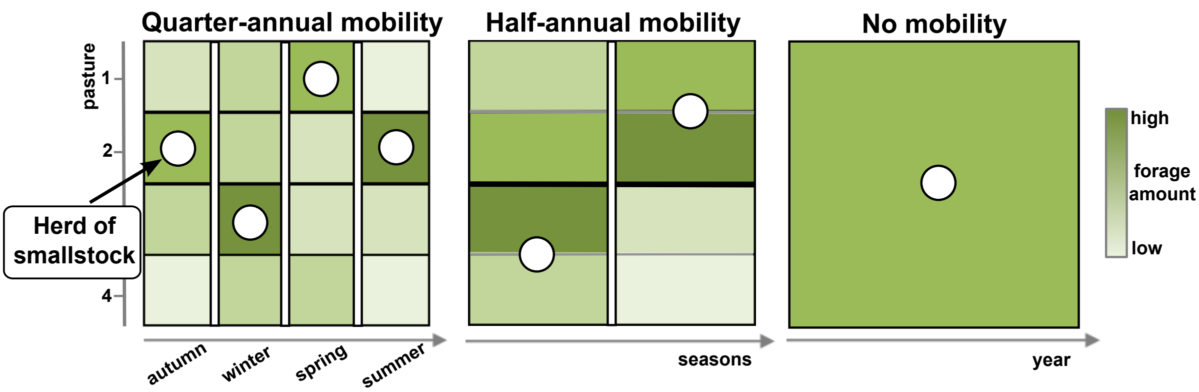


Figure 3.3: Herd movement over seasons, indicated by dots. Animals are always moved to the pasture with the highest abundance of green forage.

utilization strategies. First, the pasture area is divided into four separate pastures. Second, the pasture area is divided into two equally sized parts where each separate pasture is used during half of the year. Third, a scenario of no interseasonal mobility, where animals may use the same pasture throughout the year. In the event of movements between pastures (or in the no-mobility scenario at the end of the year), herds can be destocked if the amount of available forage is not sufficient. The amount of available forage for each season t is calculated by

$$\text{forage}_\text{t} = (G_t + R_p \cdot R_t) \cdot \text{pasture size}. \tag{3.3}$$

The forage demand by the smallstock herd is calculated for each season and the flock size is adjusted in case the available forage is not sufficient:

$$\begin{aligned} \text{demand}_\text{t} &= \text{herd size}_\text{t} \cdot \text{season length(days)} \cdot \text{daily intake} \\ &\quad (\text{if demand}_\text{t} > \text{forage}_\text{t} \rightarrow \\ &\quad \text{head of smallstock}_\text{t} = \text{forage}_\text{t}/(\text{season length} \cdot \text{daily intake})) \end{aligned} \tag{3.4}$$

where daily intake is assumed to be constant with a value of 2 kg dry matter/day, since empirical studies estimate daily intake of sheep and goats ranging between 1 and 2.5 kg dry matter per day (Carles, 1983; Peacock, 1996). Once a year animals may reproduce by

$$\text{animals}_{t+1} = \text{animals}_t + \text{animals}_t \cdot b \tag{3.5}$$

where b denotes the annual growth rate.

Implementation

The model was implemented in the computing environment Matlab version 7.1 and 10. The order of intraannual processes is scheduled as follows: First, we calculate the growth of forage and its equal distribution over seasons. Second, we simulate herd movement, grazing and recruitment. Third, we calculate the recovery of vegetation. (See Figure A.1 for an illustration of seasonal pasture development and herd movement, and Figure A.2 as an example for a single run of herd size dynamics based on three mobility scenarios.)

Parameterization and calibration

To evaluate the income by one household, we adapted the pasture size roughly to gain a minimum viable herd size of small ruminants. The minimum viable herd size is defined as that size where a herd regrows fast enough after breakdowns that the household is able to maintain its living dependent on livestock (Niamir-Fuller and Turner, 1999; LEGS, 2009). We did not find consistent estimations on the minimal herd size, neither for cattle nor for smallstock herds, since this size is very sensitive towards specific environmental conditions (LEGS, 2009). Dahl and Hjort (1976) assumed that a minimum of 30 livestock units, which are roughly equivalent to heads of cattle, are required in semi-arid regions. Following Dahl and Hjort (1976), one livestock unit equals six sheep or goats. Thus, we assume the minimum viable herd size to be $6 \cdot 30 = 180$ animals. This number is supported by empirical data on pure pastoral households in the High Atlas Mountains of Morocco (Breuer, 2007). Accordingly, we scaled the pasture area in our model to provide sufficient amount of forage for 180 head of smallstock under average rainfall conditions.

The initial standing crop of reserve biomass was set to half of the maximum capacity of reserve biomass. Plant growth was assumed to be sigmoid for ungrazed vegetation (Köchy et al., 2008) and reserve biomass was expected to be maintained under moderate grazing to assure realistic mortality rates (Table 3.1). This approach of identifying realistic parameter ranges for empirical patterns is similar to inverse or pattern-oriented modelling (Jakoby, 2011). Values for rain use efficiency and for the relation of green to reserve biomass were estimated based on an empirical study in the semi-arid rangelands of the High Atlas Mountains, Morocco (Baumann, 2009; Linstädter and Baumann, 2013) which provides data on pasture productivity and recovery Section 2.1.3. A linear relationship between rainfall and production (= constant rain-use efficiency) is not realistic but often implemented (Ruppert et al., in press 2012). In our model, this relationship is counterbalanced by the density dependence of vegetation growth. Our resulting stocking rates of close to 0.5 heads of smallstock per ha match previous estimations from empirical data and a bio-economic model in the same region (Freier et al., 2011).

Beside the already mentioned parameters, the suitable range of the remaining parameters w, gr_1, b and $m_{R,G}$. One condition that had to be fulfilled by the model was that vegetation should not degrade in the long-term under 'normal' circumstances where livestock is naturally regulated by forage availability. Therefore, the following equation must be fulfilled:

$$\underbrace{w \cdot \big(p \cdot gr_1 + (1-p)\big) \cdot G_t \cdot d \cdot R_t}_{\text{growth}} > \underbrace{(m_R + gr_2) \cdot R_t}_{\text{reduction}} \tag{3.6}$$

or

$$m_R < w \cdot \big(p \cdot gr_1 + (1-p)\big) \cdot G_t \cdot d - gr_2 \tag{3.7}$$

This function can be evaluated for different values of green biomass (G_t) or the grazed part of the pasture (p) and results in a maximum mortality rate under which reserve biomass would maintain. In Figure 3.4 we can see maximum tolerable mortality rate dependent on parameter values in gr_1 and w denoted by a surface. Below the surface lie parameters that allow reserve biomass growth, above the surface reserve biomass would degrade. One can see that gr_1 and w have a similar effect on the tolerable mortality rate and gr_1 is triggered by the partition of the grazed pasture. If green biomass is absent, no recovery of reserve biomass is possible. An overview of parameters is given in Table 3.1 with links to their sources if available (compare to Müller et al., 2007a; Schulze, 2011). For the first calibration, homogeneous pasture parameters were roughly averaged in contrast to the second calibration where heterogeneous pastures are parameterized (see for details on the latter Chapter 6).

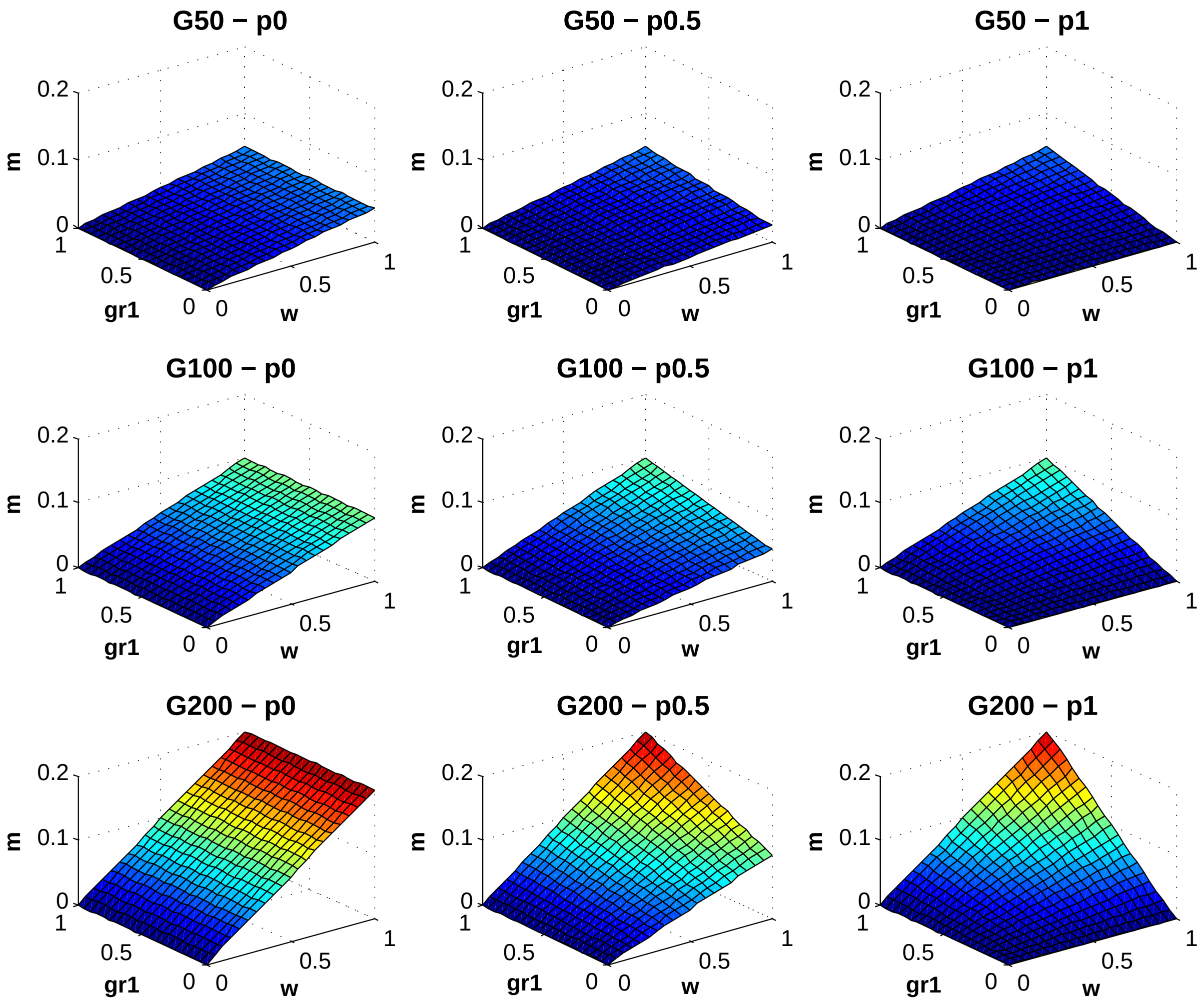


Figure 3.4: Surfaces of maximum tolerable mortality rates dependent on parameters gr_1, w, and variables G, p. The parameter space below the surface allows recovery of reserve biomass, above the surface reserve degrades.

Table 3.1: Parameters for the rangeland model with specification and default values. Sets of values differentiate characteristics of heterogeneous pastures along an altitudinal gradient from top to bottom.

Parameter	**Description**	**Values and unit (hom. | het.)**	**Equation, Sources**
$Precipitation_t$	Dataset with MAP values derived from a log-normal distribution, parameterized with the expected mean and coefficient of variance	150–350 mm, CV 0.2–0.4 | 360, 320, 240, 150 mm, *CV* 0.2, 0.2, 0.3, 0.3 (% /100)	1
$\mathrm{RUE}_{R\to G}$	Specific Rain Use Efficiency, the specific growth rate related to the reserve biomass	0.001 | $0.7 \cdot 10^{-3}, 1.4 \cdot 10^{-3}, 3 \cdot 10^{-1}, 4 \cdot 10^{-1}$ mm^{-1}	Equation 3.1, (Baumann, 2009)
m_G	Mortality rate of green (G) biomass per year	0.3	Equation 3.1
m_R	Mortality rate of reserve (R) biomass per year	0.05	Equation 3.2, (Schulze, 2011)
w	Rate of recovery of the reserve based on green biomass	0.8 | 0.6	Equation 3.2, (Schulze, 2011)
gr_1	Disturbance of w by grazing	0.5 | 0.4	Equation 3.2, (c.f. Müller et al., 2007a)
d	Carrying capacity of reserve biomass $= 1/R_{\max}$	1/(1000 kg) | 1/(5000, 3000, 2000, 500 kg)	Equation 3.2
R_{init}	Initial standing crop of reserve biomass	500 | 1000, 1000, 500, 300 $\mathrm{kg} \cdot \mathrm{ha}^{-1}$	(Baumann, 2009)
$\lambda = G/R$	Maximum proportion of green to reserve biomass, capacity for green growth	0.5 | 0.35, 0.4, 0.84, 0.96	Equation 3.1, (Baumann, 2009)
R_p	Maximum fraction of palatable reserve biomass, actual values stored in gr_2	0.1	Equation 3.3
b	Intrinsic annual growth rate of livestock population	0.2	Equation 3.5
Daily intake	Amount of dry matter grazed by animals	2 $\mathrm{kg} \cdot \mathrm{day}^{-1}$	
ΣW	Aggregated size of pastures	480 ha | 1200 ha	Equation 3.2

3.2.2 Analysis

To get a first impression on how parameter values affect the resulting herd size and its variability, we varied each parameter between its minimum and maximum values. Thus, this is not a sensitivity analysis in the strict sense where the effect of a parameter change is compared to the change in the result. However, these evaluations support the understanding of the general model behavior under varying conditions and which parameter ranges are useful to evaluate reasonable results.

Verification and sensitivity analysis

To exemplify how we analyzed the rangeland model, two parameter analyses are presented here. Figure 3.5 shows the evaluation of herd size dynamics based on variations in the recovery rate of reserve biomass (w) and the livestock growth rate (b) and we compare three different mobility scenarios. Increases in w cause higher herd sizes, values lower than 0.5 lead to long-term degradation. Interestingly, the herd sizes do not differ much between the quarter-annual and the half-annual scenario but the no mobility scenario resulted in much lower herd sizes throughout the parameter range. Further, very low growth rates of livestock ($b < 0.2$) supported higher herd sizes than high growth rates. This was explained by forage stocks that accumulated when livestock growth was much slower than vegetation growth. In contrast, very high livestock growth rates were not able to degrade the vegetation since we modeled adaptive stocking rules where in each season with less forage than demand, the livestock number was adapted to the maximum available forage. Variations in the mortality rate of green biomass (m_G – 0.05–0.8) had no effect on the herd size. This can be explained by the sequence of calculations. The complete amount of green biomass after grazing contributes to the recovery of reserve biomass. Thus, the reduction of green biomass from the last year can be mainly replenished by growth in the current year.

Validation

Since the main purpose of our model is to describe qualitative trends, it is not reasonable to validate simulation results against specific data. However, qualitative comparisons with observed pattern are helpful to support confidence in the simulated magnitude of variables (Jakoby, 2011). One example is shown in Table 3.2, where we calibrated one parameter value for the model version simulating heterogeneous pastures (recovery rate w, where the value 0.8 was standard before). Although the measured standing crop, was met by two simulated pastures, the pasture TZT had more than twice of the measured biomass. We varied the values for the reserve recovery rate and found that decreasing recovery rates also decreased the amount of sustained biomass on all pastures. Since the pasture TRB had the least reserve biomass, it was least affected by the parameter change. When the recovery was too low ($w = 0.4$), the resulting herd size was much lower than 0.5 heads per ha. Thus, we decided to adapt w to the

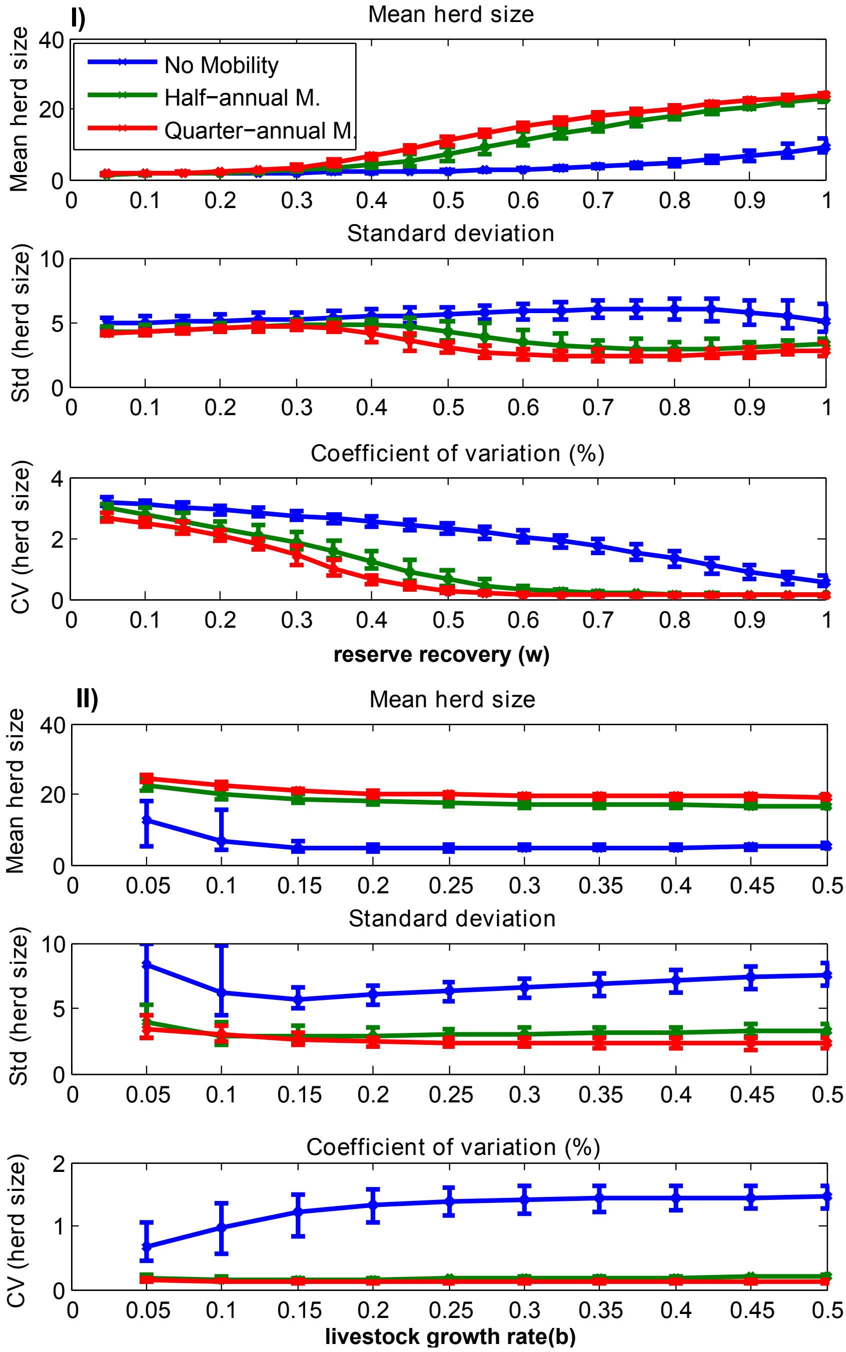


Figure 3.5: Evaluation of herd size dynamics over parameter variations comparing three mobility scenarios. I) Recovery rate of reserve biomass. II) Growth rate of livestock.

Table 3.2: Vegetation characteristics measured from study sites in 2007/2008 compared to average simulated values. Standing crop from grazed areas is compared to the average sum of green and reserve biomass after grazing.

Station	**Standing crop (kg/ha)**	**G+R (kg/ha)** w=0.8	**G+R (kg/ha)** w=0.6	**G+R (kg/ha)** w=0.4
TZT	1075	2558	1173	553
IMS	117	1336	1147	671
TAO	531	1372	1201	868
TRB	335	418	366	266

value 0.6, as it seemed a suitable compromise between accurate biomass simulation and reasonable stocking rates that can be sustained.

3.2.3 Application: Livelihood security assessment

We apply the rangeland model with the aim to evaluate herd size dynamics in terms of income for pastoral households. To assess the risk related to pastoral income, we use the herd size as a proxy for income since livestock is the direct income source and its variability reflects the variance caused by fluctuations in forage availability. Therefore, we operationalized the concept of livelihood security by the means of two threshold parameters for the analysis of herd size dynamics (see for an introduction to the livelihood security concept in Chapter 4).

Evaluation scheme for livelihood security

We developed a risk assessment scheme to evaluate herd size dynamics by taking two dimensions of risk attitude (demand levels) from households into account (Figure 3.6). The first dimension is the level of income needs by one household (τ), and the second dimension is the tolerable income risk over time (α). Income needs (τ) are specified here by a minimum viable herd size. Tolerable income risk (α) is defined as the fraction of years where the herd size drops below τ. Pastoralists may tolerate income shortfall from livestock during some years when they have alternative income sources from non-pastoral activities (Breuer, 2007).

Typically, risk increases with the length of time, so the security evaluation of the partition of secure runs decreases. With a specific tolerance of risk, security might decrease more slowly. Figure 3.7 shows under A) and C) how our risk measure α leads to discontinuous security decreases with an extending time frame (T), it even may increase (see for more illustration in Figure A.3, Figure A.3). This might lead to arbitrary and not meaningful differences of the security evaluation when using different values of the continuous parameter α. To settle this, we used an absolute risk measure by

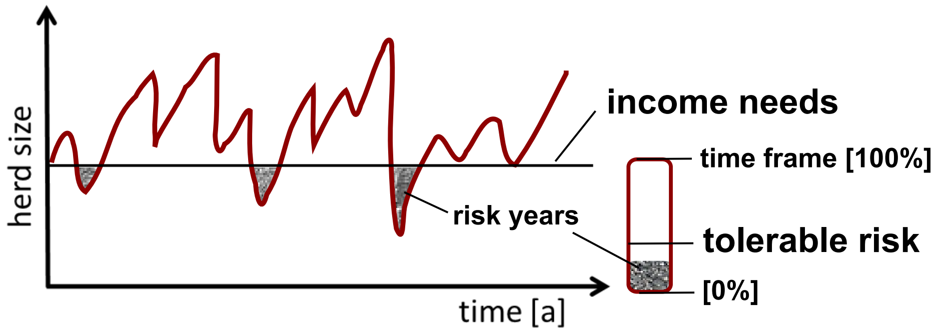


Figure 3.6: Example for a security evaluation based on income from livestock. Fluctuations were evaluated by how often they cannot meet the household's demand level. Parameters were the level of income needs and tolerable risk of income undersupply.

multiplying α with the length of the time frame (Figure 3.7, B and Ds). This allows us a more reliable comparison between different values of risk tolerance in short term evaluations. Note that risk attitude parameters (τ and α) were evaluated as secure if herd size dynamics were evaluated as secure in more than 95% of simulated runs.

Model versions and scenarios

The following studies are based on mainly two versions of the previously described rangeland model which is first the spatially homogeneous version and second the spatially heterogeneous version (see overview Figure 3.8). We compared different scenarios of mobility and precipitation regimes to investigate the specific research questions in each study. Finally, different sets of parameter variations and result figures are linked to the analyzed scenarios.

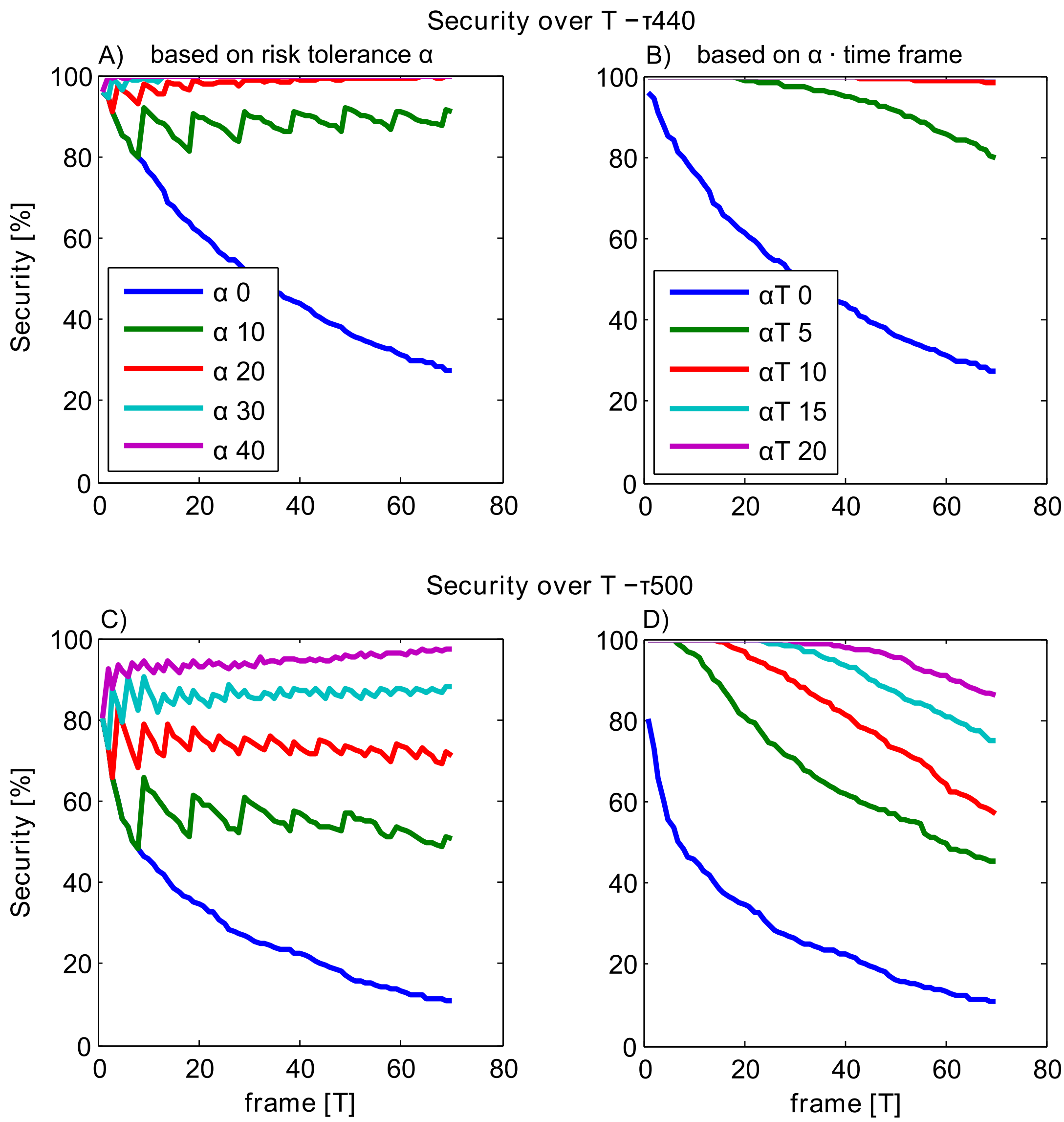


Figure 3.7: Lines show the security evaluation results for a population series (70 time steps) over increasing time frames T. For A) and C), the risk measure was based on fractions of tolerable years (α) with herd numbers lower than $\tau = 440, \tau = 500$. For B) and D), the risk measure was based on the absolute number of tolerable years with herd numbers lower than $\tau = 440, \tau = 500$

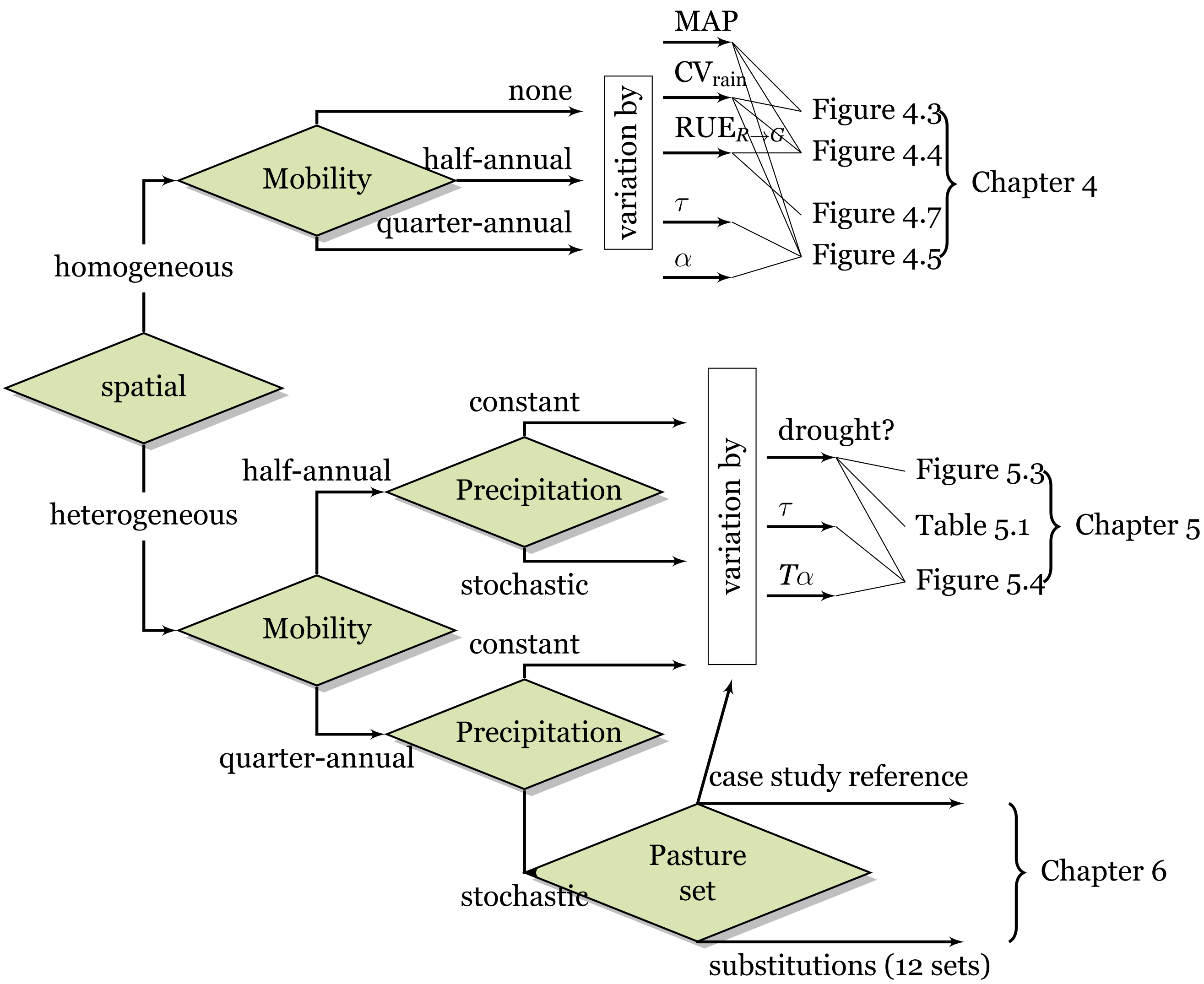


Figure 3.8: Overview of model versions and scenarios presented in the following studies linked to major result figures. Parameter names attached to arrows denote evaluations over different values, see Table 3.1 for explanation of abbreviations.

Part II

Model Applications

4 How much climate change can pastoral households tolerate?

Climate change in the form of decreasing mean annual precipitation (MAP) accompanied by increasing variability has important consequences for rangeland productivity and thus pastoral livelihood security. Here, we use a spatial simulation model to assess impacts of changing precipitation regimes, and to identify limits of tolerance for these changes beyond which pastoral livelihoods cannot be secured. We also examine strategies to control these limits.

4.1 Effects of climate change in dry rangelands

In drylands, which cover more than 40% of the surface of the earth (Neely et al., 2009), livestock is the most important source of income (Walker and Janssen, 2002). Facing scarce and variable rainfall, adaptive strategies such as mobility are required to buffer highly variable natural resources and to secure pastoralists' livelihoods (Niamir-Fuller and Turner, 1999; McAllister et al., 2009). Transhumance, the traditional use of rangelands with regular herd and household movements (Reid et al., 2008), is a good practice example for locally adapted and sustainable livelihood strategies. However, externally driven changes in the environment and the socio-economy may severely affect ecosystem services such as forage supply (Verstraete et al., 2009). Particularly climatic factors, like mean annual precipitation (MAP) and precipitation variability, have a huge impact on rangeland condition and fodder production (Williams and Albertson, 2006). Substantial climate change is expected in the form of decreasing MAP accompanied by increasing precipitation variability, which is recognized as an important driver for degradation of dryland productivity. MAP is projected to decrease by 10 to 20% in several regions in north-west Africa (Paeth et al., 2009). Therefore, climate change is expected to threaten pastoralist livelihoods. Under which local circumstances changing rainfall characteristics may limit the ability of pastoralists to secure their livelihood sustainably if they only rely on local forage resources is an open question.

In the past, research on the effects of changes in climate and land use focused mainly on the ecological subsystem, such as the supply of forage resources and their degradation. More recently, changes in the human subsystem have become more important. The main aim of these studies was to identify causal factors of sustainable pastoralism (Niamir-Fuller and Turner, 1999; Oba, 2011). In this context, political and socio-economic constraints have been identified as major factors in the marginalization of pastoralists (Oxfam, 2008). Furthermore, decreasing mobility options may greatly affect pastoral livelihood systems and therefore human well-being (Verstraete et al., 2009). However, it is still difficult to evaluate the relative importance and feedbacks between these external drivers. Now, it is crucial to analyze the vulnerability of pastoral livelihoods to combined threats within a risk-prone environment (Reed et al., 2008; Fraser et al., 2011) and to determine to what extent adaptive strategies can compensate for critical changes.

In this paper, we aim to identify changes in rainfall regimes that can be coped with by pastoral households, and changes which pose a threat to pastoral livelihood security. We hypothesize that decreasing MAP accompanied by increasing variability leads to smaller herd sizes and therewith increased risks for pastoral livelihoods. Having identified limits of tolerable precipitation regimes, we examine how robust limits are to changes in income needs, the type of vegetation and mobility.

The productivity of arid rangeland ecosystems and consequent stochastic livestock population dynamics are the subject of a controversial debate (Vetter, 2005). It was assumed that conditions of high environmental variability limit the strength of interaction between livestock and their forage resource (Ellis et al., 1993), which was used to explain limited plant response to grazing (Fernandez-Gimenez and Allen-Diaz, 1999). One implication was that these dis- or non-equilibrium systems are non-degradable, which was supported by a very recent global study (von Wehrden et al., 2012). They presented evidence that grazing degradation only takes place in areas with relatively stable annual precipitation. However, Illius and O'Connor (1999) stressed that spatial heterogeneity enables equilibrial forces in parts of the system regulating the feedback between livestock and so called key resource areas. Finally, the usefulness of the non-equilibrium theory for explaining degradation in drylands remains unclear (Gillson and Hoffman, 2007) and therewith for determining the implications for suitable management strategies.

Since only few models assess the effects of changing climatic conditions on pastures and livestock dynamics, we developed an abstract model that aims to fill this gap. It simulates perennial vegetation and compares livestock dynamics under different rainfall regimes, vegetation conditions, and mobility strategies with a quarter-annual, half-annual or no movement frequency. For calibration, vegetation data and empirical patterns were used from a case study in mountainous Southern Morocco (Linstädter and Baumann, 2013). In our analysis, we focus on increasing precipitation variability and decreasing MAP because these are main components of projected climate change in arid rangelands (Williams and Albertson, 2006; Scheiter and Higgins, 2009; Linstädter et al., 2010). In order to evaluate changes in terms of sustained pastoral livelihoods, we operationalized livelihood security for a household-based risk assessment. It can be interpreted as the household's specific risk attitude applying a strategy which ensures a certain level of income needs over time while tolerating a certain income variability. By analyzing livestock dynamics with respect to this risk attitude, we assess the household's vulnerability to climate change.

In the following, we present the modelling approach and explain how we operationalized livelihood security for the evaluation. The simulation results make it possible to differentiate between safe and unsafe precipitation regimes in order to estimate subsequent livelihood risk due to climate and land use change. Specifically, the role of sufficient pasture resting and vegetation characteristics are elaborated regarding their function in stabilizing the herbivore-vegetation system. Finally, we discuss our findings on options for sustainable pastoral livelihoods in the light of expected climate change for drylands.

4.2 Methods

The concept of our analysis was to investigate effects of projected climate change in drylands (Williams and Albertson, 2006; Linstädter et al., 2010), in terms of decreasing MAP and increasing precipitation variability, on pastoral income and thereby livelihood security (Figure 4.1). Three factors were considered to influence herd dynamics

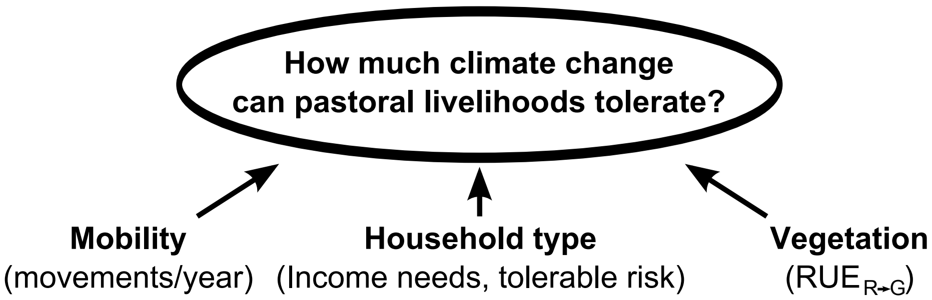


Figure 4.1: The concept of our analysis with the main research question at the center and three influencing aspects considered for analysis and discussion.

and thus income for pastoral livelihoods. First, the household type is characterized by levels of income needs and tolerable income risk. Further, the vegetation growth, specified by its rain use efficiency (RUE), determines the ability of plants to turn available water and nutritional reserves into green biomass (Le Houérou, 1984). This rate regulates the availability of forage for livestock while forage consumption feeds back on the recovery of vegetation. And third, the management of herd movements may interact with the vegetation state and may compensate for heterogeneous forage availability.

Model description

Perennial vegetation dynamics were simulated on a set of even sized pastures utilized by a herd of smallstock (Figure 4.2). The temporal resolution depends on the herd's movement frequency between pastures (quarter-annual, half-annual or none). For details on the model structure and implementation see Section 3.2.1.

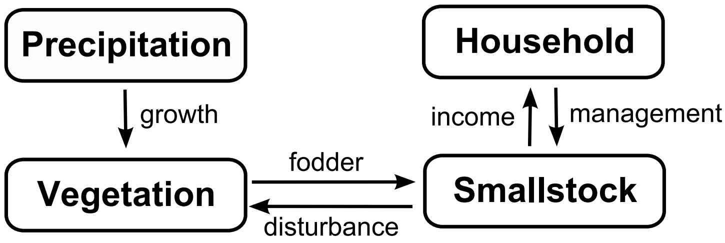


Figure 4.2: Causal diagram of a rangeland system showing components (boxes) and processes (arrows) that are simulated by our model. We investigate the impacts of precipitation regimes on vegetation and pasture utilization by smallstock. Smallstock population dynamics generate income for pastoral households. We compare household strategies with different levels of income needs, tolerable income risks, and different frequencies of smallstock mobility.

4.2.1 Evaluation scheme for livelihood security

Pastoral livelihood security on the household level is based mainly on food and economic security from livestock-related income sources (Frankenberger, 1996; Scoones, 1998). We interpret the strategy of pastoralists as one that seeks to support and fulfill a certain threshold of a household's herd size, comparable to the minimum viable herd size (Niamir-Fuller and Turner, 1999; LEGS, 2009).

Therefore, we developed a risk assessment based on herd size dynamics as a proxy for pastoral income taking into account two dimensions of pastoralists risk attitude (Table 4.1). The first dimension is the level of income needed by one household (τ), while the second dimension is the tolerable income risk over time (α). Income needs (τ) are specified by a minimum viable herd size. Tolerable income risk (α) is defined as the fraction of years where the herd size drops below τ. Accounting for the effect of stochastic precipitation, we used an additional threshold ($\Gamma = 95\%$) on simulation sets to ensure that the results were representative.

4.2.2 Model and evaluation scenarios

Simulations of herd sizes were iterated a hundred times to account for the variability caused by stochastic precipitation. Each simulation comprised 150 time steps (years). To exclude initialization effects, only the last 100 time steps were used for the evaluation of income. Implemented in the computing environment Matlab, it took ca. three minutes to simulate three mobility scenarios. Parameter sets were used to analyze changes in precipitation regimes (MAP, CV), vegetation state ($RUE_{R \to G}$), or mobility (no, half-annual, quarter-annual).

Changes in the socio-economic background of pastoral households were evaluated based on the risk assessment of model results. For example, human population growth

Table 4.1: Thresholds for maintaining a pastoral livelihood that were used for risk assessment.

Parameter	Specification	Explanation	Range
τ	Threshold for minimum herd size	Income needs of one household	100–300
α	Proportion of years where income $< \tau$	Tolerable income risk over time	0–20%
Γ	$P(\alpha_i < \alpha)$	Threshold for tolerable uncertainty in the runs over all simulations	0–5%

could result in increasing income needs and additional income from non-pastoral activities would cause an increased risk tolerance.

4.3 Results

4.3.1 Livestock production related to precipitation regimes

We compared the effects of increasing average precipitation, two levels of precipitation variability and three mobility scenarios on smallstock dynamics.

Increasing MAP and mobility supported higher herd sizes of smallstock (Figure 4.3). However, the increased coefficients of variation (CV) in precipitation had only a small effect on average herd size and on its CV. Compared to the scenario of no mobility, the two mobility scenarios with quarter-annual and half-annual movements both performed similarly well with respect to average herd sizes. Under conditions of low precipitation variability (CV=0.2), mobile herds were six times larger than immobile herds under semi-arid conditions (MAP=350 mm/yr). The difference between mobile and immobile herds decreased with increased precipitation variability (Figure 4.3, B); mobile herds were only two times larger than immobile herds then. Notably, the immobile system sustained higher average herd sizes under higher precipitation variability.

We observed different effects of precipitation variability on the mean herd size along a MAP gradient (Figure 4.4) when different specific growth rates ($RUE_{R \to G}$) were evaluated. While we observed a negative effect of precipitation variability on smallstock herd size at high specific growth rate, there was a positive effect at a low growth rate and half-annual mobility (Figure 4.4, A and C). However, under conditions of the lower growth rate, no positive effect of precipitation variability was detected when executed in a quarter-annual scenario. Similar to Figure 4.3, there is only a small difference in the average herd size of smallstock between the half-annual and the quarter-

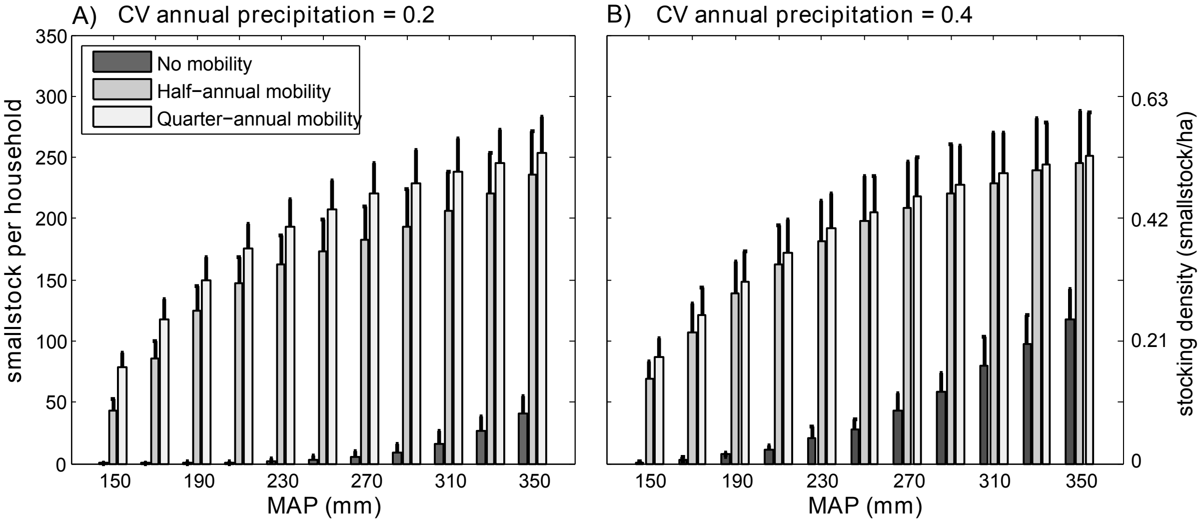


Figure 4.3: Mean and standard deviation of herd size of smallstock averaged over the set of runs (n=100). Scenarios were parameterized with increasing values for mean annual precipitation (MAP). A) displays results from simulations with a precipitation variability (CV) of 20%, B) with a variability of 40%. The value for $RUE_{R\to G}$ was constant: 0.001 mm^{-1}.

annual system.

We summarize that the mean smallstock number is more sensitive to MAP than to precipitation variability, whereas the effect of precipitation variability on smallstock numbers can be positive or negative. Within the settings of our model, increasing the frequency of herd movements had a smaller effect on smallstock numbers than switching to a pasture with a higher vegetation state.

4.3.2 Livelihood security evaluation

Given an environment with a specific precipitation regime, a pastoral household aims to secure its livelihood by applying an adequate management strategy. In the following, we first identified the limits of precipitation regimes beyond which no sufficient herd size can be supported (Figure 4.5). Second, we evaluated parameters of risk attitude (Table 4.1) and scenarios of mobility to assess how far the limits of tolerable precipitation regimes can be shifted. Comparisons of limits between safe and unsafe conditions show that bigger herds require environments with higher MAP. Higher mobility ensures pastoral livelihoods under more arid conditions (in terms of MAP). We observe a small positive effect of precipitation variability under the half-annual cycle and a small negative effect under the quarter-annual cycle. Increasing the tolerable income risk suits to shift the limits towards smaller MAP, which is a more pronounced effect when income needs are high. The comparison of limits has important management implications. That is why we used the the map of isoclines of livelihood security to highlight effects of different adaptation strategies (Figure 4.6). From the

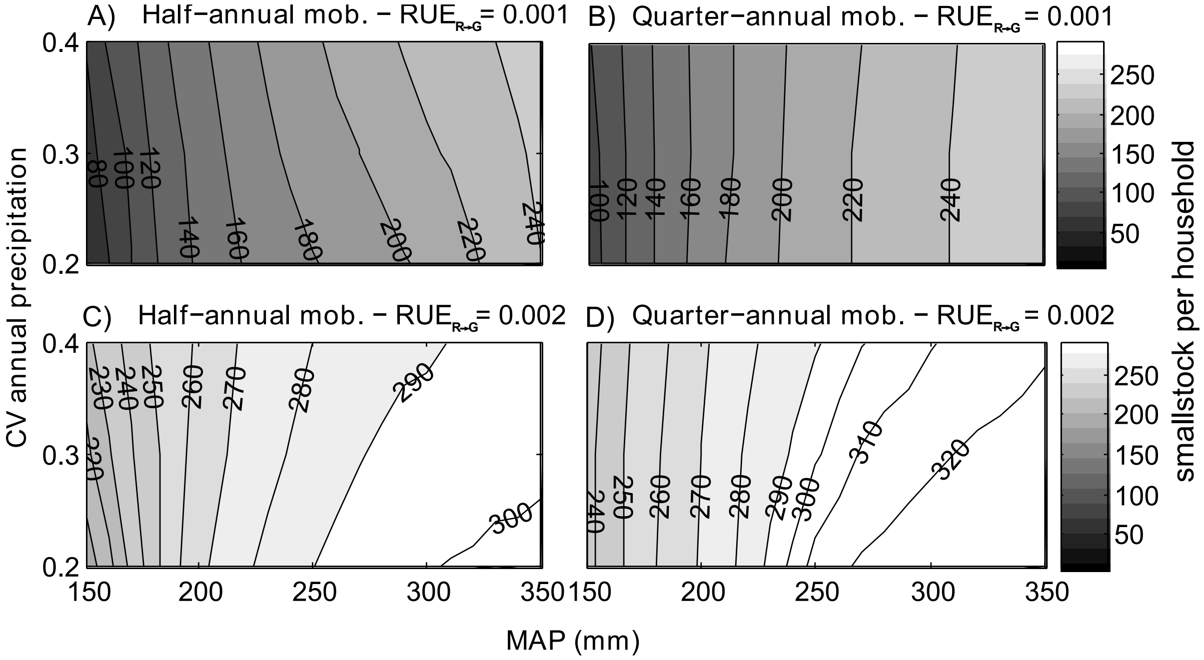


Figure 4.4: Mean herd size of smallstock for the last 100 simulation years (Lighter shades denote greater herd size). A) and C) show results for the system with half-annual mobility, A) with the value of $RUE_{R\rightarrow G} = 0.001$ mm^{-1} and C) with the value $RUE_{R\rightarrow G} = 0.002$ mm^{-1}. B) and D) show results for the same $RUE_{R\rightarrow G}$ values but under quarter-annual mobility. The contour lines are based on a linear interpolation of 105 datapoints. Lines parallel to the y-axes denote that there is no effect of CV. If lines are diagonal from the lower left to the upper right corner, CV has a negative effect on smallstock numbers. In contrast, lines running diagonally from the lower right to upper left corner denote that the CV has a positive effect.

household's point of view, within an environment of fixed precipitation characteristics, pastoralists can switch from unsafe to safe livelihood evaluation by applying suitable strategies. This is exemplified in Figure 4.6 by a household who may increase its alternative income and thereby risk tolerance or who may apply a higher mobility. Only the latter would allow for a safe livelihood evaluation in this case. Alternatively, an even higher risk tolerance than in the plotted example could also ensure a safe livelihood. Thus, this kind of analysis leads to the identification of factors that most likely pose a threat to vulnerable households when the precipitation regime and its projected changes are known.

The following analysis synthesizes to which extent mobility and pasture states modulate the critical amount of MAP that is required to secure livelihoods. We identified the critical amount of MAP at the isocline from Figure 4.5 at $\alpha = 20\%$ for a fixed CV of precipitation of 30%. Figure 4.7 shows critical MAP related to different levels of income needs. We observed an approximate linear and positive relationship between

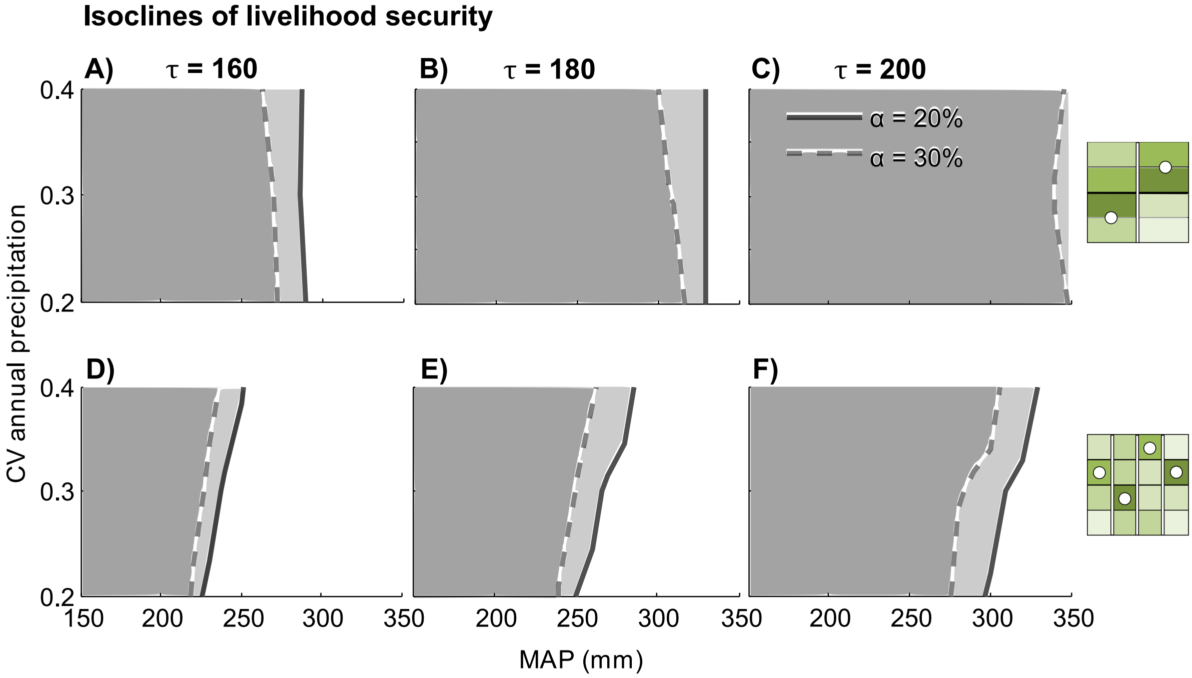


Figure 4.5: Isoclines in each plot denote limits of precipitation regimes beyond which livelihood conditions are unsafe (shaded side), with a gradation in tolerable income risk (α, based on evaluation scheme of Table 4.1). A to C show isoclines under the half-annual mobility and D to F for quarter-annual mobility. From left to right we varied the level of income needs ($\tau(headofsmallstock)$). The value for vegetation productivity was ($RUE_{R\to G} = 0.001\ \mathrm{mm}^{-1}$).

critical MAP and income needs. A higher frequency of herd movements can result in increased income at a fixed MAP, thus mobility can compensate for decreases in MAP in this case. However, using a pasture area with a higher vegetation growth rate (increased $RUE_{R\to G}$), the benefit of high mobility was less obvious. Both lines were shifted far more towards higher levels of income needs. Surprisingly, for a limited parameter range of 230 to 270 mm MAP (Figure 4.7b), the quarter-annual system was inferior to the half-annual system, in terms of critical MAP and smallstock preservation. This was caused by pasture degradation events which happened in ca. 5–10% of the runs under quarter-annual mobility. Notably, this exception was not detected by observing average smallstock numbers and their variability (as in Figure 4.3), but only by evaluating livelihood security with our risk assessment. This example revealed the impact of feedback in the ecological system, since it may influence critical thresholds for pastoral livelihoods.

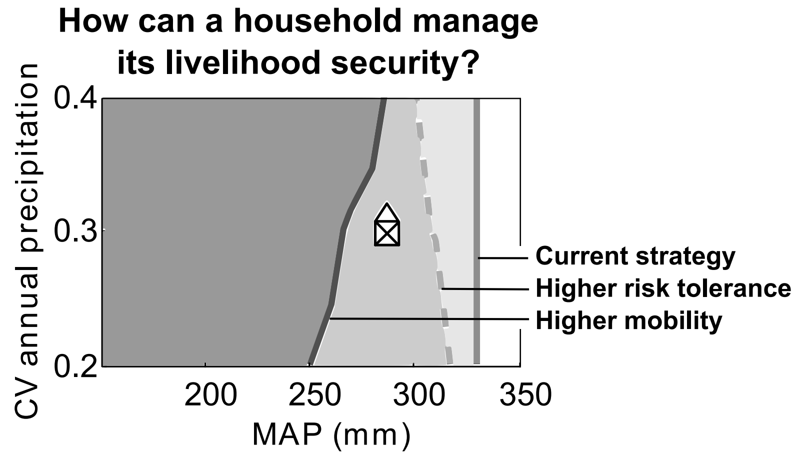


Figure 4.6: This example shows a household in a specific climate regime which is unsafe under half-annual mobility strategies. The household remains unsafe while increasing its risk tolerance by 10%, but it may become safe by applying quarter-annual mobility.

4.4 Discussion

The aim of this study was to identify tolerable limits of climate change where livelihood security of pastoral households can be locally sustained. Therefore, we used a novel approach that combines risk assessment with an ecological-economic model which allowed us to jointly analyze the effects of climate, social and vegetation change on pastoral livelihoods. Our analyses revealed how climate change and maladapted management may threaten pastoral livelihoods.

4.4.1 Different influences of climate change on livestock production

In a previous study simulating annual vegetation, increasing precipitation variability in drylands was considered as one of the main determinants of degradation in terms of losses in fodder and livestock production (Williams and Albertson, 2006). In our model, which simulates perennial vegetation, precipitation variability had little or no effect on the amount of livestock. Perennial plants use reserve biomass as a buffer which allows them to adapt to dry and variable climates (Owen-Smith, 2008). Thus, their forage provision is less vulnerable compared to short-lived plant species that depend on seedbanks in an increasingly variable environment (Morris et al., 2008). Low productive sites dominated by perennial herbs and shrubs may still be in a good state in spite of low ground cover (Baumann, 2009). Thus, a differentiation between vegetation types with respect to the dominant life form (annuals or perennials) is highly relevant for deducing changes in productivity related to precipitation variability.

Unexpectedly, greater precipitation variability caused a greater average herd size under conditions of low MAP and a low frequency of herd movements. We interpret

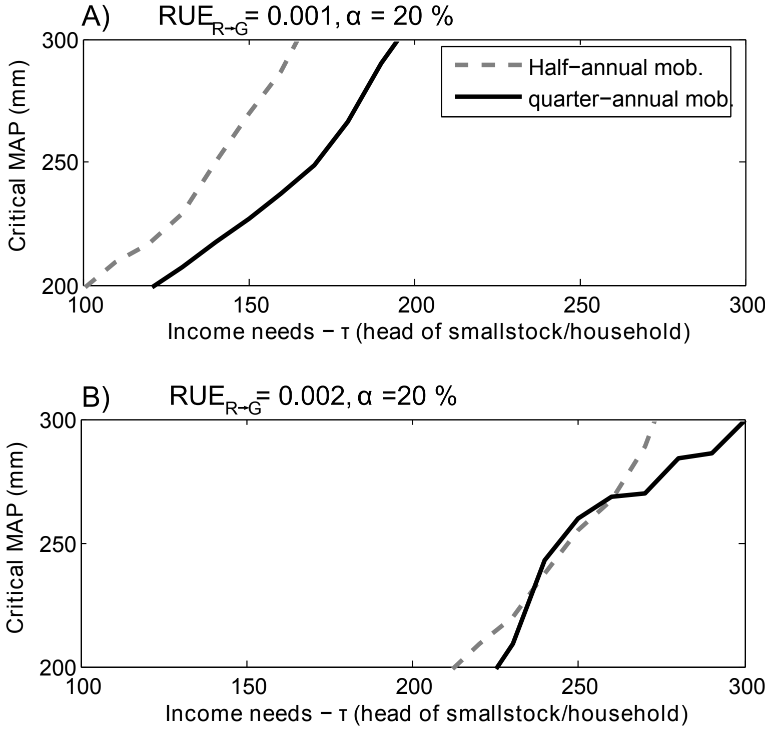


Figure 4.7: Each line denotes the critical amount of MAP required to secure livelihoods along different levels of income needs. A) shows this result for two mobility strategies in a system with a low vegetation growth rate ($RUE_{R\rightarrow G}$ = 0.001 mm^{-1}), while B) shows the result for a high growth rate ($RUE_{R\rightarrow G}$ = 0.002 mm^{-1}). CV of precipitation was 30%.

this behavior as a result of herd breakdowns that led to an accumulation of forage, because vegetation recovered faster than herds, leading to increased average herd sizes in the long-term. This phenomenon has been described as 'unintended resting' (Müller et al., 2007a). If we increased the growth rate for smallstock (b = 0.5), unintended resting became impossible and confirmed our assumption (results not shown). Sufficient resting seems to be crucial for perennial vegetation to recover. Similarly, Quaas et al. (2007) showed for a dryland system that vegetation functions as a buffer where reserve biomass can be accumulated and thereby secures future fodder and income.

4.4.2 Tolerable climate conditions to secure pastoral livelihoods on a local scale

Income is the main component of the livelihood security concept (Frankenberger, 1996). However, anticipating trends of vulnerability of income to climate change remains a challenge in dryland households (Fraser et al., 2011). Pastoral income is based on livestock raising, a natural resource which is highly dynamic. We assessed the risk of shortfalls in pastoral income evaluating two dimensions of herd size dynamics, namely, the level of income needs which can be interpreted as minimum viable herd size, and the tolerable number of years where the expected level of income is not fulfilled.

By evaluating average herd sizes related to climate conditions, we were able to differentiate conditions that enable secure livelihoods from conditions that put pastoral livelihoods at risk. This threshold between safe and unsafe conditions was further investigated against different levels of income needs. Income was highly sensitive against decreasing MAP, which is a likely projection for climate change in drylands (Haile, 2005; Paeth et al., 2009) and recognized as a driver for the vulnerability of pastoral households (Campbell et al., 2002, p. 121). The different effects from precipitation variability on herd size were mostly buffered by the livelihood level of tolerable risk. Whether pastoral households are likely affected by climate change depends on both the local precipitation regime and on specific income needs.

4.4.3 What controls the limits of tolerable climate change while sustaining pastoral livelihoods?

Multiple changes are projected and were partly observed in socio-economic systems of pastoralism, such as population growth and therewith rising income needs, or restricted pasture access regimes due to changed land use directives (ECA, 2004). Social changes that limit the adaptive capacity of pastoralists are considered to threaten their livelihoods (Niamir-Fuller and Turner, 1999; Oba, 2011). Pastoralists adopt different strategies to meet these challenges, for instance becoming partly sedentary and increasing their risk tolerance with income from non-pastoral activities (Breuer, 2007). We compared how effective these strategies would be for increasing pastoral livelihood security. Our simulations have shown that households might manage their livelihoods more effectively by adopting a suitable mobility strategy than by the relatively small benefits from increased risk tolerance. In general, higher frequency of herd movements resulted in higher average herd sizes and enabled households to utilize less productive rangelands. Thus, mobility can to a certain degree compensate for decreased MAP or increased income needs.

However, rising income needs are often accompanied by a decreasing ability to be mobile. In this way, the option of an adaptive compensation strategy may be rapidly lost, especially due to losses of labor force (Breuer, 2007). In the face of climate change it becomes even more important to protect mobility because indirectly it facilitates the management of vegetation recovery and thereby long-term pastoral utilization.

4.4.4 Importance of the ecosystem – commenting on the disequilibrium theory

We simulated the dynamics of perennial vegetation which has the capacity to build reserves for periods of scarcity. Our main focus was on the impact of a changing precipitation regime on the productivity of the rangeland and the livelihoods of pastoral households. Disequilibrium theory predicts that increased rainfall variability, which means higher frequency of droughts, will reduce livestock density (Ellis et al., 1993). However, depending on MAP but also the rain use efficiency (RUE) of the vegetation on the different pastures, increasing variability was found to have either a positive effect, no effect, or a negative effect. Note that increasing variability is accompanied by increasing frequencies of upward and downward fluctuations in precipitation. As long as MAP or RUE was low, the resulting recovery rate of the vegetation on different pastures was so low that the reserve biomass was far below its carrying capacity (or 'moving attractor' which corresponds to a 'non-equilibrium' system sensu Gillson and Hoffman (2007)). As a result, the reserve biomass can benefit from increasing upward fluctuations. This underpins the importance of sufficient resting (cf. Müller et al., 2007a) for the benefit of productivity and livelihood. Sufficient resting in wet years can be achieved either actively through sufficiently high mobility or passively through unintended resting. Whenever RUE and MAP were high, however, the situation was contrary. The recovery rate of the vegetation is so high that the reserve biomass is closer to its carrying capacity. Here, vegetation cannot benefit from increasing upward fluctuations anymore but suffers fully from the increasing downward fluctuations - to the disadvantage of long-term productivity and livelihood.

We explored the effect of an increasing variability in a spatio-temporal structured rangeland system (c.t. Illius and O'Connor, 1999). In such systems, working with concepts like density dependence, dynamic equilibrium or strength of resource-consumer interactions (Vetter, 2005; Retzer, 2006) as usually used in the equilibrium vs. disequilibrium debate is problematic. In our context, such functional relationships can be hardly determined as one would be forced to average out the responses over the different pastures, which is not straightforward. Our study presents an alternative approach to explain the effect of variability on pastoral systems. The approach is based on mechanisms (vegetation recovery, benefits from upward fluctuations, mobility mediating sufficient resting) that are fully compatible with spatio-temporal heterogeneous resource utilization rather than with averaged functional relationships.

4.4.5 Remarks on stylized rangeland models for social-ecological systems

We recognize the shortcomings of our study, which can be resolved by future extensions. So far, we did not consider transaction costs for mobility because we assumed them to be negligible in our case with its small scale region. This makes our results comparable to models of rotational grazing systems (e.g. Jakoby, 2011) or experimental studies where circumstances were identified where rotational grazing is not superior to continuous grazing (Briske et al., 2008). Using a stylized model enabled us to identify the mechanisms of why and under which circumstances mobility remains beneficial. Integrating costs for mobile activities would be an important future extension to the model which would probably show a trade-off between increasing mobility beyond the local scale and labor force or monetary investments to implement the strategy.

Since cases of pastoral households whose income is solely based on livestock raising are rare, strategies to obtain additional income or to buy supplementary fodder should be considered for further analysis. Interviews with pastoralists have shown that their choice of adaptation strategies can be very different depending on their labor force, monetary resources and social relations (Breuer, 2007).

Finally, our approach may be transfered to studies beyond rangelands whenever dynamics of ecosystem services are closely linked with livelihood security. We have developed a risk assessment tool which includes an operationalization of the concept livelihood security in stochastic environments. This analysis proved to be useful to evaluate multiple changes and managements options and to weight them against each other.

4.5 Conclusion

Projected climate change is expected to outrange the adaptive capacity of pastoralists. Our study has shown that climate change, in terms of increasing precipitation variability, may affect livestock less than decreased mean annual precipitation does. We distinguished cases with positive effects of precipitation variability, caused by sufficient resting, from cases where precipitation variability has a negative effect on livestock. Socio-economic changes in terms of increasing income needs shifted the limits of tolerable climates towards higher mean annual precipitation. Up to a certain degree, mobility allowed the maintenance of pastoral livelihoods in less productive systems and thereby compensated for climate change effects. Increases of income requirements and restricted pasture access, however, make it harder for pastoralists to move their herds around in the future and secure their livelihoods.

5 When does a drought endanger pastoral livelihoods?

Increasing frequencies of droughts pose a threat to pastoral livelihoods in drylands. Often, herdsmen mentioned specific drought events as the reason for the abandonment of pastoralism. We aim to evaluate how droughts are transmitted by the rangeland ecosystem and when these effects endanger pastoral livelihoods.

5.1 Livestock, livelihood, and shocks in pastoral systems

Livestock keeping is the most important source of income in the social-ecological systems on semi-arid rangelands (Walker and Janssen, 2002). Droughts as a shock pose a threat to pastoral livelihoods (Fafchamps et al., 1998), and the frequency of drought years is projected to increase in north African drylands (Paeth et al., 2009; Linstädter et al., 2010). In addition, nomadic pastoralists perceive droughts as primary cause for the loss of livestock and thereby livelihood (Breuer, 2007). Previous studies either investigated the dynamics of the social-ecological system of rangeland management (Janssen et al., 2000; Milner-Gulland et al., 2006) or generally analyzed the economic risk of pastoralism in a highly variable environment (McPeak, 2004; Quaas et al., 2007). However, only few studies related the ecological risk that is posed by droughts to an economic risk assessment (as exception see Smith and Foran, 1992; Hatfield and Davies, 2006). We aim to fill this gap using a simulation model and an assessment tool for livelihood security.

Droughts have often been subject to research and development agencies investigating sustainable pastoralism in drylands (see for example Scoones, 1992; Angassa and Oba, 2008; UNISDR, 2009; UNCCD, 2010). Different types of drought were specified by their domain of impact as well as temporal duration, namely meteorological, hydrological, agricultural, and socio-economic drought (Pratt et al., 1997; Thurow and Taylor, 1999; UNISDR, 2009). Meteorological droughts are defined by the duration of precipitation deficiency in comparison to a long-term average degree, whereas the subsequent hydrological and agricultural droughts are defined by the shortfall of water supply and resulting in plant growth deficits. Regarding the impact on humans, socio-economic droughts occur when the demand of a natural resource exceeds the supply as a result of rainfall-related supply shortfall (Linstädter et al., 2010). We focus on this socio-economic drought in our analysis and evaluate livelihood security as a proxy (Chapter 3.2.3). In the context of pastoralism, drought is generally described as a “slow-onset emergency” where the key livelihood is lost (LEGS, 2009), meaning that only a maximum number of years with income under-supply can be tolerated.

Previous research on droughts, particular in arid and semi-arid rangelands, focuses on stochastic precipitation as a driver for highly variable vegetation and livestock dynamics (e.g. Fernandez-Gimenez and Allen-Diaz, 1999; von Wehrden et al., 2012). In the context of the non-/disequilibrium theory, herbivore-vegetation systems behave stochastically and cannot support an interdependence of herbivores and vegetation (Illius and O’Connor, 1999). Still an open question is how degradation of productivity can be defined in such variable systems (Gillson and Hoffman, 2007), which has important implications for effective management strategies.

The perception of drought consequences by pastoral herders largely depends on pasture usage and degradation (Pratt et al., 1997). While some households may afford large distance travel with their livestock to unaffected regions (Fazey et al., 2009; Kuhn et al., 2010), for example through agistment networks (McAllister et al., 2006), others use income from non-pastoral activities (Breuer, 2007) or subsidies (Hazell et al., 2003) to provide supplementary fodder for their livestock. Although the importance of mobility for sustainable pastoralism is well known, privatization of land, tribal conflicts or governmental interventions often prevent pastoralists to make use of traditional mobility patterns (Niamir-Fuller and Turner, 1999; Oba, 2011).

Pastoral livelihoods largely depend on income from livestock raising (Gasson, 1973). Droughts do not only endanger income with varied immediate impacts, for example reduced milk yield and crop failure, but also the assets providing future income, which is the livestock itself (Scoones, 1995; McPeak, 2004). In general, livelihood security is based on adequate and sustainable access to income and resources to meet basic needs (Frankenberger, 1996). The concept of livelihood security was operationalized in order to evaluate the vulnerability of specific households in the context of development studies by the means of questionnaires (Frankenberger et al., 2000) but up to our knowledge it was not used to evaluate environmental simulations in combination with socio-economic impact factors so far.

We aim to identify shocks in the social-ecological system of mobile pastoralism that lead to insecure livelihoods. To achieve this goal, we use the abstract model for spatial heterogeneous rangelands including a feedback between the vegetation and herbivores (Chapter 3). To calibrate our model, we use data from studies in Morocco’s High Atlas Mountains on rangeland ecology (Finckh and Goldbach, 2010; Linstädter and Baumann, 2013), rangeland management (Genin and Simenel, 2011; Kuhn et al., 2010) and livelihood security (Barrow and Hicham, 2000; Breuer, 2007; Rössler et al., 2010). In Morocco, different types of pastoral strategies were observed during the last decade. Pastoral households mainly differed in their mobility and their amount of alternative income which enabled them to tolerate losses from pastoral income (Breuer, 2007). Traditionally, nomads from the High Atlas Mountains in Morocco applied a roughly quarter-seasonal transhumance cycle (Niamir-Fuller and Turner, 1999), but through governmental restrictions and expansions of land use from close-by villages, they often constrain their mobility to a half-annual cycle today (Rössler et al., 2010).

In the following, we present our modelling setup and an assessment tool for livelihood security to evaluate the herd size from simulations of different drought scenarios. Our main question is: When and how is a meteorological drought translated to an economic drought which endangers pastoral livelihoods? The following aspects are tested:

- How much of the herd shortfall after meteorological droughts is part of the long-term herd size variability?
- Can mobile pasture utilization or alternative income dampen the negative effects of meteorological droughts on pastoral livelihoods?

Finally, we discuss how likely pastoralists give up livestock raising in drylands as a direct consequence of a drought.

5.2 Methods

We developed a rangeland model which simulates a herd of smallstock driven by stochastic precipitation. Then, we evaluated herd size dynamics and their impact on livelihood security to analyze the shock effect of meteorological droughts.

The rangeland model

Our rangeland model was based on difference equations that describe the production of perennial vegetation and the feedback between the herd size and the vegetation's condition (see formal description in Chapter 3.2.1). The model simulated a set of equally sized pastures where the annual production of vegetation is driven by stochastic annual precipitation (Figure 3.2). Produced biomass was distributed seasonally according to the pastures' specific distribution of precipitation during the course of the year. While earlier versions of this model used homogeneous pastures (Müller et al. (2007a), Chapter 4, Figure 3.8), we parameterized a heterogeneous set of pastures situated along an altitudinal gradient. This gradient caused different characteristics of precipitation and the vegetation (forage growth rate, capacity of standing crop and vegetation type, see Table 3.1). Hence, our model accounts for heterogeneous spatial effects of droughts.

Meteorological drought simulations Annual precipitation series were generated using values from the log-normal distribution, which was specifically parameterized for each pasture (Table 3.1). To simulate a meteorological drought event, we placed two minimum precipitation values from a precipitation series in two successive years (years 60 and 61, not earlier to exclude initialization effects in the analysis). By this, the drought event was part of the characteristic precipitation distribution of each pasture.

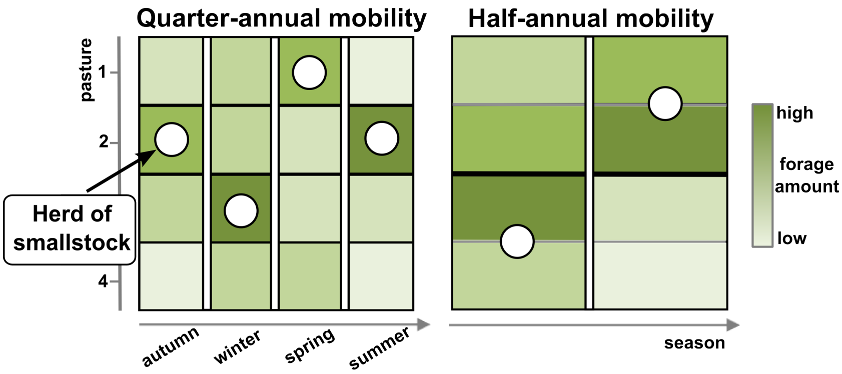


Figure 5.1: Intraannual mobility of a herd on four pastures. The quarter-annual mobility utilizes each pasture for one season, the half-annual mobility utilizes two connected pastures for two seasons before movement. Circles indicate the movement to the best pasture in each season.

Those minimum precipitation values comply with the drought definition by Pratt et al. (1997), who identified two successive years with less than 75% of the long-term average of annual precipitation as meteorological drought years. Multiple scenarios were executed for a set of 200 precipitation series to examine the effect of drought independently from stochastic conditions prior the drought event. For comparison and to assess the magnitude by which precipitation variability and droughts cause herd size fluctuations, we executed scenarios with constant precipitation and a deterministic drought of 75% from the average at the years 60 and 61.

Mobility of herd Two strategies of pasture utilization, namely quarter- and half-annual mobility were performed by scenarios. Forage from the pasture is used by a herd of smallstock that is moved seasonally to the pasture with the highest amount of forage (Figure 5.1). The herd is destocked seasonally in case of insufficient forage and may reproduce once a year before the spring season. We compared the quarter-annual against the half-annual movement strategy in terms of the sustained herd size after a fixed time frame with the onset of the drought. Parameters for mortality and growth rates of the vegetation were estimated through variation and selected empirical patterns that would enable sustainable pastoral production (see Table 3.1 for specific values, (and for the method of pattern oriented modelling see Jakoby, 2011)). Since we were interested in the drought-induced risk only, we excluded parameter ranges that would lead inherently to degradation in the current system. By doing so, drought effects can be analyzed without additional negative factors such as degradation, which may have other origins. Ecological parameters that characterize the four different pasture types along the altitudinal gradient, such as forage growth rate and maximum standing crop were extracted from a field study (Linstädter and Baumann, 2013).

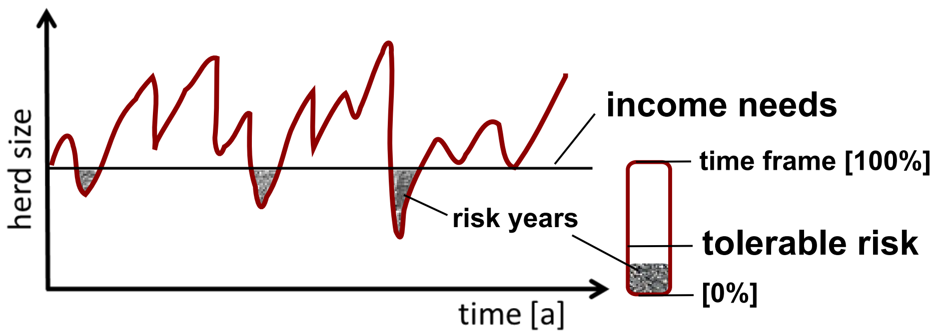


Figure 5.2: Example for a security evaluation based on income from livestock. Fluctuations were evaluated by how often they cannot meet the household's demand level. Parameters of evaluation are the level of income needs, τ and tolerable risk of income undersupply, α (redrawn from p.45).

5.2.1 Short term livelihood security assessment

Herd size dynamics, that resulted from simulations, were further evaluated as a proxy for pastoral income (see details in Chapter 3.2.3). This income is the main source for pastoral livelihoods (Frankenberger, 1996; Scoones, 1998) and the herd size variance reflects at the same time income fluctuations. In contrast to the long-term evaluation of livelihood security in Chapter 4.3.2, we aim to assess the direct and intermediate impact of droughts on pastoral households within a period of thirty years. Needs and activities in pastoral households are manifold with short and immediate effects of supply shortfall as well as delayed effects. We assume that pastoralists seek to support and fulfill a certain threshold of the herd size (comparable to the concept of a minimum viable herd size (Niamir-Fuller and Turner, 1999; LEGS, 2009)). We used our risk assessment scheme to evaluate herd size dynamics by taking two dimensions of risk attitude (demand levels) from pastoral households into account (see details in Chapter 3.2.3, p.34 and the repeated Figure 5.2). Since we were interested in the immediate but also delayed effects of drought, we evaluated 30 years of each simulation with the onset of the first year of drought (year 60–89). To compare different levels of risk attitude in such a short time frame, we had to use the absolute number of tolerable risk years ($T \cdot \alpha$) instead of the relative value (α) (see for a detailed explanation Chapter 3.2.3). Evaluating the absolute values of risk years results in a continuous function for risk.

By assessing the risk related to herd dynamics, we were able to discriminate whether the herd would fulfill the household's demand level over time or not. Specific demand levels were classified as secure when in more than 95% of simulation runs (n=200) thresholds were fulfilled.

5.3 Results

5.3.1 Herd size dynamics

The purpose of our study was to investigate how a meteorological drought translates to a situation of economic risk for one pastoral household. At first, we compared simulation results from the no-drought and the scenario with two years of drought using the quarter-annual mobility strategy (Figure 5.3, A, C). The drought causes an immediate shortfall in available forage and thereby a decrease of the herd size. But this decrease ends with the last year of drought, so that fodder and herd size recover quickly (within two years). We aimed to analyze how much of herd dynamics were caused by precip-

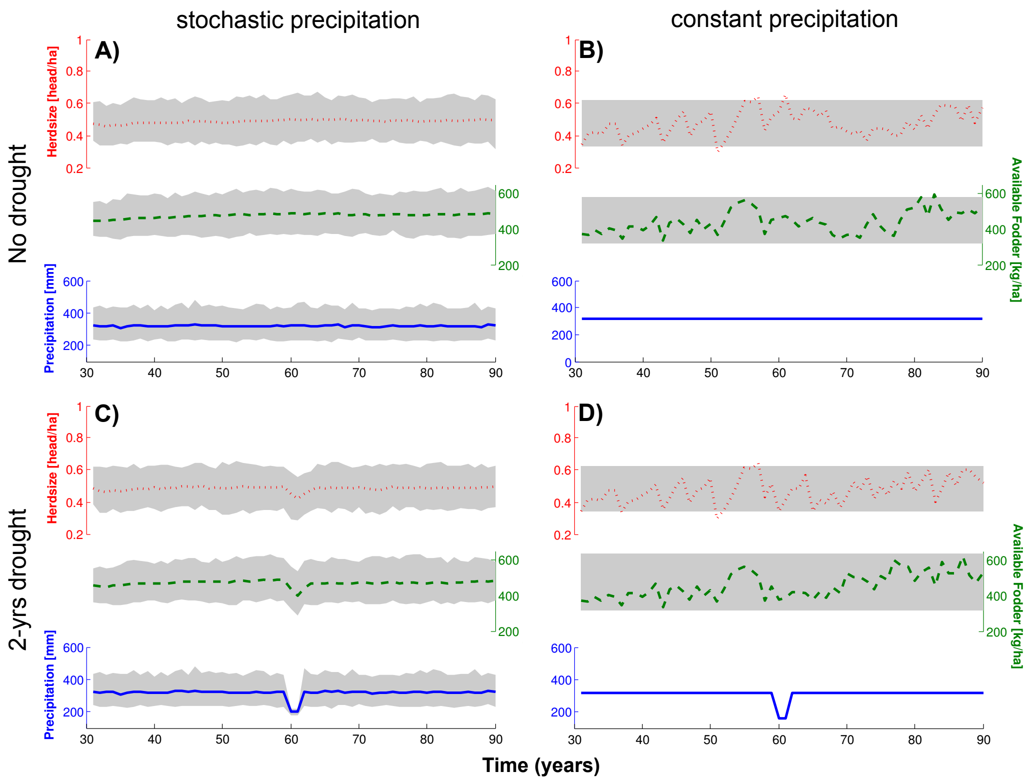


Figure 5.3: Mean herd size, fodder and precipitation from 200 simulations with 90% of data within the shaded area. A) and B) show results from the no-drought scenario, C) and D) for a scenario with two years of drought (years 60, 61). We compared quarter-annual mobility scenarios based on stochastic precipitation (A, C) with scenarios based on constant precipitation with one single run (B, D). Note that precipitation data is shown for one out of four pastures as representative example (see details of parameterization in Table 3.1).

itation stochasticity. Therefore, we compared results from scenarios with stochastic precipitation with results from one simulation based on constant precipitation. We

Table 5.1: Precipitation (MAP), fodder and herd size variability (CV) from no-drought scenarios compared to the magnitude of shortfalls after two years of drought (comparison of year 59 before drought with year 61). For calculation of the CV, the initial phase of the simulation (30 years) was excluded.

Scenario	**Evaluation**	**CV (MAP)**	**1/4-annual Mobility** forage | herd	**1/2-annual Mobility** forage | herd
stochastic	CV (no drought)	0.2–0.3	0.14 | 0.16	0.26 | 0.24
	avg. drought loss	0.37–0.54	0.18 | 0.15	0.29 | 0.22
constant	CV (no drought)	0	0.15 | 0.17	0.01 | 0.01
	drought loss	0.5	0.14 | 0.20	0.22 | 0.28

observed that the data variation per time step in the stochastic case (between the 5th and 95th percentile) was very similar to the variation over one simulation in the constant case. Plant-herbivore dynamics may fluctuate due to a timely lagged interaction in spite of a constant environment.

Further, we compared the variability (CV) of precipitation, fodder and herd size between two mobility scenarios (Table 5.1). We observed a buffer effect under stochastic simulations. This buffer is expressed by decreasing variability transmitted from precipitation to fodder and from fodder to the herd size. While the shortfall of fodder due to drought is increased compared to the long-term CV, the opposite is true for the herd size. We observed higher variability in the scenario with half-annual mobility than with quarter-annual mobility. As observed in Figure 5.3, the variability of fodder and herd size is at a similar magnitude when comparing constant and stochastic precipitation in the quarter-annual mobility scenario. However, under half-annual mobility, we found a rather stable simulation with almost no variability (Table 5.1). Only when evaluating fodder and herd size shortfalls from the drought scenario, the system was destabilized and drought caused a shortfall in both, forage and herd size, with a subsequent degradation.

5.3.2 Pastoral households affected by drought

In order to assess the effect of meteorological droughts on livelihood security, we evaluated each run based on our risk assessment. We aimed to identify demand levels (τ, $T\alpha$) which enable pastoral households to survive traditionally with income from their herd but who are endangered when facing a drought. Figure 5.4 represents these particular demand levels in dark gray, based on evaluations of herd size dynamics that resulted to be safe during the no-drought scenario but not safe in the two-year-drought scenario. For this type of evaluation, we superimposed the demand level evaluation of

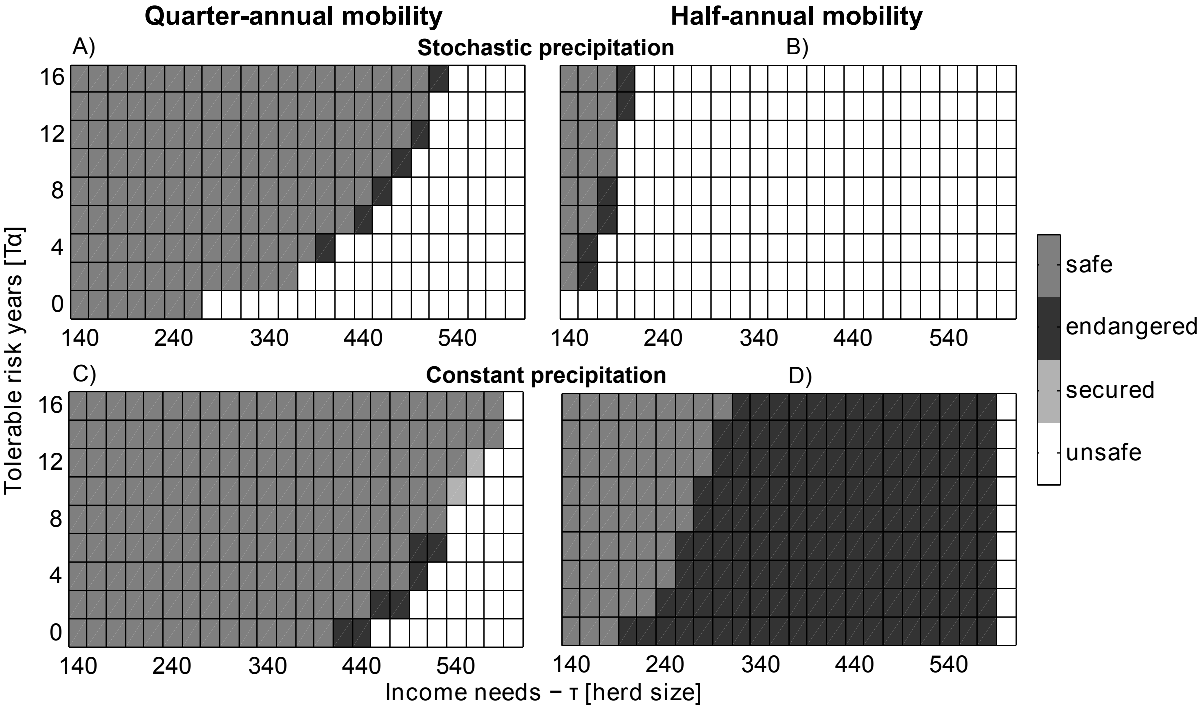


Figure 5.4: Livelihood security evaluation from herd size simulations. Household evaluation of livelihood security based on income needs and tolerable risk over 30 years ($T\alpha$). Fields with medium gray indicate demand levels which were classified as *safe* in both scenarios (without drought, with two years of drought). White indicates demand levels which were classified as *unsafe* in both scenarios. Dark gray indicates demand levels which were classified as unsafe only in the drought scenario (*endangered*). Light gray denotes the contrary where demand levels classified as only safe in the drought scenario. A, C and B, D contrast two mobility strategies with A, B based on stochastic precipitation and C, D on constant precipitation.

herd size dynamics based on a scenario without a drought with a demand level evaluation based on a scenario with two years of drought. Figure 5.4 shows the difference between these two scenario evaluations. For example, the herd size demand of $\tau = 240$ without any risk tolerance ($T\alpha = 0$) was fulfilled under both precipitation scenarios (Figure 5.4, A), but the demand of $\tau = 300$ under none of them. Other demand levels were evaluated as safe in both scenarios with and without a drought (denoted by medium gray). Demand levels that were too high to be fulfilled by the underlying herd size simulation without a drought, were identified as *unsafe*. Interestingly, most of the demand levels were either evaluated as safe or unsafe without a effect by the drought.

We compared the effects of different mobility strategies on the secured demand levels. Although used pastures had the same size, the half-annual cycle resulted in much lower levels of the sustained herd-size. In terms of livelihood security, less levels of income needs were sustained by both, the no-drought or two-year-drought scenario (Figure 5.4, B). Using alternative income in order to increase the level of tolerable risk, $T\alpha$ (years with income undersupply), would improve the secured income from livestock when applying the quarter-annual cycle but would not help at a half-annual cycle.

For another example, one can look at the sustained herd size at the level of no alternative income. Under quarter-annual mobility, a size of 260 heads was sustained. Compared to half-annual mobility, less than half of the herd size under quarter-annual mobility was sustained. By contrast to half-annual mobility, two years of drought endangered less than 10% of the herd size.

For the purpose of understanding (instead of a projection of a realistic scenario), we also evaluated the livelihood security for one scenario of constant precipitation where the precipitation value equals the average from the stochastic scenario. Although the average herd size under quarter-annual mobility is very similar between the precipitation scenarios (0.5 head/ha (constant prec.) vs. 0.49 head/ha (stochastic prec.)), the single simulation based on constant precipitation resulted in a much higher level of fulfilled income needs (by $> 50\%$) at a level of no risk tolerance. This can be caused by the sensitivity of the risk assessment towards the number of runs evaluated. Occasionally, scenarios of constant precipitation resulted in stable herd sizes, which were heavily affected by the drought event. So, apparently stable scenarios were the least resilient against extreme droughts in our simulations (large dark area in Figure 5.4 D).

5.4 Discussion

The social-ecological system of pastoral range management faces the risk of an increased frequency of droughts in drylands due to climate change (Linstädter et al., 2010). However, the relation of meteorological droughts to shortfalls of herd size and thereby a socio-economic risk for pastoral livelihoods was not clear so far. Understanding the relationship between a shock like drought and livelihood security requires to specify how the effects are transmitted through the biophysical, economic and social system through which people obtain food (Dilley and Boudreau, 2001). We used time series of livestock simulation to evaluate pastoral livelihood security. Thereby, we linked ecological rangeland dynamics with the livelihood of one pastoral household in the light of different management strategies such as mobility. This innovative approach distinguishes the effect of a meteorological drought from other possible drivers and analyses at the same time the combined effect of droughts with various socio-economic factors.

5.4.1 Instantaneous translation of a meteorological drought to shortfall of herd

In our simulation, meteorological droughts were expressed by 37–54% deficiency of the mean annual preciptation over two years. The specific value per pasture depended on the pasture location within the altitudinal gradient. The magnitude of precipitation deficiency lies well in the upper range of 25 to 50% deficiency specified for droughts by Pratt et al. (1997). As a consequence, we observed an instant forage shortfall that was closely followed by a shortfall of the herd size by 15% under quarter-annual and 22% under half-annual mobility. This is quite low compared to reports on 30–50% of livestock shortfalls after severe droughts in East and Central Africa (Scoones, 1992; Aklilu and Wekesa, 2002; Le Houérou, 2006). The deviance can partly be explained by the type of livestock, since smallstock like sheep and especially goats can be more drought tolerant than cattle. Smallstock browses on shrubs and woody plants and is not confined to grasses (browsing includes more ingestible quantity of dry matter) (Grenot, 1992). Thus the buffering effect for drought transmission depends mostly on the vegetation type and well adapted herbivores. Since we simulated perennial vegetation, a large part of woody shrubs is still available as forage in years with low precipitation (c.t. Müller et al., 2007a). In contrast, most studies on droughts so far investigated areas with cattle grazing on perennial grasses (for example Hein, 2006; Angassa and Oba, 2007) where forage and livestock shortfalls after droughts can be more pronounced.

5.4.2 Droughts are part of natural dryland herbivore dynamics

Interestingly, the magnitude of the shortfall of the herd due to drought in our simulation lies completely within the range of long-term variability. As precipitation stochasticity was often seen as a driver for vegetation and herd size degradation (Williams and Albertson, 2006; Ritten et al., 2010), we examined how much variability of livestock was caused by precipitation in our model. Contrary to our expectations, we found that the largest part of variability was inherent to the herbivore-vegetation dynamics. This could be explained by a time lag in the interaction between herbivores and vegetation which is known to lead to coupled oscillations (Owen-Smith, 2007). The evidence for a very low sensitivity of simulated herd sizes towards precipitation variability was already shown earlier for the case of homogeneous pastures (Chapter 4). From this perspective, droughts are unavoidable events where the risk of losing an important livelihood asset must be considered in advance. Long traditional systems of pastoralism developed adaptive strategies that allowed secure livelihoods. However, current changes in the socio-economic environment challenge the options to maintain traditional pastoral livelihoods (Breuer, 2007).

5.4.3 Mobility is advantageous over alternative income for dampening longterm drought effects

We aimed to test whether droughts endanger livelihoods more or less than decreased mobility. Our results have shown that herd sizes which were sustained by the quarter-annual cycle, were reduced by over 50% in scenarios using the half-annual cycle. Less mobility forced a higher intensity of forage use which induced a degradation in the beginning of the simulation to a lower level of the sustained herd size. In contrast, drought affected less than 10% of the income needs that were sustained without the drought for both mobility scenarios. Notably, this effect was not increased under half-annual mobility. Thus, rather than specific drought events, long-term management was decisive for rangelands productivity and thereby pastoral livelihood security. This is in agreement with case studies in Ethiopia on wealth evaluations of pastoral households (Lybbert et al., 2004), where household-specific factors accounted for most observed variability. Further, it was shown that an increase of household vulnerability is not primarily the consequence of drought, but of uneven socio-economic drivers (Hassen, 2008). However, grazing experiments from Senegal have shown that in dry years under heavy grazing pressure rangeland productivity was significantly reduced (Hein, 2006). This was interpreted as an indicator for vulnerability of the ecosystem and people for drought. We recommend to evaluate larger time scales for the livelihood security on the household level ($>$ 10 years) to integrate long-term trends (or a probability distribution) rather than the immediate effects of droughts.

Pastoralists perceive droughts often as a trigger for the collapse of pastoral households (Breuer, 2007). However, the perception of droughts may also rise as a result of an increased food and income demand due to population growth or as a result from land use change (Pratt et al., 1997; Thurow and Taylor, 1999; Western and Nightingale, 2004; Davies and Bennett, 2007). To implement effective adaptation strategies, pastoralists need to decide whether they invest in risk tolerance to future drought events by alternative income or in maintaining high mobility and thereby sustaining a good rangeland condition. Based on our analysis, negative effects of decreased mobility could not be compensated by a high risk tolerance ($> 50\%$ income from non-pastoral activities). By acknowledging these benefits of mobility, policies might better support sustainable pastoralism.

5.4.4 Less mobility affects herd sizes worse than drought alone

Mobility was often discussed as a critical strategy for pastoralists in drylands (Oba, 2011), either by escaping the effects of droughts through large scale movements to unaffected areas (McAllister et al., 2006) or by tolerating drought and using local key resources as buffering forage stock (Ngugi and Conant, 2008). A change of pasture access regimes is a likely threat in Morocco due to expansion of close-by villages as well as governmental interventions that seek to provide incentives for pastoralists to become sedentary (Breuer, 2007). Since it seems obvious that the herd size is decreased by limiting the absolute size of pastures, we made an even stronger argument: Although the absolute pasture size remained, our model has shown that the management strategy alone makes a big difference. This was also observable in Morocco, where poor households often miss sufficient labor force to conduct the full transhumance cycle (Rössler et al., 2010). Our results support that decreasing mobility could have more negative impacts on pastoralists livelihood security than one event of a meteorological drought. However, single households might still abandon pastoralism shortly after a drought since they were also exposed as vulnerable prior the drought event. Note, that our study did not investigate a sequence of droughts, as they are projected to increase in the future. Nevertheless, it is important to recognize that management can make a crucial difference and that it can be of much more relevance when analyzing vulnerable livelihoods in drought prone areas. The reason for households abandoning pastoralism is often more likely to be related to decreased mobility options than to the environmental hazard alone.

5.5 Conclusion

We conclude that a meteorological drought alone does not endanger most pastoral livelihoods. Concurrent population growth as well as restricted mobility, because of diverse socio-economic reasons, pose a greater risk. Focusing on drought-induced risk for pastoral livelihoods can be misleading when instead political action is required to ensure adequate access regimes to pastures or markets for growing populations of people. As the requirements of sustainable pastoralism are not universal (Davies and Bennett, 2007), one should carefully consider the long-term livelihood evaluation beyond immediate effects of shocks.

6 What key traits of dryland vegetation can sustain smallstock?

Land use change in drylands combined with effects of climate change challenges pastoral range utilization and thereby pastoralists' livelihood base. Thus, viable options of using heterogeneous, highly variable and changing rangelands are crucial. In this chapter, we investigate the different performance of pastures utilized by a group of pastoralists along an altitudinal gradient in the High Atlas Mountains of Morocco.

6.1 Forage as a manageable ecosystem service

Pastoral livelihoods in drylands are tightly connected to the ecosystem functioning of livestock and vegetation (Scoones, 1999; Thornton et al., 2007). The production of forage in arid rangelands is highly variable and spatially heterogeneous, which makes sustainable pasture utilization a challenging task (McAllister et al., 2006; Fynn, 2012). Traditional pastoralists have adapted to variable forage availability by mobile grazing strategies such as the transhumance cycle (Kuhn et al., 2010; Akasbi et al., 2012). However, the utilization of rangelands for pastoralism competes with alternative land use strategies such as irrigated agriculture. Furthermore, heterogeneous rangelands may be affected differently by future global changes in climate (Howden et al., 2007).

Besides climatic gradients, spatial heterogeneity may also result from a heterogeneous redistribution of plant resources within a landscape due to lateral water transport (Güntner and Bronstert, 2004; Linstädter and Bolten, 2007). Water and nutrients typically accumulate in lowland positions of a landscape, for example in proximity to river courses, or in depressions (Wilcox and Thurow, 2006). This spatial heterogeneity affects the functioning of individual ecosystems and entire regions (Chapin III et al., 2011). Particularly in dryland environments, the redistribution of water may facilitate a primary productivity on the landscape level that is higher than it would be under more homogeneous circumstances (Noy-Meir, 1981). This observation triggered – within the context of the disequilibrium theory - the development of the "key resource" concept. Key resources are defined as those (vegetation) resources whose supply determines the size of a key factor (Illius and O'Connor, 2000). Thus, livestock herd is expected to be in a long-term equilibrium with the key resource which means a density-dependent regulation of livestock populations driven by the limitation of forage provision on local pastures (Illius and O'Connor, 2000). Because this definition of a key resource is rather abstract, and not of practical value when searching mechanisms of sustainable range management on a landscape level (Linstädter and Bolten, 2007), key resources have recently been re-labeled as 'dry season foraging zones' (Ngugi and Conant, 2008) or 'functional dry-season habitats'. This seems to be a plausible and pragmatic approach for identifying key resources in a given pastoral system, as it is often a question of availability of habitats within a region which are able to provide forage during the dry season that determines the size and stability of herbivore populations (Illius and O'Connor, 2000; Owen-Smith, 2004).

However, the time when a certain area or ecosystem within a heterogeneous landscape is grazed does not explain why (and how) it should exert a density-dependent regulation of a livestock population, sustain a relatively higher stocking rate, or prevent the livestock herd from population crashes. Hence, an operational approach for identifying those characteristics which make an area or ecosystem a 'key' resource is still missing. It is the purpose of this chapter to identify those characteristics. Specifically, we aim to understand what functional vegetation traits are linked to comparatively large and stable livestock populations.

Plants are known to adapt to grazing impacts, but it is still an open question how different plant traits aggregate to an ecosystem functioning providing different services (Violle et al., 2007; Lavorel and Grigulis, 2012). These traits can be classified within the fundamental trade-off between efficient resource capture and resource conservation first described for leaves as the 'leaf economics spectrum' (Wright et al., 2004). Functional traits on the individual level can influence processes at higher organizational levels. Hence, the performance of traits can be assessed on various levels (Violle et al., 2007; Shipley, 2010). For example, resource capture can be measured as the net photosynthetic rate of leaves, a trait closely related to resource capture within the leaf economics spectrum (Wright et al., 2004) which is conceptually equivalent to a plant's relative growth rate (referring to the 'plant economics spectrum' described by Freschet et al. (2010)). Resource capture on the community level can be measured as specific aboveground net primary production (related to a 'plant community economics spectrum' by Frenette-Dussault et al., 2012; Perez-Ramos et al., 2012). The latter expresses primary productivity on a per gram of biomass basis instead of a ground area basis (Garnier et al., 2004), which has also been termed 'ecosystem production efficiency' (Reich et al., 1997) .

The 'ecological performance' of vegetation at the regional scale facing diverse environmental impacts such as variable climate and grazing depends on the combined response of multiple traits (Violle et al., 2007). We aim to identify functional vegetation traits that serve as a key factor for sustaining a livestock population and denote these traits as 'key traits' hereafter. We observed a climatic and altitudinal gradient that determined the establishment and adaptation of a gradient in plant types. Using this vegetation data from Southern Morocco, we investigate the following questions:

1. Which pasture is a key pasture, i.e. is most crucial in sustaining a high and stable herd size?
2. Which vegetation traits are key traits, i.e. are characteristic for the key pasture

identified?

3. What factors control the performance of key pastures and key vegetation traits? What role do the other pastures and the management strategy play?

We answer these questions using the abstract and rule-based simulation model of a spatially heterogeneous rangeland (Chapter 3). Four pastures are parameterized by vegetation data from pastures utilized by one group of nomadic herdsmen named Ait Toumert (see Linstädter and Baumann, 2013). First, we operationalize the concept of key resources and provide a mechanistic definition for a 'key pasture' which we apply to evaluate scenarios of different pasture sets. Thereby, we identify the pasture with the relatively highest contribution to the herd size. Second, we compare the influence of vegetation traits during the simulation to identify traits which correlate most with the herd size. Finally, we discuss our findings in the light of sustainable adaptive strategies related to key vegetation traits and key pastures.

6.2 Methods

To identify key traits of local pastures in the regional utilization context, we parameterize a spatially implicit rangeland model. Further, we provide a new definition for key pastures which was applied to evaluate pasture performance. For that purpose, we developed a simulation setup that exchanges pastures systematically. Finally, we compared the sensitivity of the sustained herd size against functional vegetation traits.

6.2.1 Observed gradients and trade-offs along an altitudinal gradient

Climate and vegetation data were collected from a region inhabited by a group of pastoral nomadic people in the High Atlas Mountains, Morocco. During a vegetation exclosure experiment, standing crop was measured before and after the growing season to estimate the local production on four sites (Table 6.1, see details in Linstädter and Baumann (2013)). We selected vegetation traits that describe the different abilities of resource capture and resource conservation. For resource capture, we chose a specific growth rate termed rain use efficiency (Le Houérou, 1984) which is further related to the reserve biomass (similar to the relative growth rate by Poorter and Garnier, 2007) (cf. the model description in Chapter 3). The resource conservation is approximated by the maximum potential of reserve biomass. Thus, our model simulates green and reserve biomass (Noy-Meir, 1982). For the purpose of model parameterization, we use the hypothesis of the plant economics spectrum that, on the resource acquisition versus conservation rate trade-off, leaves, stems and roots occur at the same position (Freschet et al., 2010). Hence, it is less important in which of their organs (leaves, stems, and/or roots) plant individuals conserve their acquired resources, and the general ability of plants to conserve their resources in storage tissue can be modeled.

Table 6.1: Pasture characteristics supporting pastoral livelihood, used for model calibration and evaluation (compare to Scoones, 1999).

Resource type (Baumann, 2009)	**Precipitation** MAP (mm), CV (%) (Schulz et al., 2010)	**Vegetation** $RUE_{R->G}$ ($kg\ G \cdot (kg\ R \cdot mm)^{-1}$), R_{max} (kg/ha) (Baumann, 2009)	**Tenure regime** (Kuhn et al., 2010)
A – Summer pasture: Oromediterranean shrubland	358 mm, 18%	$0.7 \cdot 10^{-3}$, 5000	Tribal access, Agdal
B – Intermediate pasture: *Juniperus* woodsteppe	317 mm, 20%	$1.4 \cdot 10^{-3}$, 3000	Tribal access
C – Winter pasture: *Artemisia* steppe	240 mm, 32%	$3 \cdot 10^{-3}$, 2000	Common property
D – Far winter pasture: *Hammada* semidesert	150 mm, 29%	$4 \cdot 10^{-3}$, 500	Common property

We found a gradient in vegetation characteristics in terms of their functionality as productive forage plants along the climatic gradient (Figure 6.1). Northern pastures on high altitudes (A, B) are limited by a short growing season, and plants are specialized in conserving resources. In contrast, pastures in the south (C, D) are efficient in resource capturing by the means of a fast acquisition rate, but they are limited by the small amount of annual precipitation. The type of vegetation resources in one region has often a consequence in the type of management system applied (Scoones, 1999). While valuable resources are often used by exclusive rights, uncertain and less valuable resources are commonly managed. In our pasture gradient, we found both systems in practice. The reliable provision of forage from high altitude pastures relates to the strict distribution of areas between different fractions of nomadic households. In addition, the access to summer pastures is restricted by a collective decision on opening and closing dates called Agdal (Ilahiane, 1999). The pastures at lower altitudes are associated with uncertain forage provision and thereby commonly used without exclusive rights (Rössler et al., 2010).

6.2.2 Operational definition of key pastures

From the perspective of herbivore-vegetation dynamics, some resources are considered as a key factor in determining the herbivore population size (Illius and O'Connor, 1999). One may conclude that the absence of key resources in an arid rangeland would

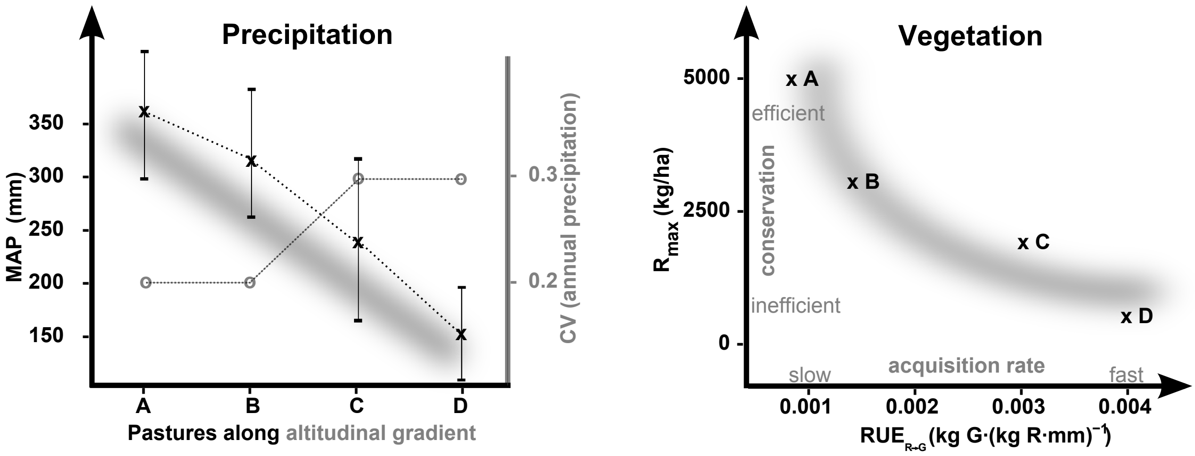


Figure 6.1: **Left:** Precipitation gradient along altitudinal gradient of pastures. A – summer pasture, B – intermediate pasture, C – close winter pasture, D – far winter pasture (see Chapter 2 for details). **Right:** Location of pastures based on two traits capturing the tradeoff between divergent strategies (resource acquisition, *x*-axis, and resource conservation, *y*-axis).

cause a shortfall of the herd. If pastoral households were solely based on income generated from a minimum amount of livestock, a shortfall of the herd for example due to a restricted access to the key resource would undercut the demand of local land users (that would have been sustained with a present key resource in the system). To test the performance of heterogeneous pastures in a region utilized by one herd, we developed the following definition:

Definition 1 (Key pasture)**.** A key pasture is a pasture which ensures the provision of forage for livestock to sustain the number of animals. A key pasture is crucial for keeping a livestock population above a critical level determined by local land users' demand and livelihood security.

Based on this definition, we expect that excluding this pasture would decrease the resulting herd size. To examine which of the considered pastures contributes most to sustaining a viable (but dynamic) herd size, we compare the herd size that is sustained by a set of pastures including the pasture of interest with a herd size using a pasture set excluding this pasture. Since we do not know which of our pastures serves as key, we have to exchange each pasture in a systematic way.

6.2.3 Scenario setup to evaluate key pastures

Figure 6.2 shows the systematic substitution of pastures grouped into four sets, where one pasture type is excluded in each set. The abbreviation of scenario names is constructed with the capital letter of the excluded pasture followed by a small letter for the pasture which substitutes the earlier. The quality of pastures was inversely identi-

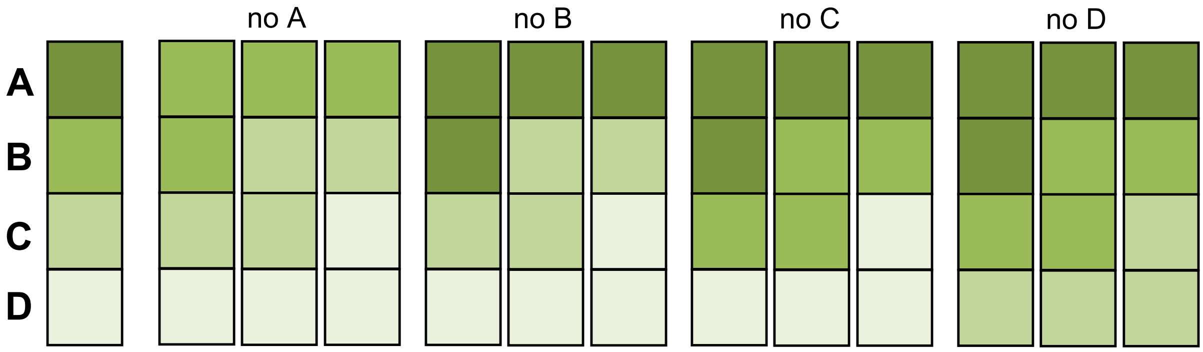


Figure 6.2: Pasture setup to investigate relative productivity

fied by the extent to which the herd size drops in each scenario of their absence. Since large sample sizes are expected from repeated simulations, an analysis of variance can result in significant differences although the effect is relatively small. Therefore, we calculated effect sizes, namely Hedges' g, which is the standardized mean difference to the reference scenario.

6.3 Results

6.3.1 Pasture performance in terms of the herd size

Figure 6.3 shows the distribution of simulated herd sizes from each pasture set scenario. An absence of pasture C caused the strongest downward deviation, and pasture sets containing two times pasture C had the highest upward deviation. An analysis of variance resulted in significant differences between the reference and all scenarios except the 'noAb' scenario ($p < 0.05$). Since the sample size from each scenario is very large (170 time steps times 50 repetitions), already small differences in mean values between scenarios were evaluated as significant. To differentiate the magnitude by which scenarios differ from the reference scenario, we evaluated the standardized mean difference by calculating the effect size Hedges' g (Hedges and Olkin, 1985). Results are shown in Figure 6.4 with each dot depicting the effect size between a certain scenario and the reference. Similar to the interpretation of Cohens' d effect sizes, values can be classified into small, medium and large effects (shown in gray shades). We found three scenarios that deviate upwards from the reference and all of them are based on pasture sets that contained pastures C twice. In contrast, all scenarios that were based on pasture sets without C resulted in a large downward deviation compared to the reference. This is strong evidence that pasture C is a key pasture in the context of pastures A, B, and D. Further, the ranking of effect sizes revealed medium effects for scenarios excluding pasture D which makes D the second important pasture in our set. Scenarios without pasture B and substituted by A or D had only small or medium effects. The least effect resulted from scenarios excluding A where it was not substituted by C.

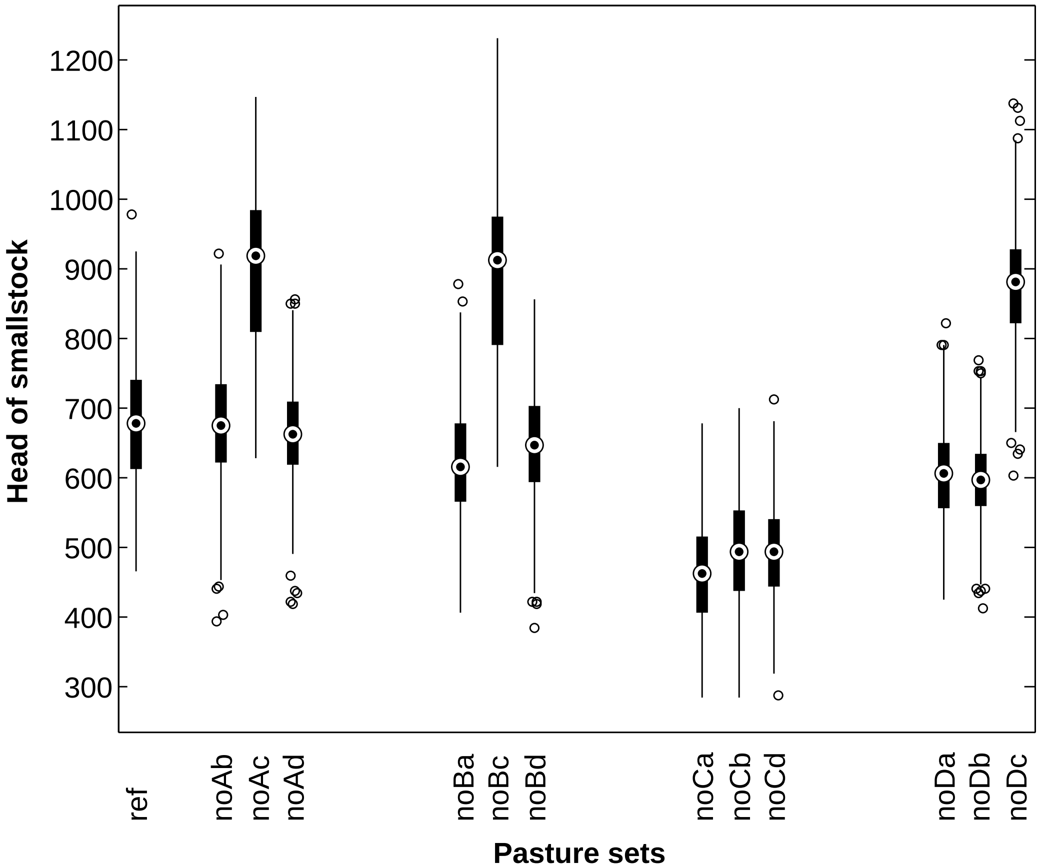


Figure 6.3: Distribution of herd sizes from different scenarios of exchanged pasture sets, see Section 6.2.3 for nomenclature of scenarios. (Ensemble $n = 50$, time frame = 170, without 30 years initialization, 'ref' denotes the reference scenario).

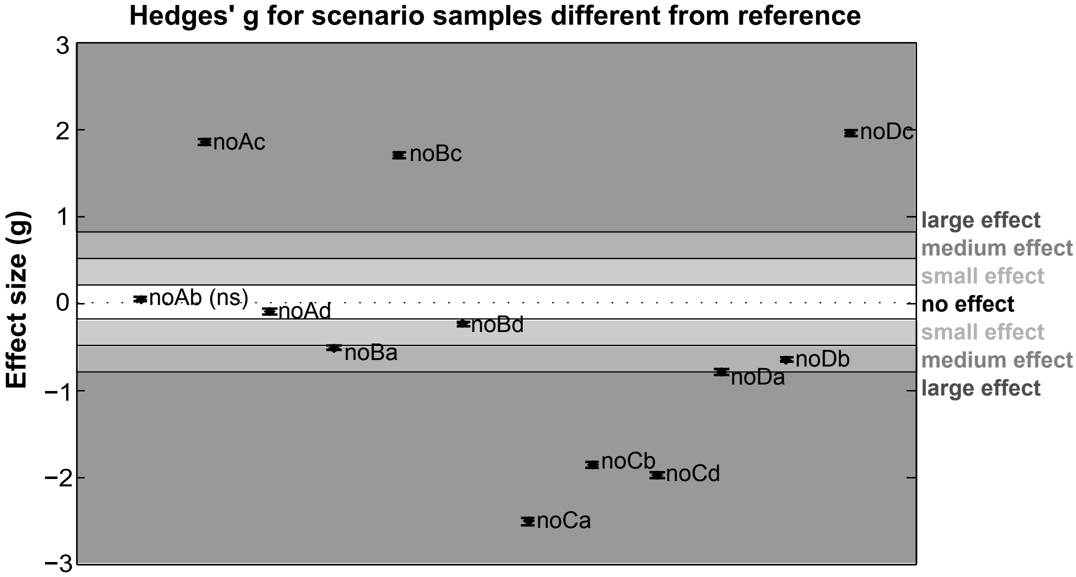


Figure 6.4: Hedges' g with confidence interval (95%) between each scenario and the reference. Effects between $\pm$ 0.2 and $\pm$ 0.5 are classified as small, effects between $\pm$ 0.5 and $\pm$ 0.8 as medium, and effects beyond $\pm$ 0.8 are classified as large effects. Values were multiplied by -1 to visualize effects in the same direction as herd size samples differ.

6.3.2 Vegetation traits related to pasture performance

To find out which vegetation traits enabled pasture C to perform in a way that it was identified as a key pasture, we monitored vegetation states during the simulation of the pastures in the reference scenario. The hypothesis was that herd sustenance is somehow related to high forage production and a low variance by the vegetations buffering capacity. Therefore, we collected state values from each pasture of used forage and reserve biomass (Figure 6.5). The amount of forage used on each pasture corresponded to the distribution of seasonal visits on the pasture set. Note that pasture C was identified as a key pasture earlier. Some indication for this finding is also reflected by the fact that pasture C evidently contributes by far the largest part of forage to the herd and the largest part of visits compared to other pastures. However, the second largest effects on the herd size were identified for pasture D, although this was contributing the least in terms of forage biomass. This can be explained with the results from the next evaluation step (Figure 6.5, III) where pasture D had by far the smallest base of reserve biomass explaining the small production. A low state of reserve biomass could indicate a bad state of the pasture. However, the relation of reserve biomass to its maximum potential amount ($R/R_{\max}$) reveals that pasture D is closer to the potential maximum $R_{\max}$ than all the other pastures. This means that it is less heavily affected by the relatively small number of seasonal visits. In contrast, pastures A and B are far below their specific maximum of reserve biomass indicating a greater grazing

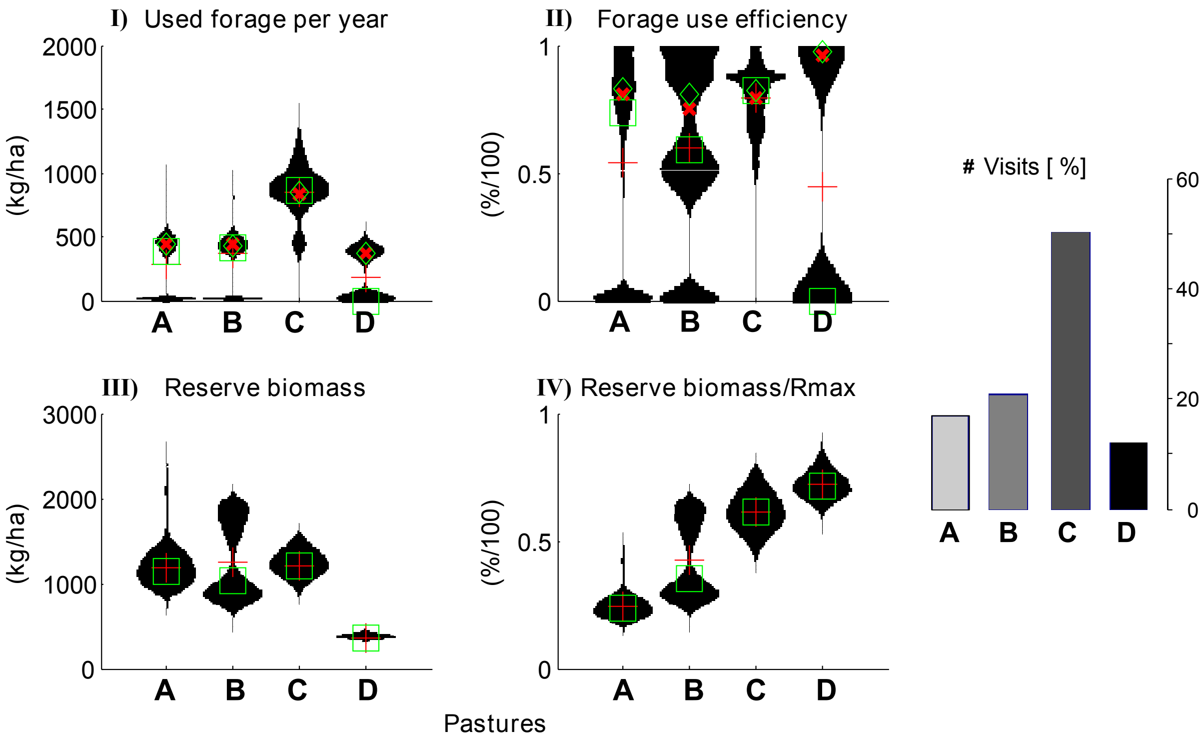


Figure 6.5: Distributions of annual forage and reserve biomass values from the reference simulation (violin plots). I) shows the amount of annual used forage ($kg \cdot ha^{-1} \cdot year^{-1}$) from each pasture. II) shows forage use efficiency (used/available forage) where the red x denotes the mean and the green diamond the median of the distribution without zero values. The red cross denotes the mean, the green rectangle the median of each complete distribution. III) shows the standing reserve biomass on each pasture and IV) the proximity of reserve biomass to its maximum. (ns) denotes that this scenario was not significantly different from the reference (ANOVA, $p < 0.05$).

pressure that lacks sufficient resting and recovery times. However, the distribution of pasture usage enables enough resting time for pasture C as its absolute state of reserve biomass is above the state of A, B and D.

6.3.3 Sensitivity of herd size to various vegetation traits

To quantify which of the different vegetation traits is more relevant for the herd size, we conducted a sensitivity analysis varying trait values in the key pasture C. We found a larger effect of varied amounts of maximum reserve biomass $R_{\max}$ on the herd size than by equal changes in the specific growth rate of vegetation $\mathrm{RUE}_{R\to G}$. $R_{\max}$ corresponds to an ecological capacity K which determines the amount of forage thereby the theoretical sustained herd size. $\mathrm{RUE}_{R\to G}$instead is analog to r and determines how fast a pasture may recover after grazing events or disturbance. Interestingly, when decreasing parameters $R_{\max}$ and $\mathrm{RUE}_{R\to G}$, the herd size differed more from the reference than increasing parameter values, which implies a nonlinear effect.

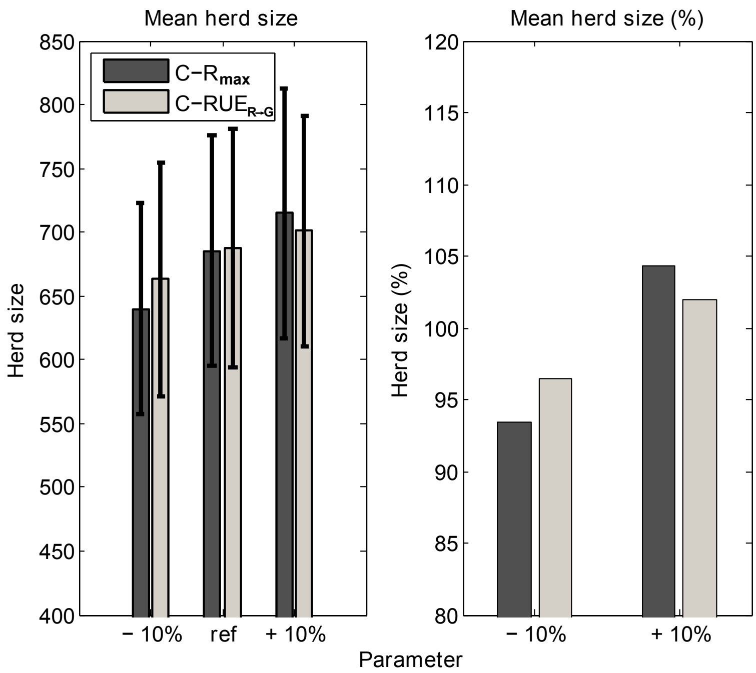


Figure 6.6: Sensitivity of herd size to variation in vegetation traits in pasture C. Values were varied in the same parts for the two opposing traits, maximum reserve biomass and specific growth rate ($\mathrm{RUE}_{R\to G}$).

6.4 Discussion

The aim of this regional rangeland use for securing pastoral livelihood and local vegetation investigation was to identify pastures or traits that contribute more than average to herd size sustenance despite variable annual precipitation. This analysis could help pastoralists to facilitate high performance of pastures in short terms by suitable utilization strategies without sacrificing long-term buffer and recovery capabilities.

6.4.1 Mean herd sizes from substituted pasture scenarios reveal the key pasture

We operationalized the concept of key resources by defining the function of a key pasture within a specific grazing system, which is not an absolute performance criteria. As the presence of key pastures determines the achievable herd size (Illius and O'Connor, 2000), the absence of the key pasture would cause a shortfall of the herd size compared to the scenario including the key pasture. We simulated these hypothetical scenarios using the spatially implicit rangeland model developed in this thesis and evaluated the herd size distribution as a result from the systematic exclusion and substitution of pasture types. Different pasture types were characterized by a climatic gradient and vegetation traits parameterized by field study data. The pasture-specific vegetation traits were located between the extreme ends of efficient conservation and efficient acquisition within the plant economic spectrum (see for example Violle et al., 2007).

From the perspective of livestock, one would expect that the most productive pasture has the highest value in forage contribution. However, variability in precipitation, as it is common for drylands, demands that vegetation is also partially able to conserve resources and to buffer temporal variability. As it was shown in various studies on individual plant traits, plants specialize in the specific combination of resource acquisition and conservation, which has consequences for the productivity of forage on the regional scale (Wright et al., 2004; Violle et al., 2007; Shipley, 2010). In our case, highly productive pastures face also much lower annual precipitation that caused a trade-off and made it unclear to assess from the beginning which of them contributed most to herd size sustenance.

The inverse pasture evaluation based on their particular absence in simulated scenarios revealed that one pasture from the middle of the gradient, named 'winter pasture' (Pasture C), had the highest relative value in supporting the herd size. All scenarios without this pasture have shown the highest negative effect size compared to the reference scenario, which is the closest to the real case. This innovative test provides strong evidence that the winter pasture is the key pasture in our system. Beyond identifying this most valuable pasture in terms of the sustained herd size, we were able to rank the other pastures using the effect sizes. The pasture characterized by the highest growth rate resulted being in the second place ('far winter pasture') and the highest conservative pasture on the last ('summer pasture').

6.4.2 Local pasture performance and key vegetation traits

The ranking of pastures in their ability to support the herd size can be explained by taking a closer look at the local vegetation dynamics over the simulation. The amount of annual used forage was highest for our key pasture and on an equal level for the other pastures. Interestingly, other pastures were rested in some years while the key pasture was used twice a year during a quarter-seasonal movement course. The relation of used forage compared to the available forage per year revealed that despite the heavy use of the key pasture, it was less intensively used. Consequently, it was better able to recover from grazing and remaining productive while other pastures required complete years of resting.

In contrast to the key pasture, the second rated pasture ('far winter pasture', Pasture D) was most intensively used in the years when not rested, but therefore it was used in the least number of years. This can be explained by the resource base, which is represented by the amount of reserve biomass. The 'far winter pasture' had the lowest amount of reserve biomass compared to the other pastures and consequently a relatively low forage production. If related to the maximum potential reserve biomass R_{max}, the 'far winter pasture' was the closest to its maximum reserve conservation and therefore the least hampered by grazing pressure. Interestingly, both pastures specialized in efficient conservation were the least able to recover from grazing which resulted in a below-average level of reserves.

Further, we tested which of the different traits in the key pasture was more important for high livestock numbers. Although high forage production resulting from high efficiency in nutrient acquisition seemed to be the more important trait, the herd size was more sensitive to changes in the maximum reserve biomass R_{max} than to the specific growth rate $\text{RUE}_{R\rightarrow G}$. This can only be explained with the location of the key pasture within the plant economics spectrum. Since conservation efficiency is the less pronounced trait and limiting factor in the key pasture, its ability to build reserve is the key trait in terms of herd size sustenance.

6.4.3 The regional context determines the performance of key pasture and key traits

Summarizing the results in terms of bottlenecks in regional livestock production, the first bottleneck for sustaining a large herd size was high forage production of the key pasture. But, the second bottleneck was related to the relatively low reserve conservation on the 'far winter pasture'. This highlights the importance of the regional context where herd sustenance is not only dependent on high forage provision by one key pasture but also on resting, recovery, and buffering ability of the associated pastures.

The suitable distribution of grazing pressure over time and available pastures is subject to conscious management decisions by pastoralists. Therefore, the relative value of different pasture types in a region can be linked to specific management strategies and institutions (Scoones, 1999). The contrasting types were exemplified by Scoones in a case study from Zimbabwe by high-value resources under private property and low-value resources under loose common-property regime. We compared our findings on pasture performance to observed management decisions by nomadic herdsmen in Southern Morocco. It is true that the 'far winter pasture' is spared in many years since the forage availability is very uncertain and dependent on very small scale precipitation events (Kemmerling, 2008). Contrary to the findings by Scoones, our key pasture is in a communal management without exclusive grazing rights. Several socio-economic aspects could be the cause for this divergence of resource quality and tenure. First, beside the nomadic herds, the area of the 'winter pasture' is very much used by herds of nearby villages. Since our model simulated the area that is approximately used by one household, we could not account for such competitive situations. Second, the winter season was reported as one where herdsmen face the scarcest forage availability. And finally, pastoral households differ highly by their specific number of family members, labor force, and income from wage labor that affect their mobility decisions (Kuhn et al., 2010). In most years households invest in supplementary feeding instead of distant travel. Contrary to the communal pastures, the 'summer pasture', which we evaluated as least important, is exclusively used by the group of 'Ait Tomert' nomads. This is evidence for a high appreciation of this resource type by nomads which was also confirmed by interviews (Kemmerling, 2008) where herdsmen described the summer season as very reliable. Since our valuation focused on pasture performance regarding their function as a 'key' (= bottleneck), this is likely not helpful to identify reliable and locally valuable resources.

The divergence of model evaluations and local perceptions proves how complex and important the interaction of the social and the resource system is. Even if local users are aware of their key pastures, this is not enough to determine sustainable land-use strategies (Mutinda et al., 2008). Not only the inherent value in terms of pasture performance, but the relative value in relation to the seasonal and household-specific demand is crucial (Scoones, 1999). This implies that the relationship between resource quality and management cannot be determined from a single investigation perspective but should be subject of a holistic social-ecological analysis.

6.4.4 Revisiting the concept of key resources

The concept of key resources aims to analyze the management of more or less coupled vegetation-herbivore systems where livestock is regulated by the key resource (Illius and O'Connor, 2000). Whether a key resource is degradable within the context of a highly variable environment is still an open question (Hambler et al., 2007) and beyond the scope of this study. However, using a mechanistic approach to investigate the pasture performance allowed us to identify the traits of pastures that function as a key. Further, we found that the question whether there is a key pasture in the system or not cannot be answered in a binary way in terms of presence or absence. Much more, the pasture performance is a continuous feature which is built from many local vegetation traits together and influenced by the regional context of resource use. Since the long-term performance of pastures facing precipitation variability and changing land use cannot be tested by a field experiment, our simulation approach offers new insights into the valuation and suitable management of pasture resources.

6.5 Conclusion

This study evaluated pasture performance in a regional context of mobile pastoralism and in relation to the concept of key resources. Our analyses helped to identify crucial resources in terms of locally differing vegetation traits that livestock and people heavily rely on. This has implications for pastoral management during land use changes where shifts occur in the forage vegetation and its functional traits related to grazing. Our results imply that the focus on livestock production and pasture-use efficiency in drylands is often misleading. The regional context is crucial since grazing pressure shifts quickly in times with heterogeneous forage availability and consequently the time and part of resting, buffering and recovery of vegetation. The idea of having a key in the system is less a question of presence or absence but of a differentiated evaluation of pasture performance that results in a gradual spectrum of importance for livestock sustenance. Therefore, this study critically evaluated the concept of key resources and refined its application to rangeland system analysis.

7 Research by playing: a board game on nomadic pastoralists

This chapter illustrates how research on mobile pastoralism motivated the development of a strategic board game. Its purpose is to present insights on range management in an easily understandable way and to foster discussions between disciplinary experts. I demonstrate how collected research results on pasture ecology and herd management by pastoral households provided the basis for rules and processes in the game. Although these rules are rather simple, their combination has proved useful in providing a first impression of and to raise awareness for the nomadic way of life. Beyond the picture of how nomadic households are embedded in their environment, the game enables insights into the world of modelling and simulation. Just like the rules built the game environment, one can translate these rules to build a computer model (e.g. Michelin, 2006). Similar to one round in the game which is one realization of an event's sequence, a computer simulates these events and executes time-expensive analyses.

In the following, I introduce the aims of the game development in more detail. After that, I describe the structure and rules of the game using a protocol that was originally developed for agent-based models. Finally, I summarize experiences from plays with students at different ages and reflect on meaningful applications of the board game for research and education.

7.1 Background and aim of the game

The board game was developed in the context of a research project on mobile pastoralism (Nomads and Sedentaries[1]). It was used within the final exhibition of the project in the "Museum für Völkerkunde" in Hamburg. The general purpose of the exhibition was to present research results on nomadic people that are often related to or interacting with sedentaries[2]. The presented contents ranged from 5000 years old objects to current histories and tools from the everyday life of mobile herdsmen. Each participating project was asked to provide materials and information on their research area which could be experienced in an interactive way, for instance wool or handicraft products from nomadic people.

Compared to specific objects, images or textual insights, the results from our project "Nachhaltigkeit (post-)nomadischer Ressourcennutzung unter Globalem Wandel: Konzeptionelles Verständnis durch ökologisch-ökonomische Modellierung"[3] were of a more general nature. Model analyses provide an overview of the underlying rules in the social-ecological system of pastoralism, for example the requirement of herd mobility to make use of the spatio-temporal forage availability (see Chapter 4.4.3). The challenge was to integrate multiple aspects of nomadic range management and communicate these research results in an understandable way. To reach this goal, we decided to build a board game which introduces typical experiences of nomadic herdsmen to

[1]SFB 586, http://www.nomadsed.de
[2]http://www.brisante-begegnungen.de
[3]http://www.nomadsed.de/en/projects/projects-2008-2012/project-e10/index.html

several players. The playing area consists of pasture fields on which forage grows. By taking the role of a nomadic household, the players' task is to manage and grow their herds of sheep. They can do so by moving sheep to suitable pasture fields or buying supplementary forage. Unforeseeable events, such as diseases or changed access regimes to pastures, may interfere with each player's strategy.

From our perspective, the board game functions as a transdisciplinary contribution to environmental education. Players may realize the connectivity of unpredictable events and their impact on the livelihood of nomadic pastoralists. Natural resources are scarce and subject to variable availability, which often endangers pastoral livelihoods. Risk-averse management and sustainable landuse enables players to sustain their herd. Further, cooperation between herders is often advantageous and illustrates the meaning of social networks.

We aimed to confront visitors in the museum with typical experiences and events that require active decision making by herdsmen. Thus, we initially collected key messages that we wanted to demonstrate with the game:

- Mobility is required to feed animals, otherwise pastures degrade under constant use.
- Uncertainty of climate, market and governmental regulations may hinder successful application of strategies.
- Successful strategies must not exhaust resources rapidly. Instead, risk-averse behavior by building up reserves provides advantages.
- Strengthening the social network by cooperation between herders is advantageous.
- The herd is the real capital of herdsmen, only animals provide interest, the income and basis for pastoral livelihoods.

Many colleagues were involved with developing, testing and crafting the game. They are acknowledged via the german game description that is available on the project's website[4].

[4] http://www.nomadsed.de/fileadmin/user_upload/redakteure/bilder/teilprojekte/ausstellungsprojekt/spiela-9.pdf

7.2 The strategic board game 'NomadSed'

In the following, I will describe the main structure and rules of the game. As the requirements concerning a comprehensive game description are similar to a model description, I use a standard protocol for agent-based models, namely ODD (which stands for overview, design and details) introduced by Grimm et al. (2010). This protocol fosters a structured overview about modelling design which supports the comprehensive documentation, understanding and review of models. For describing the player's decisions, I also use parts of the recent update ODD+D for agent-based landuse models and decision making (Müller et al., submitted 2012). However, while the protocol includes agents that can be represented in a computer model, I will refer to real players in the following. As a consequence, not all aspects of creative decision making can be described.

Figure 7.1: School kids starting the game, photo by Mareike Abdank.

After the game description, I will shortly summarize experiences collected from several plays with colleagues, museum visitors and students at different ages (Figure 7.1). Using questionnaires, I asked players about their impression of nomadic life and what they think might be successful strategies to secure pastoral livelihoods. Finally, I evaluate how far the game rules and experiences reflected the previously intended key messages of the game (Chapter 7.3).

7.2.1 Overview of rules and processes in the pastoral environment

The overview of a model description is intended to give an introduction to the general purpose, involved entities and simulated processes. The board game resembles in many ways the model whereas entities refer to the included pieces, and processes refer to the rules.

Purpose We aim to use the game as a tool to communicate experiences about nomadic pastoralists' life and their decision making. The game was intended for people generally interested in pastoralism with an age above ten years in different educational contexts. Playing the game might also be used to introduce scientists of different fields connected to pastoralism to each other's field of research.

Entities The landscape consists of 26 hexagon units, each of which contains a pasture field. Two types of pastures are available, namely grassland (dark green) and steppe (light green). The explicit layout of pastures is flexible and can be changed from one to the next play. Each field can be identified by a pair of a letter and a number, similar to a chess board.

Each player receives a token representing the herdsman and a token for the tent with an individual color. Three to five players may take part in the game. Thus, pieces are provided in five different colors. When a tent or herdsman is placed on a pasture field, this field is occupied and cannot be used by other players without a cooperation agreement. Players get four sheep pieces in the beginning, colored like their tent and herdsman.

A thief is represented by a distinct black figure which is played by the game moderator. Its only purpose is to steal herds. Further entities such as a merchandiser at the market, or governmental institutions may influence the game through event cards.

One round of the game denotes approximately one year in the life of the herdsmen, and within one play five rounds are executed. Each player's goal is to maximize the number of sheep.

Processes Every round in the game consists of four phases (Figure 7.2).

1. **Forage grows** on each pasture field. Forage pieces are represented by green marbles. On unused pastures, two forage marbles are added on grasslands and one marble is added on the steppe fields. Pastures with sheep experience a reduced growth of one forage marble for grasslands and none for steppe fields. In the beginning of the third round or later, one card for the regional event is drawn which may affect growth on pasture fields.

2. **Players move their sheep** in order to feed them with sufficient forage. Each head of sheep requires one forage marble to sustain throughout the year (round). In order to achieve this goal, players use their four available actions points which represent a nomadic household's annual labor power and are replenished every round. However, each player's options to make use of action points are determined by individual event cards (Table 7.1) drawn before the tokens are actually moved. It is against this backdrop that the player has to adopt strategies according to these rules.

   It takes one action point to move a herd, no matter how many heads the herd counts, to the neighboring pasture. If forage is not sufficiently available, the player either may buy supplementary fodder from the market or needs to sell

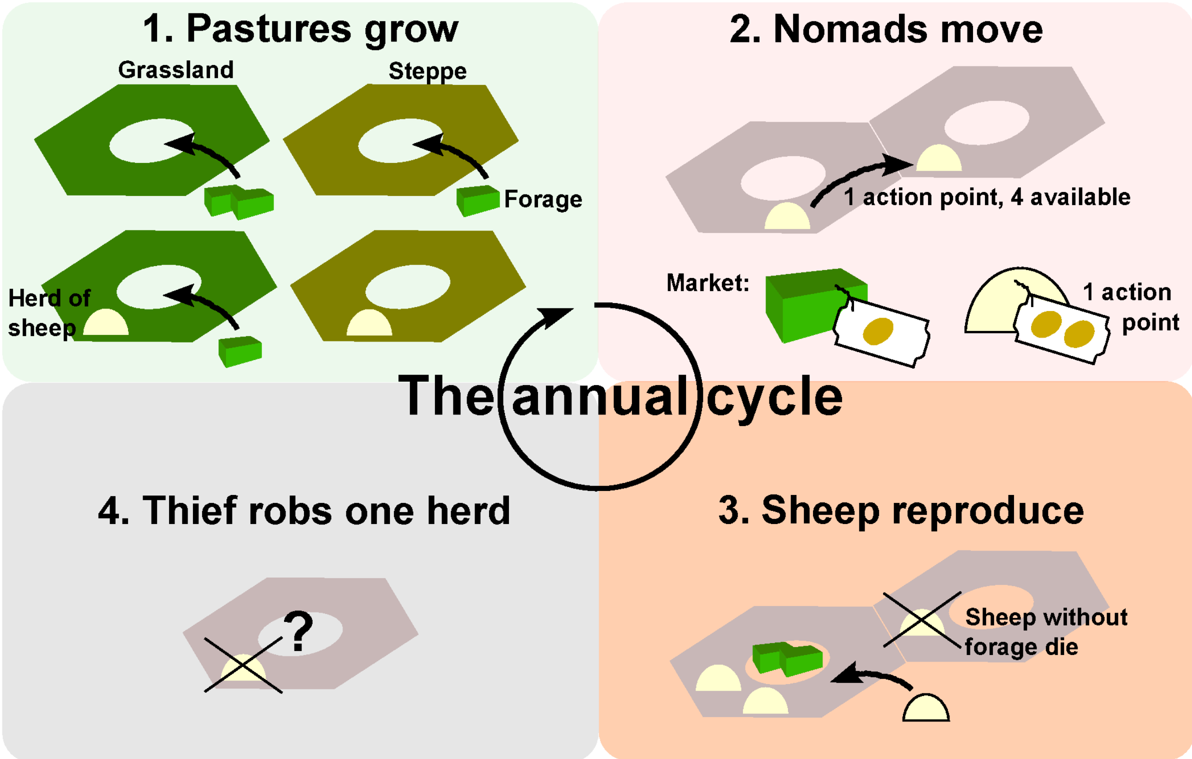


Figure 7.2: Intraannual sequence of events for one round in the board game.

sheep. To sell sheep from one pasture, another action point is required. The player may also decide to buy additional sheep from the market (see for details on decision making in Section 7.2.2). If a player buys sheep from the market, he can put them on any free field. Each round either buying or selling is possible so that trade is not misused for sheep movement. A participants turn is concluded by moving the herdsman 'for free'. Herds resting on a pasture with a herdsman or at the tent are protected from being stolen from a thief.

3. After the end of player's turn, **sheep are fed** in the third phase. Forage marbles are removed from each pasture according to the head of sheep standing there. Sheep that can not find sufficient forage are removed from the game. After that, pairs of sheep reproduce and one lamb per pair is added. If players decided to put sheep of different herds (colors) together, the ownership of the resulting lamb is decided by chance (e.g. by placing sheep of two colors into a bag and drawing one of them). The player receiving the lamb pays a coin to the cooperating herdsman.

4. Finally, the **thief is played**. For that, one player draws a field number onto which the thief is placed. If the pasture is occupied by an unprotected sheep herd, the thief steals the complete herd. Otherwise the thief moves along the field numbers to look for unprotected herds. If he cannot find a herd, he is removed from the board.

7.2.2 Design concepts including decisions by herdsmen

The middle part of the description is a collection of concepts that constitute the design of the model.

Theoretical and empirical background We used very abstract rules of thumb reported from the literature to translate ecological rangeland processes and their management into the game. These rules are mainly independent from specific rangeland areas in the world and time scales.

- Dryland pastures are less productive under constant use, which has the consequence that sufficient resting is required for higher productivity (Müller et al., 2007a).
- The annual reproduction rate of sheep, which is recruitment minus mortality, is assumed to be 0.5. This is a very rough approximation without references in order to keep the units in the game simple.
- Livestock is more valuable to herders than money on a bank account, which is often not accessible for rural people. Animals are the herdsmen's capital (Breuer, 2007).
- Cooperation between herders such as pasture sharing is profitable. Networks exist to take care of animals from relatives when forage availability is spatially and temporally heterogeneous (Breuer, 2007). A formal network between non-relative pastoralists can be institutionalized by agistment (McAllister et al., 2006)
- Theft of animals is common. Especially when livestock is well fed, the chance of theft is increased which motivates some pastoralists to feed their animals not more than absolutely necessary.
- Uncertainty of weather and extreme events such as droughts, changed market prices, and changed pasture access regimes may endanger pastoral households' livelihood security (Breuer, 2007; Bretan, 2010).

Regional and individual events are introduced to the game when players draw cards. These events are connected to observations in case studies where we present only a few examples (see Section 7.2.3). We did not use empirical data for any quantitative relationship in the game, they are fully abstract and specified in order to keep the play attractive for players. For example, events that would destroy a complete household are reduced in their impact to maintain players active during the game.

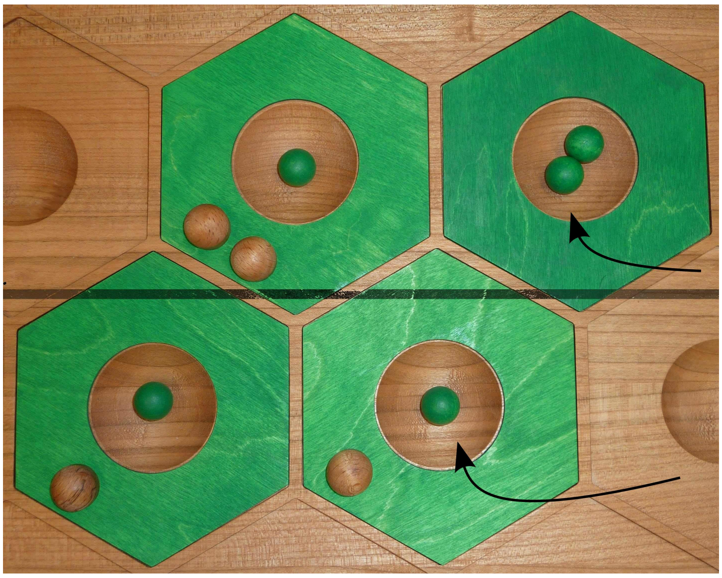


Figure 7.3: Comparison of sheep distributions to exemplify forage growth and recovery on grassland pastures. Above the black line, two sheep stand together and let one pasture resting. It recovers and grows two forage marbles instead of one. In contrast, below the line sheep are equally distributed so that each pasture produces only one forage marble. That makes a total of two forage marbles compared to three in the top case.

Individual decision making In each round, each household takes its turn to care about its sheep. Depending on the drawn event card, labor force, and money available, different actions are applicable (Figure 7.4). Each round, the order of turns changes so that the advantage of being early is distributed more equally between players throughout the game. The actions on which players decide is highly dependent on the available forage and precedent decisions by other players. The objective of each household is to grow their own herd. Future versions may differ by the goal, e.g. each house maintaining a certain minimum size.

Individual prediction Future growth of sheep and pastures is known based on the current forage availability. But decisions by other players, events in the natural or social environment may interfere with pasture regrowth and cannot be predicted.

Interaction Players may support each other directly with gifts or any kind of cooperation. For example, it is profitable to bring single sheep together for sharing their offspring. Or, the service of guarding a herd can be payed. There are no rules restricting cooperation between players.

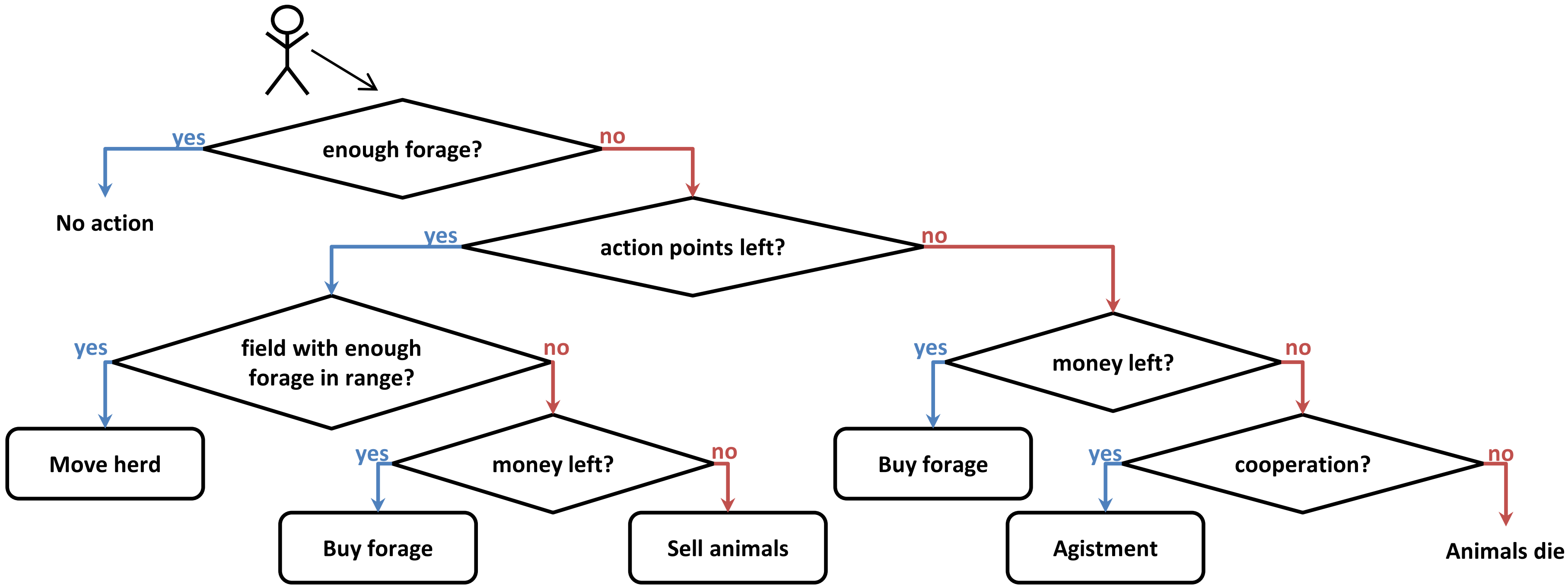


Figure 7.4: The decision graph shows one typical sequence of questions that each player needs to answer when it is their turn. Depending on available forage, labor force in terms of action points or money the player might weigh several options against each other to feed their herd. Players' preferences as well as prior actions from other players may change the order of questions and decisions made.

Stochasticity During initialization the 'home' fields for the tent and herdsman are drawn by each player. It can be advantageous then if the tent can be placed on a dark green field. Individual and regional event cards introduce further stochasticity. For example, some rounds can be affected by unfavorable market conditions. Finally, the thief is placed by chance on one field from where he moves to look for unprotected herds.

Observation At the end of the game, the success of players is calculated. The number of accumulated sheep per household counts twice, coins count single. The remaining forage is documented.

The resource use of pastures on the board often decreases during the game due to the competitive exploitation behavior of herdsmen. This has the consequence that destocking of animals often becomes necessary during the forth and fives round.

7.2.3 Details on the setup and events

Implementation The board game was physically built and its design developed by students from the University of Art in Berlin. They and further support is acknowledged in the German game description.[5]

Initialization The pastures initially contain the amount of forage that would grow within one year without grazing pressure. Each household gets four sheep and two coins as a starting capital. Sheep are distributed freely on unoccupied pastures. They may be occupied by precedent players' sheep, tent or herdsman.

Input data For individual and regional events (Table 7.1 and Table 7.2), we collected reports on typical experiences from case studies from different pastoral societies. The purpose was to offer a variety of response options to the players complementary to rules for sheep feeding while they are informed about everyday life experiences by mobile herdsmen. The accuracy of stories on events was partly adjusted in order to fit to units used in the game.

7.3 Game experiences and the relation to research

Since the board game was intentionally designed for demonstration in a museum, at first not many activities for further testing and application were organized. However, after first positive feedback, the board game was part in a students project (7th grade) and part of several public events at the Helmholtz Center for Environmental Research

[5] http://www.nomadsed.de/fileadmin/user_upload/redakteure/bilder/teilprojekte/ausstellungsprojekt/spiela-9.pdf

Table 7.1: Examples for individual events affecting single households from a set of 32 cards.

Story	Action	Comment	Reference
"Your son sends money from labor work in spain."	"You get one coin."	Positive event.	Breuer (2007)
"Your brother works for a livestock transport company this year."	"He transports one of your herds to a free field without cost."	Positive event that becomes more beneficial towards the end of the game.	Breuer (2007)
"This year's harvest of caterpillar fungus was abundant"	"You receive two coins"	Event relating to a source of income of Tibetian herders.	Gruschke (2009); Winkler (2009)
"A storm damaged your home field and the surrounding area."	"Take away the forage from your and the western field."	Negative event hampering the beneficial use of the home field.	
"Your summer pasture (field of herdsmen) was chosen for reforestation by the government."	"Move your animals from this field and remove the field itself."	This event has often no directly negative effects when field was efficiently grazed.	(Wang et al., 2010)

Table 7.2: Examples for regional events that affect all players in one round from a set of 12 cards.

Story	Action
"New Zealand sold a surplus of lamb meat to the Arab countries."	"Sheep prices are reduced to one coin."
"The price of grain fodder increased due to speculation in the global trade."	"Forage costs two coins per marble this round."
"There is a drought on all steppe fields, existing forage is reduced by one marble. On fields without forage occupied by sheep, one animal dies."	"Herders might protect their sheep by buying supplementary fodder. But due to the drought, the price for fodder is two coins."

in Leipzig. It was used especially during visits from younger kids. In the following, I will summarize players' statements about the board game itself and the impressions they got about the life as mobile pastoralist.

7.3.1 Feedback from questionnaires

From more than 20 games played during one year, feedback was collected from over 65 players. First, some notes on what they liked in the game: The environment, design and idea, challenge in strategic thinking, flexibility of the landscape, real life impressions, and the thief. Second, notes on what players disliked: Thief, strategies that do not succeed, long duration (including discussions, one play lasted two hours). Then players were asked about their impressions on nomadic life:

- Much looking after the sheep and money is required
- Sustaining sheep is challenging
- Difficult decisions
- Strategies impossible since options are event driven
- Challenging and exciting life
- Boring since all is about livestock
- Pastoralists do not use more from nature than they need
- Friends are helpful

When it came to strategies, young students were more likely to present ideas. Mobility was often the first named, cooperation and selling sheep was rarely mentioned. Grown ups did often mention that strategies cannot be well applied since chance was perceived as more important. Thus, from the earlier mentioned learning objectives, mobility was mostly recognized beside the challenging kind of decisions herdsmen make. During the games, I often observed a decline in the number of sheep sustained during the last round. Interestingly, this fact was never used by players in the feedback round to conclude that sustaining their sheep would require to maintain certain reserves and to avoid overstocking. On the contrary, one student mentioned that pasture resting is useless if the forage is used by other herdsmen afterwards.

7.3.2 Further ideas for evaluation and development

The usual setup of pasture fields contained 15 steppe and 11 grassland fields. This can be evaluated in terms of productivity to derive the maximum number of sheep that can be sustained over unlimited time Table 7.3. Without mobility, each grassland sustains

Table 7.3: The maximum number of sustained sheep in the game can be derived from the type, number, and utilization strategy of pasture fields in the game. See an example of high mobility utilization in Figure 7.3. The number of theoretically sustainable sheep is compared to the average number of sheep at the end of played games.

Fields	Mobility	Sustainable herd size	Average herd size after five rounds
11 grasslands, 15 steppe	low	18	
11 grasslands, 15 steppe	high	23	45.2
15 grasslands, 16 steppe	low	23	
15 grasslands, 16 steppe	high	30	51.5

one sheep. But with mobility, three sheep can be sustained using two grassland fields. Steppe fields cannot sustain any sheep without resting time. When comparing the number of the maximum sustained herd size with the average herd size at the end of the game, one can see a large difference. Since the goal of the game is the maximization of the herd, no player aims to sustain a certain herd size very long. This behavior contributes to a very efficient exploitation of the available forage resources without considering the long-term consequences. Very often players perceived a sharp decline of forage and herd size between the fourth and fifth round. A longer game or a different set of goals would require a complete different set of strategies. The choice between strategies was often discussed during debriefing of the game.

These observations allow further discussions and testing of very general natural resource problems. The previous set of rules was intended to motivate typical game situations with a larger focus on competition than cooperation between players. The situation of competitive resource exploitation is remindful of the 'tragedy of commons' described by Hardin (1968). There have been numerous studies about human strategies on resource exploitation by using for example game theoretic, participatory, or modelling approaches (e.g. Janssen et al., 2009). One might use the board game of nomadic pastoralists to discuss the options and constraints for either more cooperative or competitive behavior in an uncertain environment. In the following, I propose alternative sets of goals and modalities of playing:

- One goal for all players: Sustaining six or more sheep per household over six rounds.

- Two competing groups: Every player should sustain six or more sheep but the group with larger herds wins (only meaningful in a version with an even number of players).

- Individual goals are drawn by each player in the beginning: Mixture of competitive and cooperative aims, the first player fulfilling the goal wins.

For the next development steps, it is important to focus on the learning goals at first. The implementation into the game will often be a decision between the more realistic view where elements of fun are sacrificed and a playing procedure which people simply enjoy. Until now, our the aim was to find a compromise between these seemingly contradicting aims.

7.3.3 Relevance for education and interdisciplinary communication

From the experiences collected from the game development and playing, I see four major fields of useful application.

First, the game serves as educational tool for very complex topics such as sustainable land use under uncertainty and cooperative versus competitive resource distribution. By selecting certain subsets of event cards, one might adapt the complexity of debriefing to the educational level of students. Further, a selection of suitable event cards may narrow down the focus to one related topic. This can be the way of life of nomadic people, their culture and social network, or sustainable use of arid rangelands. A comparable application of a board game in the context of climate change has been evaluated by Eisenack (2012).

The second kind of application would be public communication. The board game is open for a broad audience and is able to raise awareness for a very specialized group of people. But nomadic people may serve as a very general example for problems of natural resource management. Further, the game raises interest in the methodology of our research. The rules of the game are comparable to the models we developed and thereby it is easier to explain how we work. The game is suitable to demonstrate how computer models simulate certain aspects of a system under study. It also shows the limits of computer models, for example, where human decisions are far more diverse and creative than a simulation could predict.

The explanation of a specific field of research would be the third application of the game. Since the context is an interdisciplinary one, the simplified language of the game enables researchers to discuss related topics from very different perspectives (see also Eisenack, 2012). Playing the game motivates a debriefing where researchers differentiate between more realistic or artificial experiences from the game. This may function as a 'door opener' to researchers from neighboring fields to exchange their knowledge and views in more detail. For the development of our board game, more than twenty researchers were involved from at least five different major fields.

Finally, the fourth field of application could be participatory research. Stakeholders such as decision makers on land use, representatives from development organizations, or even professional pastoralists may engage in participatory activities to reflect on their conditions, to identify open questions and to manage their environment. This was done before with the purpose of model refinement, mutual education, and landscape planning in the context of livestock systems (Martin et al., 2011) but also agroecosystems (e.g. Bousquet et al., 2007; Etienne et al., 2003).

Concluding, I summarize some of the traits of the board game that make it so appealing to use in the presented contexts. The game provides a safe and informal environment to get interested in a quite complex topic. It is possible to gradate the problems before they get overwhelming. During the face-to-face interaction, most players are integrated easily into different situations of the everyday life of pastoralists. The role play is a typical game trait with which most people are familiar with (e.g. Eisenack, 2012). This enables them to step into each others perspective very easily. Also the design of the wooden handcraft of pieces provides a sensory attraction and attention even when it is not your turn. Finally, the board game on nomadic pastoralists is simple enough to start playing at once, but also complex enough to raise interest for more rounds.

8 Synthesis and Outlook

The aim of this thesis was to evaluate diverse climate and land use changes in their combined effect on sustainable pastoralism in drylands. To achieve this goal, we developed an ecological-economic rangeland model and conducted scenario analyses of pastoral management strategies. Results were assessed via an innovative approach using an operationalization of livelihood security. By doing this, we built a bridge between natural and social impact factors on pastoralism and identified options and constraints of sustainable management strategies. The presented tools and methodologies contribute to a mechanistic understanding of the complex social-ecological system of pastoralism in drylands.

8.1 General conclusions from this thesis

We presented three modelling studies in which we evaluated different aspects of change in pastoral systems. The first study focused on climate change in terms of precipitation patterns in drylands that can be tolerated by pastoral livelihoods. The second study evaluated changes in the socio-economic background of pastoral households against the vulnerability towards droughts. The third study analyzed the heterogeneous vegetation from Southern Morocco to find out which pasture serves as a key in the sustenance of the herd size. Finally, we presented a strategic board game as an alternative approach to link ecological and social views on pastoralism and that facilitates a broad understanding of sustainable pastoralism.

8.1.1 Mastered methodological challenges

The main methodological challenge was to identify the suitable level of abstraction for the model. Which structural information is necessary to answer questions regarding a multitude of interrelated and interacting processes? As this is mostly a development process of try and error, it is beyond the scope of this study to provide a final answer. However, regarding the complexity of social-ecological systems, some practical hints can be given for future modelling research.

When it comes to identify the most important traits of a pastoral system, the following key words might come up: spatial heterogeneity, temporal variability, vegetation productivity, grazing pressure, herd composition, management strategies, mobility, market prices, pasture access regimes. Despite the importance of all of them, it makes sense to simulate only some aspects at once to start learning from the simplified system. This strategy leads to the development of several model versions where each one is particularly suitable to analyze one question. At the end, the set of specialized models can provide a holistic and at the same time differentiated understanding of the system (see Figure 3.8). However, the level of detail is mostly dependent on the available data sources. Thus, the comprehensive integration of diverse processes in our rangeland model has mainly resulted from the unique combination of large research projects, of which this work was a part.

We have started with a rangeland model parameterized for a homogeneous region to analyze climate change effects. The goal was to link simulation results with livelihood security assessments which provided the framework for further evaluations. Thereby we linked changes in the biophysical system to the socio-economic consequences. This has been done before in the context of commercial rangelands (Janssen et al., 2000; Walker and Janssen, 2002; Jakoby, 2011), but not regarding household-based sustainability in terms of livelihood security.

Intra-annual variability and spatial heterogeneity are two of the rare features included in previous rangeland models, as many models run on an annual timescale. Using a very abstract model has the advantage that specific input data is not always a necessity, but it has the shortcoming that simulation results cannot be tested against field data. However, qualitative trends were derived to formulate new hypotheses. We found a compromise by extending the first model version with spatial data in a stepwise way. This enabled us to evaluate qualitatively, for example, the transmission of drought effects as a combined response of natural and socio-economic aspects. Finally, the model environment was used as laboratory to conduct experiments on different pasture sets that would have been impossible in reality. By doing so, hypotheses on sustainable range management were generated that can be subject of refined field studies in the future.

Despite the seemingly contradictory aims of disentangling and integrating different sources of change, using specialized model versions and simulation experiments based on the same core helped us in tackling these opposite perspectives. Summarizing, the complementary use of simplified and complex model versions facilitated general understanding and built a link between abstract theories and specific case studies.

8.1.2 Pastoral livelihoods facing global change

Since pastoral livelihoods face a multitude of concurrent changes, it is crucial to analyze their vulnerability to the combined threats in a risk-prone environment (Fraser et al., 2011). Single aspects of sustainable pastoralism have frequently been investigated before, either from an ecological perspective on plant-herbivore dynamics or from an anthropological perspective on the basis of livelihood security. However, the full integration of these perspectives has been missing so far.

Regarding the tolerance of climate change by pastoralists, our study revealed that increasing precipitation variability reduced livestock less than expected. We found cases with positive effects of precipitation variability, which were caused by sufficient resting, in contrast to cases that had negative effects on livestock. Socio-economic changes in terms of increasing income needs shifted the limits of tolerable climates towards higher mean annual precipitation. However, up to a certain degree, mobility allows the maintenance of pastoral livelihoods in less productive systems and thereby compensates for climate change effects. We conclude that it is important to consider climate change and human requirements together to create appropriate climate change mitigation strategies in pastoral systems.

As a part of projected climate change, drought events are often perceived as the ultimate cause for losing pastoral livelihoods. However, from our drought scenario evaluation, we conclude that a meteorological drought alone does not endanger most pastoral livelihoods. Concurrent population growth as well as restricted mobility are socio-economic constraints that pose a greater risk. These constraints can have multiple causes such as reduced labor force for herding, the necessity of wage labor, or governmental restrictions in pasture access. Focusing on drought-induced risk as short-term consequences for pastoral livelihoods can be misleading when instead political action is required to ensure an adequate and flexible access regime to pastures or markets. As the requirements of sustainable pastoralism are not universal (Davies and Bennett, 2007), one should carefully consider the long-term livelihood evaluation beyond immediate effects of shocks.

Returning to the pasture as our starting point, we finally evaluated the vegetation traits in a heterogeneous region to identify the key pasture which is mainly responsible for the sustenance of the herd. Our results imply that the focus solely on livestock production and pasture use efficiency in drylands is often misleading. The regional context is crucial since grazing pressure shifts quickly in time with heterogeneous forage availability and consequently the part of resting, buffering and recovery of vegetation. The specific implication for different optional management strategies is subject for further investigations.

Summarizing, this thesis contributed to a generalized but at the same time differentiated understanding of sustainable pastoralism. We developed modelling tools and evaluation methods that allow the investigation of diverse drivers from the natural and the social system in their isolated and combined effect. Simulation analyses were used to find a new prioritization of which factors enable or endanger sustainable livelihoods. Conclusively, projected climate change may outrange the adaptive capacity of pastoralists when accompanied by the likely increase of income requirements and restricted pasture access.

8.2 Future perspectives on arid rangelands

Some scholars interpreted ongoing transitions in pastoral societies at a collective tipping point at which pastoralism as we know it disappears (Galvin, 2009). The final sections provide an outlook on which issues may gain relevance in future research on animal husbandry in drylands.

8.2.1 Interdisciplinary mobility research

In the area of research on mobility the question of 'how to make use of heterogeneously distributed resources' cannot only be treated from the natural, but also from the social science perspective. The respective disciplines in the area of natural and social science approach the question 'why are people mobile' from different points of view. Whereas the natural sciences (as positive descriptive sciences) aim to identify correlations between measurable traits objectively, such as temporal resource variability and movement frequency, the social sciences (as rather normative sciences) investigate the subjective causes by trend from mobile actors themselves.

As nomadic mobility is threatened by multiple causes (Oba, 2011), its understanding as a husbandry practice where pastoralists achieve a wide range of cultural, social and economic goals is indispensable to face future challenges (Behnke et al., 2011). An integrative approach including natural and social science perspectives to understanding nomadic mobility may serve as a model of how complex systems of natural resource use can be managed to support human livelihoods sustainably.

One tool to achieve this goal of synergistic and problem-driven research is agent-based modelling. This includes natural structures and processes and the model addresses the subjects and their decision making explicitly.

8.2.2 Building sustainable livelihoods – security in a changing world

Making a living from land is already a challenging task in many parts of the world, particularly in drylands. The investigated changes of climate and land use in pastoral areas put a considerable further pressure on dependent livelihoods. In addition, projected population growth and reduced access to land (fragmentation, land grabbing) leads first to intensification and subsequently to conflicts about land (Galvin, 2009). In this situation, where more and more people are marginalized on less land, traditional systems and social institutions weaken and bear the potential of collapse (Haile, 2005).

Thus, we could learn from pastoralism as a strategy based on flexibility, adaptive capacity (learning) and social kinship that results in long-term sufficiency. To investigate these complex social-ecological systems, more simple and but also more mechanistically differentiated models are needed to create a toolbox of testing environments for future perspectives.

Traditional pastoralism seems to dissolve but may due to its inherent adaptive capacity, develop new forms of livestock rearing (Galvin, 2009). As many changes accelerate and their combined effect puts pressure on pastoral households, one may find a multitude of locally different responses to it. Problem oriented modelling approaches, as presented in this study, are powerful tools that at the same time evaluate short-term options for livelihood security but that can also facilitate research on long-term sustainable resource use under uncertainty.

Appendix A

Gallery of figures that did not make it into the story

Simulation results

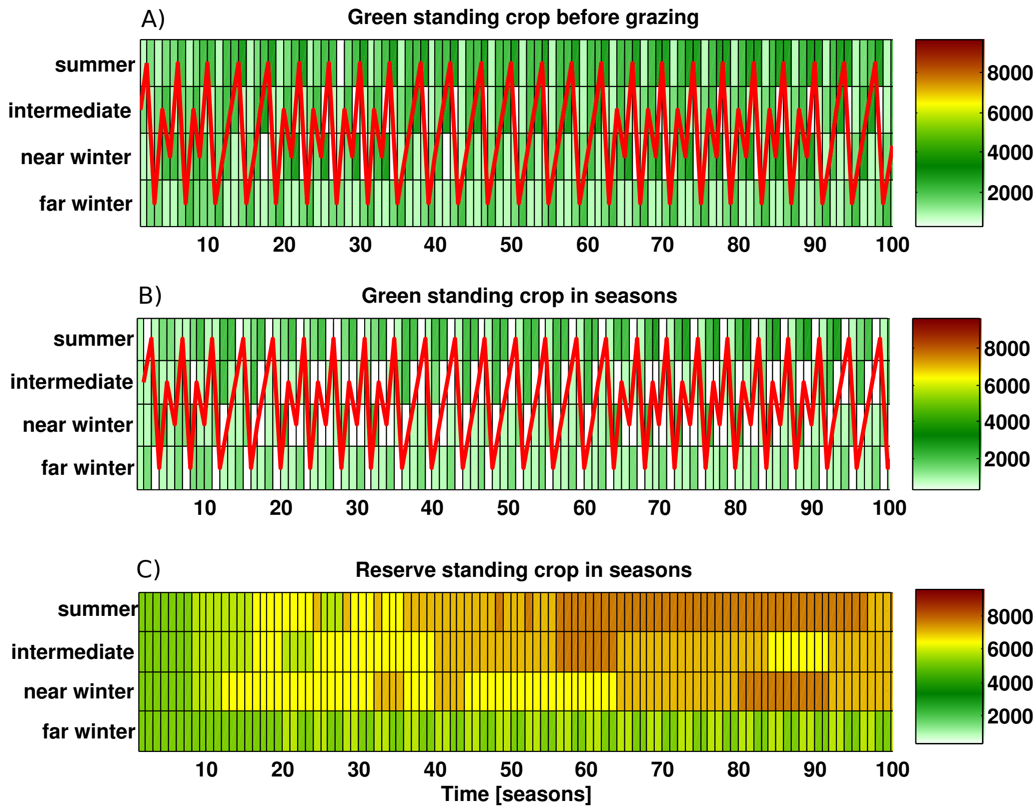


Figure A.1: Seasonal states of green biomass, A) before grazing, B) after grazing, and reserve biomass (C). Seasonal stock movement is denoted by the red line. One can observe that the far winter pasture has the lowest state of reserve biomass during the simulation whereas the other pastures accumulate reserve biomass.

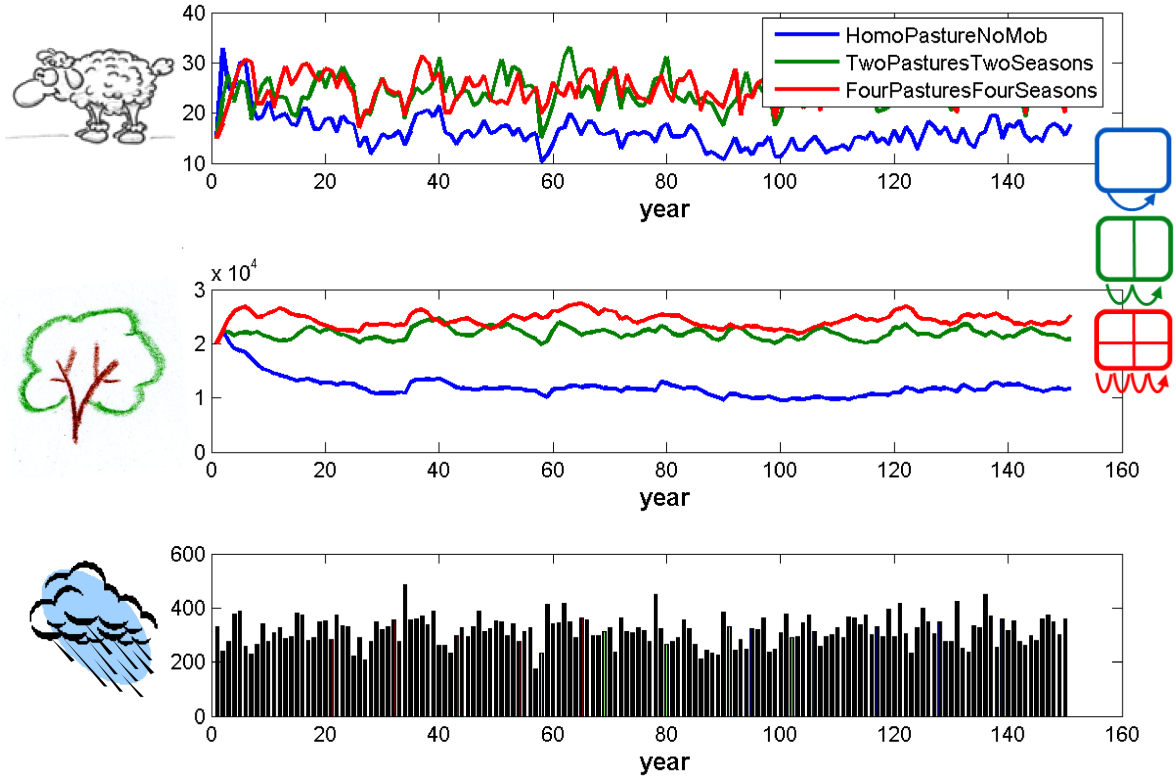


Figure A.2: A simulation comparison of smallstock and forage dynamics between three mobility scenarios based on the same precipitation regime.

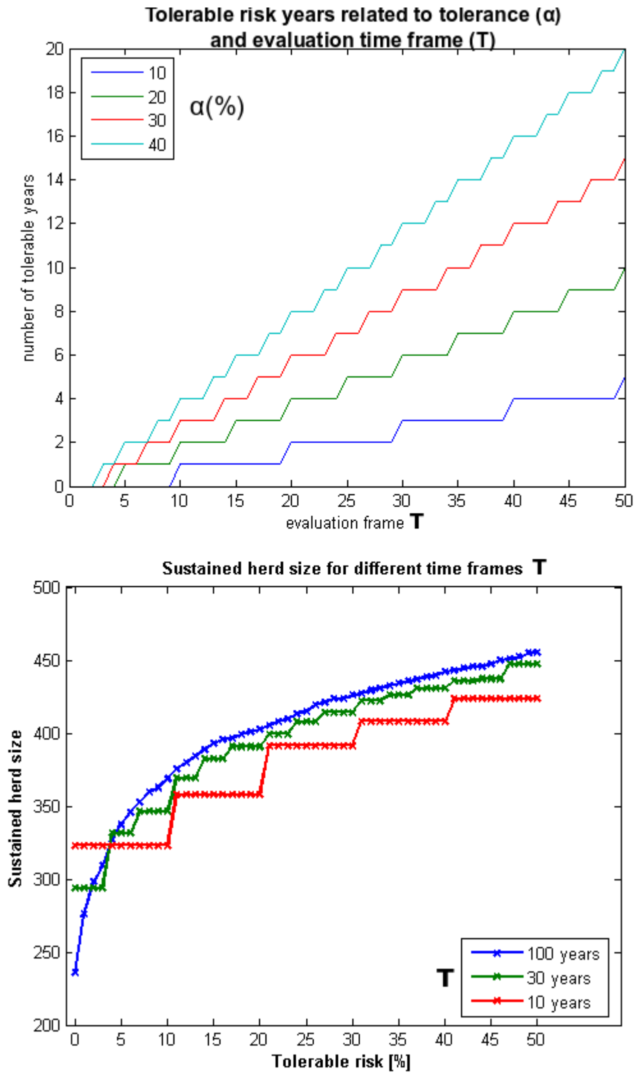


Figure A.3: **Top:** The number of tolerable risk years increases with the evaluated time frame in a discontinuous way. This behavior is the cause for the discontinuous function described in Figure 3.7 A and C. **Bottom:** The threshold of the herd (τ) that can be sustained from a given simulation increases with greater risk tolerance. Using a large time frame, e.g. 100 years, results in a continuous function (blue). If the evaluated time frame is shorter than 100 years, the threshold function becomes discontinuous. As a consequence, risk evaluations on such short time frames are not comparable between different levels of risk tolerance. A solution to tackle this was presented in Section 5.2.1.

Why was a simulation under 1/2-annual mobility superior to 1/4-annual mobility?

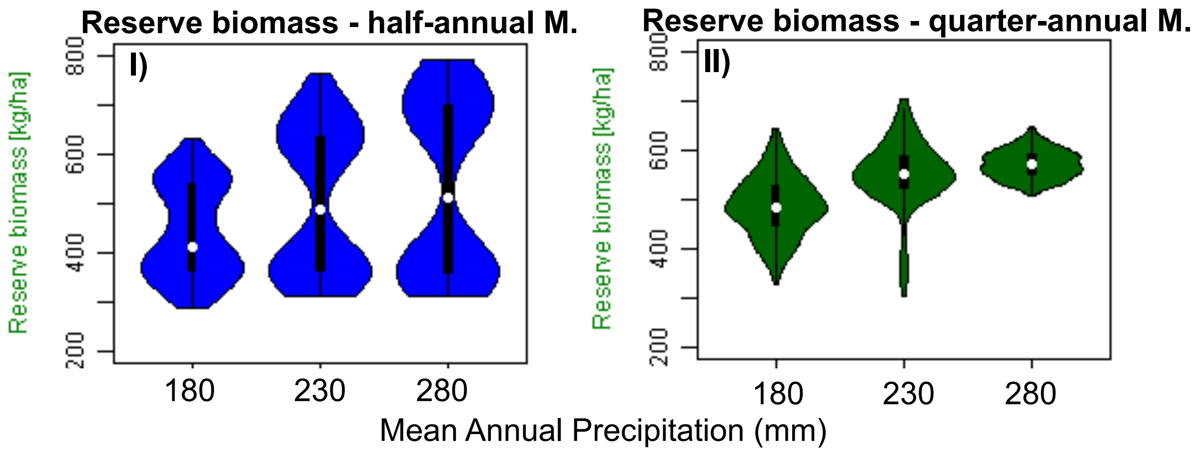


Figure A.4: Reserve biomass states resulting simulation under varying precipitation conditions, refers to Figure 4.7 in Chapter 4. I) shows reserve biomass from half-annual mobility scenarios, II) from quarte-annual mobility scenarios. Bimodal distributions result from emerging heterogeneity in pastures (initialization was homogeneous). The case of MAP = 250 mm is the one where herd size evaluations of 1/2-annual mob. were superior to scenario of 1/4-annual mob. The average values of reserve biomass cannot explain this result, but see Figure A.5.

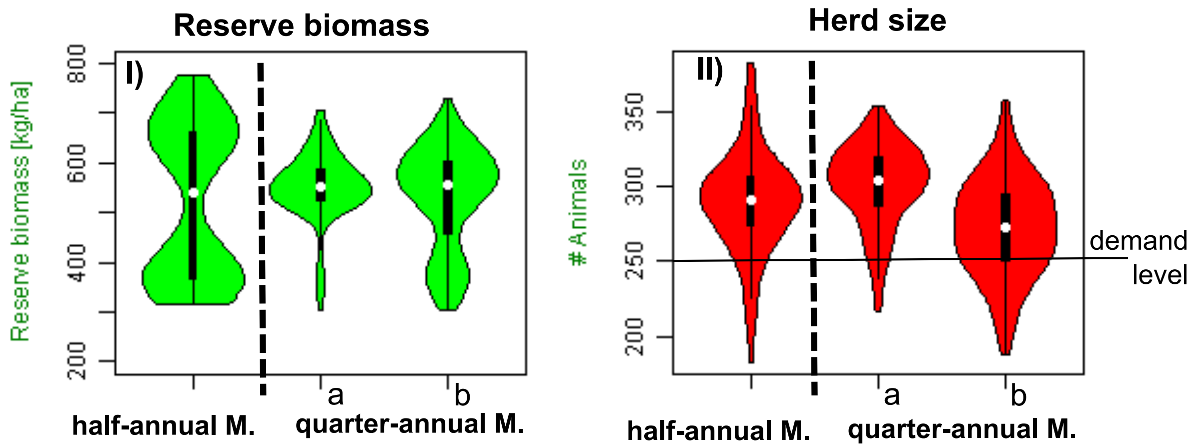


Figure A.5: I) shows again reserve biomass states for the critical (MAP=250 mm) , but this time two different runs were evaluated from the 1/4-annual mobility scenario (a and b). One can see in the right figure II) that these two modes had severe effect on the herd size and consequentially on the risk assessment. While runs in mode a were well above the evaluated demand level, runs in mode b were even worse of then under the 1/2-annual mobility scenario. Runs in mode happened to be more often than in 5% of the runs, thus these simulations were more often evaluated as insecure.)

Bibliography

Abel, N. *Carrying capacity, rangeland degradation and livestock development policy for the communal rangelands of Botswana.* Technical report, Overseas Development Institute, 1993.

Akasbi, Z.; Oldeland, J.; Dengler, J. and Finckh, M. *Social and ecological constraints on decision making by transhumant pastoralists: a case study from the Moroccan Atlas Mountains.* Journal of Mountain Science, 9:307–321, 2012. ISSN 1672-6316. doi 10.1007/s11629-009-2320-8.

Aklilu, Y. and Wekesa, M. *Drought, livestock and livelihoods: lessons from the 1999-2001 emergency response in the pastoral sector in Kenya.* Technical report, Humanitarian Practice Network, Overseas Development Institution, 2002.

Angassa, A. and Oba, G. *Relating long-term rainfall variability to cattle population dynamics in communal rangelands and a government ranch in southern Ethiopia.* Agricultural Systems, 94(3):715 – 725, 2007. ISSN 0308-521X. doi 10.1016/j.agsy.2007.02.012.

Angassa, A. and Oba, G. *Herder Perceptions on Impacts of Range Enclosures, Crop Farming, Fire Ban and Bush Encroachment on the Rangelands of Borana, Southern Ethiopia.* Human Ecology, 36:201–215, 2008. ISSN 0300-7839. 10.1007/s10745-007-9156-z.

Animut, G. and Goetsch, A. *Co-grazing of sheep and goats: Benefits and constraints.* Small Ruminant Research, 77(2-3):–145, 2008. ISSN 0921-4488.

Argumedo, A. and Pimbert, M. *Traditional resource rights and indigenous people in the Andes.* IIED, London, 2005.

Asner, G.; Elmore, A.; Olander, L.; Martin, R. and Harris, A. *Grazing systems, ecosystem responses, and global change.* Annual Review of Environment and Resources, 29:261–299, 2004. ISSN 1543-5938.

Barrow, C. and Hicham, H. *Two complimentary and integrated land uses of the western High Atlas Mountains, Morocco: the potential for sustainable rural livelihoods.* Applied Geography, 20(4):369–394, 2000. ISSN 0143-6228.

Baumann, G. *How to assess rangeland condition in semiarid ecosystems? The indicative value of vegetation in the High Atlas Mountains, Morocco.* Ph.D. thesis, Botanical Institute, University of Cologne, Cologne, Germany, 2009.

Behnke, R. H.; Fernandez-Gimenez, M. E.; Turner, M. D. and Stammler, F. *Pastoral migration: mobile systems of livestock husbandry*, chapter 10, pages 144–171. Oxford University Press, 2011.

Bousquet, F.; Castella, J.-C.; Trébuil, G.; Barnaud, C.; Boissau, S. and Kam, S. P. *Using multi-agent systems in a companion modelling approach for agroecosystem management in South-east Asia.* Outlook on Agriculture, 36(1):57–62, 2007. doi 10.5367/000000007780223650.

Bretan, A. *Die syrische Steppe. Mobile Viehzucht, internationale Entwicklungshilfe und globale Märkte.* Reichert, 2010.

Breuer, I. *Livelihood Security and Mobility in the High Atlas Mountains.* In J. Gertel and I. Breuer, editors, *Pastoral Morocco: Globalizing Scapes of Mobility and Insecurity*, volume 7, pages 165–179. Nomaden und Sesshafte, Wiesbaden, 2007.

Briske, D. D.; Derner, J. D.; Brown, J. R.; Fuhlendorf, S. D.; Teague, W. R.; Havstad, K. M.; Gillen, R. L.; Ash, A. J. and Willms, W. D. *Rotational Grazing on Rangelands: Reconciliation of Perception and Experimental Evidence.* Rangeland Ecology & Management, 61(1):3–17, 2008. ISSN 1550-7424. doi 10.2111/06-159R.1.

Campbell, B.; Jeffrey, S.; Kozanayi, W.; Luckert, M.; Mutamba, M. and Zindi, C. *Household Livelihoods in Semi-arid Regions: Options and Constraints.* Center for International Forestry Research, 2002.

Campbell, B. and Stafford Smith, D. *A synthesis of recent global change research on pasture and rangeland production: reduced uncertainties and their management implications.* Agriculture, Ecosystems and Environment, 82:39–55, 2000. Printed.

Carles, A. *Sheep production in the tropics.* Oxford University Press, 1983.

Chapin III, F.; P., M. and P., V. *Landscape heterogeneity and ecosystem dynamics – Principles of Terrestrial Ecosystem Ecology.* Springer New York, 2011.

Dahl, G. and Hjort, A. *Having herds*, volume 2. Department of Social Anthropology, University of Stockholm, 1976.

Davies, J. and Bennett, R. *Livelihood Adaptation to Risk: Constraints and Opportunities for Pastoral Development in Ethiopia's Afar region.* Journal of Development Studies, 43(3):490–511, 2007. doi 10.1080/00220380701204422.

Davies, J. and Hatfield, R. *The Economics of Mobile Pastoralism: A Global Summary.* Nomadic Peoples, 11:91–116(26), 2007. doi doi:10.3167/np.2007.110106.

Davis, D. K. *Indigenous knowledge and the desertification debate: problematising expert knowledge in North Africa*. Geoforum, 36(4):509–524, 2005. ISSN 0016-7185.

Dilley, M. and Boudreau, T. E. *Coming to terms with vulnerability: a critique of the food security definition*. Food Policy, 26(3):229–247, 2001. ISSN 0306-9192. doi 10.1016/S0306-9192(00)00046-4.

Dougill, A.; Fraser, E. and Reed, M. *Anticipating Vulnerability to Climate Change in Dryland Pastoral Systems: Using Dynamic Systems Models for the Kalahari*. Ecology and Society, 15(2):–, 2010.

ECA. *Land Tenure Systems and their Impacts on Food Security and Sustainable Development in Africa*. Technical report, Economic Commission for Africa, 2004.

Eisenack, K. *A Climate Change Board Game for Interdisciplinary Communication and Education*. Simulation & Gaming, 43 (4):1–21, 2012. doi 10.1177/1046878112452639.

Eisold, J. *Rangeland use in Northwestern Namibia – An integrated analysis of vegetation dynamics, decision-making processes and environment perception*. Ph.D. thesis, University of Cologne, 2009.

Ellis, J.; Coughenour, M. and Swift, D. *Range Ecology at Disequilibrium – New Models of Natural Variability and Pastoral Adaption in African Savannas*, chapter Climate variability, ecosystem stability, and the implications for range and livestock development, pages 31–41. Overseas Development Institute, 1993.

Epstein, J. M. *Why Model?* Journal of Artificial Societies and Social Simulation, 11(4):12, 2008. ISSN 1460-7425.

Etienne, M.; Le Page, C. and Cohen, M. *A Step-by-Step Approach to Building Land Management Scenarios Based on Multiple Viewpoints on Multi-agent System Simulations*. JASSS-The Journal of Artificial Societies and Social Simulation, 6 (2), 2003.

Fafchamps, M.; Udry, C. and Czukas, K. *Drought and saving in West Africa: are livestock a buffer stock?* Journal of Development Economics, 55(2):273–305, 1998. ISSN 0304-3878.

FAO, Agriculture and Consumer Protection. *Improving the livelihoods of pastoralist families and communities*. Technical report, Agriculture and Consumer Protection, FAO, 2009.

FAO, Mountain Partnership Secretariat, UNCCD, SDC, CDE. *Highlands and Drylands – mountains, a source of resilience in arid regions*. Technical report, Published by FAO, UNCCD, Mountain Partnership, Swiss Agency for Development and

Cooperation, and CDE, with the support of an international group of experts. Rome, 2011.

Fazey, I.; Gamarra, J. G.; Fischer, J.; Reed, M. S.; Stringer, L. C. and Christie, M. *Adaptation strategies for reducing vulnerability to future environmental change*. Frontiers in Ecology and the Environment, 8(8):414–422, 2009. ISSN 1540-9295. doi 10.1890/080215.

Fernandez-Gimenez, M. and Allen-Diaz, B. *Testing a non-equilibrium model of rangeland vegetation dynamics in Mongolia*. Journal of Applied Ecology, 36:871–885, 1999. doi doi:10.1046/j.1365-2664.1999.00447.x.

Fernandez-Gimenez, M. E. and Le Febre, S. *Mobility in pastoral systems: Dynamic flux or downward trend?* International Journal of Sustainable Development & World Ecology, 13(5):341–362, 2006. doi 10.1080/13504500609469685.

Finckh, M. and Goldbach, H. *Vegetation dynamics under climate stress and land use pressure in the Draa catchment*. In P. Speth; M. Christoph and B. Diekkrüger, editors, *Impacts of global change on the hydrological cycle in West and Northwest Africa.*, pages 274–281. Springer, Berlin, 2010.

Finckh, M. and Poete, P. *Vegetation map of the Drâa basi*. In O. Schulz and M. Judex, editors, *IMPETUS Atlas Morocco. Research results 2000-2007*, pages 31–32. Department of Geography, University of Bonn., 2008.

Folke, C. *Traditional knowledge in social-ecological systems*. Ecology and Society, 9(3):7, 2004. ISSN 1195-5449. doi ISI:000228087500001.

Frankenberger, T. *Measuring household livelihood security: an approach for reducing absolute poverty*. Food Forum (newsletter) No. 34. Washington, DC, Food Aid Management, pages 1–6, 1996.

Frankenberger, T. R.; Drinkwater, M. and Maxwell, D. *Operationalizing household livelihood security*. In *Forum on Operationalizing Participatory Ways of Applying Sustainable Livelihoods Approaches*. 2000.

Fraser, E. D.; Dougill, A. J.; Hubacek, K.; Quinn, C. H.; Sendzimir, J. and Termansen, M. *Assessing Vulnerability to Climate Change in Dryland Livelihood Systems: Conceptual Challenges and Interdisciplinary Solutions*. Ecology and Society, 16:3, 2011.

Fratkin, E. and Mearns, R. *Sustainability and Pastoral Livelihoods: Lessons from East African Maasai and Mongolia*. Human Organization, 62:112–122, 2003.

Freier, K. P.; Schneider, U. A. and Finckh, M. *Dynamic interactions between vegetation and land use in semi-arid Morocco: Using a Markov process for modeling* *rangelands under climate change*. Agriculture, Ecosystems & Environment, 140(3-4):462–472, 2011. ISSN 01678809. doi 10.1016/j.agee.2011.01.011.

Frenette-Dussault, C.; Shipley, B.; Léger, J.-F.; Meziane, D. and Hingrat, Y. *Functional structure of an arid steppe plant community reveals similarities with Grime's C-S-R theory*. Journal of Vegetation Science, 23(2):208–222, 2012. ISSN 1654-1103. doi 10.1111/j.1654-1103.2011.01350.x.

Freschet, G. T.; Cornelissen, J. H. C.; Van Logtestijn, R. S. P. and Aerts, R. *Evidence of the 'plant economics spectrum' in a subarctic flora*. Journal of Ecology, 98(2):362–373, 2010. ISSN 1365-2745. doi 10.1111/j.1365-2745.2009.01615.x.

Fynn, R. W. S. *Functional Resource Heterogeneity Increases Livestock and Rangeland Productivity*. Rangeland Ecology & Management, 65(4):319–329, 2012. ISSN 1550-7424. doi 10.2111/REM-D-11-00141.1.

Galvin, K. A. *Transitions: Pastoralists Living with Change*. Annual Review of Anthropology, 38(1):185–198, 2009. doi 10.1146/annurev-anthro-091908-164442.

Garnier, E.; Cortez, J.; Billés, G.; Navas, M.-L.; Roumet, C.; Debussche, M.; Laurent, G.; Blanchard, A.; Aubry, D.; Bellmann, A.; Neill, C. and Toussaint, J.-P. *Plant Functional Markers Capture Ecosystem Properties During Secondary Succession*. Ecology, 85(9):2630–2637, 2004. ISSN 0012-9658. doi 10.1890/03-0799.

Garnier, E. and Navas, M.-L. *A trait-based approach to comparative functional plant ecology: concepts, methods and applications for agroecology. A review*. Agronomy for Sustainable Development, 32:365–399, 2012. ISSN 1774-0746. doi 10.1007/s13593-011-0036-y.

Gasson, R. *Goals and Values of Farmers*. Journal of Agricultural Economics, 24(3):521–542, 1973. ISSN 1477-9552. doi 10.1111/j.1477-9552.1973.tb00952.x.

Genin, D. and Simenel, R. *Endogenous Berber forest management and the functional shaping of rural forests in Southern Morocco: implications for shared forest management options*. Human Ecol., 39:257–269, 2011.

Gilles, J. L.; Hammoudi, A. and Mahdi, M. *Making the common work: Theory, practice and policy*, chapter Oukaimedene, Morocco: A High Mountain Agdal, pages 229–246. San Francisco ICS Press., 1992.

Gillson, L. and Hoffman, M. *Rangeland ecology in a changing world*. Science, 315(5808):53–54, 2007. ISSN 10.1126/science.1136577.

Güntner, A. and Bronstert, A. *Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas*. Journal of Hydrology, 297(1–4):136 – 161, 2004. ISSN 0022-1694. doi 10.1016/j.jhydrol.2004.04.008.

Goodhue, R. and McCarthy, N. *Traditional property rights, common property, and mobility in semi-arid African pastoralist systems*. Environment and Development Economics, 14:29–50, 2009. ISSN 1355-770X.

Grenot, C. *Ecophysiological characteristics of large herbivorous Mammals in arid Africa and the Middle East*. Journal of Arid Environments, 23:125–155, 1992.

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

Grimm, V.; Berger, U.; DeAngelis, D. L.; Polhill, J. G.; Giske, J. and Railsback, S. F. *The ODD protocol: A review and first update*. Ecological Modelling, 221(23):2760 – 2768, 2010. ISSN 0304-3800. doi DOI:10.1016/j.ecolmodel.2010.08.019.

Grimm, V.; Revilla, E.; Berger, U.; Jeltsch, F.; Mooij, W. M.; Railsback, S. F.; Thulke, H.-H.; Weiner, J.; Wiegand, T. and DeAngelis, D. L. *Pattern-Oriented Modeling of Agent-Based Complex Systems: Lessons from Ecology*. Science, 310(5750):987–991, 2005. doi 10.1126/science.1116681.

Gross, J.; McAllister, R.; Abel, N.; Stafford Smith, D. and Maru, Y. *Australian rangelands as complex adaptive systems: A conceptual model and preliminary results*. Environ.Modell. & Softw., 21(9):1264–1272, 2006. ISSN 1364-8152.

Gruschke, A. *Ressourcennutzung und nomadische Existenzsicherung im Umbruch. Die osttibetische Region Youshu (Quinghai, VR China)*. Ph.D. thesis, University of Leipzig, 2009.

Haile, M. *Weather patterns, food security and humanitarian response in sub-Saharan Africa*. Philosophical Transactions of the Royal Society B: Biological Sciences, 360(1463):2169–2182, 2005. doi 10.1098/rstb.2005.1746.

Hambler, C.; Canney, S. M.; Coe, M. J.; Henderson, P. A. and Illius, A. W. *Grazing and "Degradation"*. Science letters, 316, 2007.

Hardin, G. *The Tragedy of the Commons*. Science, 162(3859):1243–1248, 1968. doi 10.1126/science.162.3859.1243.

Hassen, A. *Vulnerability to Drought Risk and Famine: Local Responses and External Interventions among the Afar of Ethiopia, a Study on the Aghini Pastoral Community*. Ph.D. thesis, University of Bayreuth, 2008.

Hatfield, R. and Davies, J. *Global Review of the Economics of Pastoralism*. Technical report, IUCN, 2006.

Hazell, P.; Oram, P. and Chaherli, N. *Managing livestock in drought-prone areas of the Middle East and North Africa: Policy issues*. In H. Löfgren, editor, *Research in Middle East Economics*, pages 79–104. Elsevier, 2003.

Hedges, L. V. and Olkin, I. *Statistical methods for meta-analysis*. Academic Press, Inc., 1985.

Hein, L. *The impacts of grazing and rainfall variability on the dynamics of a Sahelian rangeland*. J.Arid Environ., 64(5):488–504, 2006.

Higgins, S. I.; Kantelhardt, J.; Scheiter, S. and Boerner, J. *Sustainable management of extensively managed savanna rangelands*. Ecological Economics, 62(1):102 – 114, 2007. ISSN 0921-8009. doi DOI:10.1016/j.ecolecon.2006.05.019.

Howden, S. M.; Soussana, J.-F.; Tubiello, F. N.; Chhetri, N.; Dunlop, M. and Meinke, H. *Adapting agriculture to climate change*. Proceedings of the National Academy of Sciences, 104(50):19691–19696, 2007. doi 10.1073/pnas.0701890104.

Ilahiane, H. *The Berber Agdal institution: Indigenous Range Management in the Atlas Mountains*. Ethnology, 38(38):21–45, 1999.

Illius, A. and O'Connor, T. *On the Relevance of Nonequilibrium Concepts to Arid and Semiarid Grazing Systems*. Ecological Applications, 9:798–813, 1999.

Illius, A. W. and O'Connor, T. G. *Resource heterogeneity and ungulate population dynamics*. Oikos, 89(31):283–294, 2000.

Ince, D. C.; Hatton, L. and Graham-Cumming, J. *The case for open computer programs*. Nature, 482:485–488, 2012. doi 10.1038/nature10836.

Jakoby, O. *Risk management in semi-arid rangelands: Modelling adaptation to spatio-temporal heterogeneities*. Ph.D. thesis, University of Osnabrück, 2011.

Janssen, M. A.; Radtke, N. P. and Lee, A. *Pattern-Oriented Modeling of Commons Dilemma Experiments*. Adaptive Behavior, 17(6):508–523, 2009.

Janssen, M. A.; Walker, B. H.; Langridge, J. and Abel, N. *An adaptive agent model for analysing co-evolution of management and policies in a complex rangeland system*. Ecol.Model., 131(2-3):249–268, 2000.

Johnson, D. *The North African environment at risk*, chapter Development trends and environmental deterioration in the agropastoral systems of the Central Middle Atlas, Morocco., pages 35–54. Boulder, Colorado: Westview Press, 1996.

Köchy, M.; Mathaj, M.; Jeltsch, F. and Malkinson, D. *Resilience of stocking capacity to changing climate in arid to Mediterranean landscapes*. Regional Environmental Change, 8(2):73–87, 2008.

Kemmerling, B. *Sustainable range management-local strategies of a pastoral nomadic group in the High Atlas Mountains, Morocco*. Master's thesis, 2008.

Kuhn, A.; Heidecke, C.; Roth, A.; Goldbach, H.; Burkhardt, J.; Linstädter, A.; Kemmerling, B. and Gaiser, T. *The importance of resource management for livelihood security under climate change*. In P. Speth; M. Christoph and B. Diekkrüger, editors, *Impacts of global change on the hydrological cycle in West and Northwest Africa*, II-5.1, pages 565–590. Springer, Berlin, 2010.

Lavorel, S. and Grigulis, K. *How fundamental plant functional trait relationships scale-up to trade-offs and synergies in ecosystem services*. Journal of Ecology, 100(1):128–140, 2012. ISSN 1365-2745. doi 10.1111/j.1365-2745.2011.01914.x.

Le, Q. B.; Seidl, R. and Scholz, R. W. *Feedback loops and types of adaptation in the modelling of land-use decisions in an agent-based simulation*. Environmental Modelling & Software, 27/28(0):83 – 96, 2012. ISSN 1364-8152. doi 10.1016/j.envsoft.2011.09.002.

Le Houérou, H. *Rain use efficiency: a unifying concept in arid-land ecology*. Journal of Arid Lands, 7:213–247, 1984.

Le Houérou, H. *Environmental constraints and limits to livestock husbandry in arid lands*. Sécheresse, 17:10–18, 2006.

LEGS. *Livestock Emergency Guidelines and Standards*. Technical report, Livestock Emergency Guidelines and Standards Project, 2009.

Levins, R. *The strategy of model-building in population biology*. American Scientist, 4:421–431, 1966.

Linstädter, A. and Baumann, G. *Abiotic and biotic recovery pathways of arid rangelands: Lessons from the High Atlas Mountains, Morocco*. CATENA, 103:3–15, 2013.

Linstädter, A.; Baumann, G.; Born, K.; Diekkrüger, B.; Fritzsche, P.; Kirscht, H. and Klose, A. *Land use and land cover in Southern Morocco: Managing unpredictable resources and extreme events*. In P. Speth; M. Christoph and B. Diekkrüger, editors, *Impacts of global change on the hydrological cycle in West and Northwest Africa*, II-5.1, pages 611–632. Springer, Berlin, 2010.

Linstädter, A. and Bolten, A. *Space matters - sustainable range management in a highly variable environment*. In O. Bubenzer; A. Bolten and F. Darius, editors, *Africa Praehistorica*, pages 104–107. Institut für Ur- und Frühgeschichte der Universität zu Köln, Forschungsstelle Afrika, Köln, 2007.

Lybbert, T. J.; Barrett, C. B.; Desta, S. and Layne Coppock, D. *Stochastic wealth dynamics and risk management among a poor population**. The Economic Journal, 114(498):750–777, 2004. ISSN 1468-0297. doi 10.1111/j.1468-0297.2004.00242.x.

Lybbert, T. J.; Kusonose, Y.; Magnan, N. and Fadlaoui, A. *Drought Risk and Drought Response in Morocco: Vulnerability, Risk Perceptions and Drought Coping among Rainfed Cereal Farmers*. In *AAEA & ACCI Joint Annual Meeting, Milwaukee, Wisconsin*. Agricultural & Applied Economics Association, 2009.

Lybbert, T. J. and McPeak, J. *Risk and intertemporal substitution: Livestock portfolios and off-take among Kenyan pastoralists*. Journal of Development Economics, 97(2):415–426, 2012. ISSN 0304-3878. doi 10.1016/j.jdeveco.2011.06.004.

Martin, G.; Felten, B. and Duru, M. *Forage rummy: A game to support the participatory design of adapted livestock systems*. Environmental Modelling & Software, 26(12):1442–1453, 2011. ISSN 1364-8152. doi 10.1016/j.envsoft.2011.08.013.

McAllister, R.; Stafford Smith, D.; Stokes, C. and Walsh, F. *Patterns of accessing variable resources across time and space: Desert plants, animals and people*. J.Arid Environ., 73:338–346, 2009. ISSN 0140-1963.

McAllister, R. R.; Gordon, I. J.; Janssen, M. A. and Abel, N. *Pastoralists' Responses To Variation Of Rangeland Resources In Time And Space*. Ecol.Appl., 16(2):572–583, 2006.

McPeak, J. *Contrasting income shocks with asset shocks: livestock sales in northern Kenya*. Oxford Economic Papers, 56(2):263–284, 2004. doi 10.1093/oep/gpf040.

MEA. *Ecosystems and human well-being: synthesis*. Island Press, Washington, DC, 2005.

Michelin, M. *Can a game put engineering students in an active learning mode? A first experiment in sustainable agricultur teaching*. In K. Elleithy, editor, *Advances in Computer, Information, and Systems Sciences, and Engineering*, chapter Can a game put engineering students in an active learning mode? A first experiment in sustainable agricultur teaching, pages 343–349. Springer, 2006.

Milner-Gulland, E.; Kerven, C.; Behnke, R.; Wright, I. and Smailov, A. *A multi-agent system model of pastoralist behaviour in Kazakhstan*. Ecological Complexity, 3(1):23 – 36, 2006. ISSN 1476-945X. doi 10.1016/j.ecocom.2005.05.004.

Müller, B.; Angermüller, F.; Drees, R.; Dreßler, G.; Groeneveld, J.; C., K.; Schlüter, M.; Schulze, J.; Weise, H. and Schwarz, N. *Describing human decisions in agent-based social-ecological models - ODD+D an extension of the ODD protocol*. Environ. Model. Softw., submitted 2012.

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

Müller, B.; Linstädter, A.; Frank, K.; Bollig, M. and Wissel, C. *Learning from Local Knowledge: Modeling the Pastoral-Nomadic Range Management of the Himba, Namibia*. Ecological Applications, 17(1):1857–1875, 2007b.

Morris, W. F.; Pfister, C. A.; Tuljapurkar, S.; Haridas, C. V.; Boggs, C. L.; Boyce, M. S.; Bruna, E. M.; Church, D. R.; Coulson, T.; Doak, D. F.; Forsyth, S.; Gaillard, J. M.; Horvitz, C. C.; Kalisz, S.; Kendall, B. E.; Knight, T. M.; Lee, C. T. and Menges, E. S. *Longevity can buffer plant and animal populations against changing climatic variability*. Ecology, 89(1):19–25, 2008.

Murphree, M. *Beyond Fences. Seeking Social Sustainability in Conservation.*, chapter Common property, communal property and open access regimes. Vol. 2: A Resource Book, Gracia, ed. Gland, Suiza: IUCN., 1997.

Mutinda; Mark and Aboud, A. *Community perceptions concerning key ecological resources at risk in Baringo district, Kenya*. In O. C. of 2008 IGC/IRC Conference, editor, *Multifunctional Grasslands in a Changing World*, C4, 62, pages 1005–1005. Guangdong People's Publishing House, Guangzhou, 2008.

Neely, C.; Bunning, S. and Wilkes, A. *Review of evidence on drylands pastoral systems and climate change – Implications and opportunities for mitigation and adaptation*. Technical report, Land Tenure and Management Unit (NRLA), Land and Water Devision, FAO, 2009.

Ngugi, M. and Conant, R. *Ecological and social characterization of key resource areas in Kenyan rangelands*. J.Arid Environ., 72(5):820–835, 2008. ISSN 0140-1963.

Niamir-Fuller, M. and Turner, M. D. *A review of recent literature on pastoralism and transhumance in Africa*. In M. Niamir-Fuller, editor, *Managing Mobility in African Rangelands – The legitimization of transhumance*, pages 18–46. FAO and the Beijer International Institute of Ecological Economics, 1999.

Noy-Meir, I. *Arid Land Ecosystems*, chapter Spatial effects in modeling of arid ecosystems, pages 411–432. Cambridge University Press, Cambridge, 1981. 25.

Noy-Meir, I. *Stability of plant-herbivore models and possible applications to savanna*. In B. Huntley and B. Walker, editors, *Ecology and Tropical Savannas*, Ecological Studies: Analysis and Synthesis, pages 591–609. Springer, Berlin, 1982.

Oba, G. *Mobility and the Sustainability of the Pastoral Production system in Africa: Perspectives of Contrasting Paradigms*. In *Future of Pastoralism*. 2011.

O'Connor, T. G. and Everson, T. M. *Population dynamics of perennial grasses in African savanna and grassland.* In G. P. Cheplick, editor, *Population Biology of Grasses*, pages 333 – 365. University of New York, 1998.

Olea, P. P. and Mateo-Tomás, P. *The role of traditional farming practices in ecosystem conservation: The case of transhumance and vultures.* Biological Conservation, 142(8):1844 – 1853, 2009. ISSN 0006-3207. doi DOI:10.1016/j.biocon.2009.03.024.

Omer, R.; Hester, A.; Gordon, I.; Swaine, M. and Raffique, S. *Seasonal changes in pasture biomass, production and offtake under the transhumance system in northern Pakistan.* J.Arid Environ., 67(4):641–660, 2006.

Owen-Smith, N. *Functional heterogeneity in resources within landscapes and herbivore population dynamics.* Landscape Ecology, 19:761–771, 2004. ISSN 0921-2973. 10.1007/s10980-005-0247-2.

Owen-Smith, N. *Introduction to Modeling in Wildlife and Resource Conservation.* Blackwell Publishing Inc, 2007.

Owen-Smith, N. *The refuge concept extends to plants as well: storage, buffers and regrowth in variable environments.* Oikos, 117(4):481–483, 2008. ISSN 1600-0706. doi 10.1111/j.0030-1299.2008.16310.x.

Oxfam. *Survival of the fittest. Pastoralism and climate change in East Africa.* Technical report, Oxfam International, 2008.

Paeth, H.; Born, K.; Girmes, R.; Podzun, R. and Jacob, D. *Regional climate change in tropical and northern Africa due to greenhouse forcing and land use changes.* Journal of Climate, 22:114–132, 2009.

Peacock, C. *Improving goat production in the tropics.* Oxfam/FARM-Africa, 1996.

Perez-Ramos, I. M.; Roumet, C.; Cruz, P.; Blanchard, A.; Autran, P. and Garnier, E. *Evidence for a 'plant community economics spectrum' driven by nutrient and water limitations in a Mediterranean rangeland of southern France.* Journal of Ecology, 100(6):1315–1327, 2012. ISSN 1365-2745. doi 10.1111/1365-2745.12000.

Poorter, H. and Garnier, E. *Ecological significance of inherent variation in relative growth rate and its components.* In V. F. Pugnaire Fl., editor, *Functional plant ecology, 2nd edn.*, pages 67–100. CRC, Boca Raton, 2007.

Pratt, D. J.; Le Gall, F. and de Haan, C. *Investing in Pastoralism – Sustainable Natural Resource Use in Arid Africa and the Middle East.* Technical paper no. 365, The World Bank, 1997.

Quaas, M.; Baumgärtner, S.; Becker, C.; Frank, K. and Müller, B. *Uncertainty and sustainability in the management of semi-arid rangelands*. Ecol.Econ., 62(2):251–266, 2007.

Reed, M. S.; Dougill, A. J. and Baker, T. R. *Participatory Indicator Development: What can Ecologists and Local Communities Learn from each other*. Ecological Applications, 18(5):1253–1269, 2008. ISSN 1051-0761. doi doi:10.1890/07-0519.1.

Reich, P. B.; Walters, M. B. and Ellsworth, D. S. *From tropics to tundra: Global convergence in plant functioning*. Proceedings of the National Academy of Sciences, 94(25):13730–13734, 1997.

Reid, R. S.; Galvin, K. A. and Kruska, R. S. *Global Significance of Extensive Grazing Lands and Pastoral Societies: An Introduction*. In K. A. Galvin; R. S. J. Reid; R. H. Behnke and N. T. Hobbs, editors, *Fragmentation in Semi-Arid and Arid Landscapes: Consequences for Human and Natural Systems*, pages 1–24. Springer Netherlands, 2008. ISBN 978-1-4020-4906-4.

Retzer, V. *Impacts of grazing and rainfall variability on the dynamics of a Sahelian rangeland revisited –new insights from old data*. J.Arid Environ., 67(7):157–164, 2006.

Ritten, J. P.; Frasier, W. M.; Bastian, C. T. and Gray, S. T. *Optimal Rangeland Stocking Decisions Under Stochastic and Climate-Impacted Weather*. American Journal of Agricultural Economics, 92(4):1242–1255, 2010. doi 10.1093/ajae/aaq052.

Roth, A. *Impact of climate change and stocking rates on pasture systems in SE Morocco – An Application of the SAVANNA Ecosystem Model*. Ph.D. thesis, University of Bonn, 2010.

Rössler, M.; Kirscht, H.; Rademacher, C.; Platt, S.; Kemmerling, B. and Linstädter, A. *Migration and resource management in the Drâa Valley, Southern Morocco*. In P. Speth; M. Christoph and B. Diekkrüger, editors, *Impacts of global change on the hydrological cycle in West and Northwest Africa*, II-5.1, pages 633–646. Springer, Berlin, 2010.

Ruppert, J.; Holm, A.; Miehe, S.; Muldavin, E.; Snyman, H.; Wesche, K. and Linstädter, A. *Meta-analysis of rain-use efficiency confirms indicative value for degradation and supports non-linear response along precipitation gradients in drylands*. J.Veg.Sci., in press 2012.

Sandford, S. *Pastoral Strategies and Desertification: Opportunism and Conservation in Dry Lands*. In B. Spooner and H. Mann, editors, *Desertification and Development*, pages 61–80. Academic Press, London, 1982.

Scheiter, S. and Higgins, S. *Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach*. Global Change Biol, 15(9):2224–2246, 2009.

Schlüter, M.; McAllister, R. R. J.; Arlinghaus, R.; Bunnefeld, N.; Eisenack, K.; Hölker, F.; Milner-Gulland, E.; Müller, B.; Nicholson, E.; Quaas, M. and Stöven, M. *New Horizons for Managing the Environment: A Review of Coupled Social-Ecological Systems Modeling*. Natural Resource Modeling, 25(1):219–272, 2012a. ISSN 1939-7445. doi 10.1111/j.1939-7445.2011.00108.x.

Schlüter, M.; Müller, B. and Frank, K. *MORE – Modeling for Resilience Thinking and Ecosystem Stewardship (Working paper, April 10, 2012)*. SSRN, 2012b.

Schmolke, A.; Thorbek, P.; DeAngelis, D. L. and Grimm, V. *Ecological models supporting environmental decision making: a strategy for the future*. Trends in Ecology & Evolution, 25(8):479 – 486, 2010. ISSN 0169-5347. doi 10.1016/j.tree.2010.05.001.

Schulz, O. *Analyse schneehydrologischer Prozesse und Schneekartierung im Einzugsgebiet des Oued M'Goun, Zentraler Hoher Atlas (Marokko)*. Ph.D. thesis, University of Bonn, 2007.

Schulz, O. *Precipitation in the upper and middle Drâa basin*. In O. Schulz and M. Judex, editors, *IMPETUS Atlas Morocco. Research Results 2000-2007*, volume 2, pages 19–20. Department of Geography, University of Bonn, Bonn, Germany, 2008.

Schulz, O.; Finckh, M. and Goldbach, H. *Hydro-meteorological measurements in the Drâa catchment*. In P. Speth; M. Christoph and B. Diekkrüger, editors, *Impacts of global change on the hydrological cycle in West and Northwest Africa*, I-4.3, pages 122–131. Springer, Berlin, 2010.

Schulze, J. *Risk Measures and Decision Criteria for the Management of Natural Resources Under Uncertainty – Application to an Ecological-Economic Grazing Model*. Master's thesis, University of Greifswald, 2011.

Scoones, I. *Coping with drought: Responses of herders and livestock in contrasting savanna environments in Southern Zimbabwe*. Human Ecology, 20(3):293–314, 1992.

Scoones, I. *Living with Uncertainty: New Directions in Pastoral Development in Africa*. Oxford University Press, Oxford, 1995.

Scoones, I. *Sustainable rural livelihoods: a framework for analysis*. Brighton, Institute of Development Studies, 1998.

Scoones, I. *Ecological dynamics and grazing-resource tenure: a case study from Zimbabwe*. In M. Niamir-Fuller, editor, *Managing Mobility in African Rangelands – The legitimization of transhumance.*, pages 217–235. FAO and the Beijer International Institute of Ecological Economics, 1999.

Shipley, B. *From plant traits to vegetation structure. Chance and selection in the assembly of ecological communities*. Cambridge University Press, Cambridge, UK, 2010.

Smith, M. S. and Foran, B. *An approach to assessing the economic risk of different drought management tactics on a South Australian pastoral sheep station*. Agricultural Systems, 39(1):83 – 105, 1992. ISSN 0308-521X. doi 10.1016/0308-521X(92) 90006-A.

Steinschulte, H. *The recovery of pasture plants at four altitudinal levels along the High Atlas Mountains, Morocco*. Master's thesis, University of Bonn, 2011.

Thornton, P.; Boone, R.; Galvin, K.; BurnSilver, S.; Waithaka, M.; Kuyiah, J.; Karanja, S.; Gonzalez-Estrada, E. and Herrero, M. *Coping strategies in livestock-dependent households in east and southern Africa: A synthesis of four case studies*. Human Ecology, 35(4):461–476, 2007. ISSN 0300-7839.

Thurow, T. L. and Taylor, C. A. *Viewpoint: The Role of Drought in Range Management*. Journal of Range Management, 52(5):413–419, 1999. ISSN 0022409X. ArticleType: research-article / Full publication date: Sep., 1999 / Copyright Â© 1999 Allen Press.

Tietjen, B. and Jeltsch, F. *Semi-arid grazing systems and climate change: a survey of present modelling potential and future needs*. J.Appl.Ecol., 44(9):425–434, 2007.

UNCCD. *Drylands Matter, and why?* 2010. Last access 13.11.2011.

UNISDR. *Drought Risk Reduction Framework and Practices: Contributing to the Implementation of the Hyogo Framework for Action*. Technical report, United Nations secretariat of the International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 2009.

Verstraete, M. M.; Scholes, R. J. and Smith, M. S. *Climate and desertification: looking at an old problem through new lenses*. Frontiers in Ecology and the Environment, 7(8):421–428, 2009. ISSN 1540-9295. doi doi:10.1890/080119.

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

Violle, C.; Navas, M.-L.; Vile, D.; Kazakou, E.; Fortunel, C.; Hummel, I. and Garnier, E. *Let the concept of trait be functional!* Oikos, 116(5):882–892, 2007. ISSN 1600-0706. doi 10.1111/j.0030-1299.2007.15559.x.

von Wehrden, H.; Hanspach, J.; Kaczensky, P.; Fischer, J. and Wesche, K. *Global assessment of the non-equilibrium concept in rangelands*. Ecological Applications, 22(2):393–399, 2012. ISSN 1051-0761. doi 10.1890/11-0802.1.

Walker, B.; Carpenter, S.; Anderies, J.; Abel, N.; Lebel, G.; Norberg, J.; Peterson, G. and Pritchard, R. *Resilience Management in Social-ecological Systems: a Working Hypothesis for a Participatory Approach*. Conservation Ecology, 6(61):–, 2002.

Walker, B. H. and Janssen, M. A. *Rangelands, pastoralists and governments: interlinked systems of people and nature*. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 357(1421):719–725, 2002. doi 10.1098/rstb.2001.0984.

Wang, Z.; Song, K. and Liangjun, H. *China's Largest Scale Ecological Migration in the Three-River Headwater Region*. AMBIO, 39:443–446, 2010.

Western, D. and Nightingale, D. *Environmental change and the vulnerability of pastoralists to drought: A case study of the Maasai in Amboseli, Kenya*. In *Africa Environment Outlook Case Studies: Human Vulnerability to Environment Change*. UNEP, 2004.

Wilcox, B. P. and Thurow, T. L. *Emerging Issues in Rangeland Ecohydrology: Vegetation Change and the Water Cycle*. Rangeland Ecology & Management, 59(2):pp. 220–224, 2006. ISSN 15507424.

Williams, C. A. and Albertson, J. D. *Dynamical effects of the statistical structure of annual rainfall on dryland vegetation*. Global Change Biology, 12(5):777–792, 2006. ISSN 1365-2486. doi 10.1111/j.1365-2486.2006.01111.x.

Winkler, D. *Caterpillar Fungus (Ophiocordyceps sinensis) Production and Sustainability on the Tibetan Plateau and in the Himalayas*. Asian Medicine, 5:291–316, 2009.

Wright, I. J.; Reich, P. B.; Westoby, M.; Ackerly, D. D.; Baruch, Z.; Bongers, F.; Cavender-Bares, J.; Chapin, T.; Cornelissen, J. H. C.; Diemer, M.; Flexas, J.; Garnier, E.; Groom, P. K.; Gulias, J.; Hikosaka, K.; Lamont, B. B.; Lee, T.; Lee, W.; Lusk, C.; Midgley, J. J.; Navas, M.-L.; Niinemets, U.; Oleksyn, J.; Osada, N.; Poorter, H.; Poot, P.; Prior, L.; Pyankov, V. I.; Roumet, C.; Thomas, S. C.; Tjoelker, M. G.; Veneklaas, E. J. and Villar, R. *The worldwide leaf economics spectrum*. Nature, 428(6985):821–827, 2004. ISSN 0028-0836. doi 10.1038/nature02403.

Zemmrich, A.; Manthey, M.; Zerbe, S. and Oyunchimeg, D. *Driving environmental factors and the role of grazing in grassland communities: A comparative study along an altitudinal gradient in Western Mongolia*. Journal of Arid Environments, 74(10):1271 – 1280, 2010. ISSN 0140-1963. doi 10.1016/j.jaridenv.2010.05.014.

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Erklärung

Ich versichere, dass ich die von mir vorgelegte Dissertation selbständig angefertigt, die benutzten Quellen und Hilfsmittel vollständig angegeben und die Stellen der Arbeit – einschließlich Tabellen, Karten und Abbildungen –, die anderen Werken im Wortlaut oder dem Sinn nach entnommen sind, in jedem Einzelfall als Entlehnung kenntlich gemacht habe; dass diese Dissertation noch keiner anderen Fakultät oder Universität zur Prüfung vorgelegen hat; dass sie – abgesehen von unten angegebenen Teilpublikationen – noch nicht veröffentlicht worden ist sowie, dass ich eine solche Veröffentlichung vor Abschluss des Promotionsverfahrens nicht vornehmen werde. Die Bestimmungen der Promotionsordnung sind mir bekannt. Die von mir vorgelegte Dissertation ist von Prof. Michael Bonkowski betreut worden.

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