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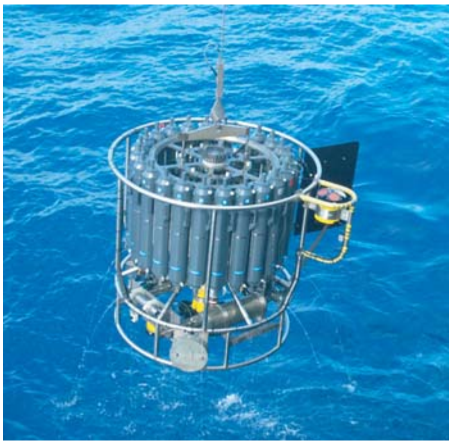
Modelling alternative land use regimes in semi-arid Morocco

Assessment of perspectives in a changing environment

Korbinian Peter Freier



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Anschrift / Address

Max-Planck-Institut für Meteorologie
Bundesstrasse 53
20146 Hamburg
Deutschland

Tel.: +49-(0)40-4 11 73-0
Fax: +49-(0)40-4 11 73-298
Web: www.mpimet.mpg.de

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Korbinian Peter Freier
Max-Planck-Institut für Meteorologie
Bundesstrasse 53
20146 Hamburg

Universität Hamburg
Forschungsstelle Nachhaltige Umweltentwicklung
Bundesstraße 55
20146 Hamburg
Germany

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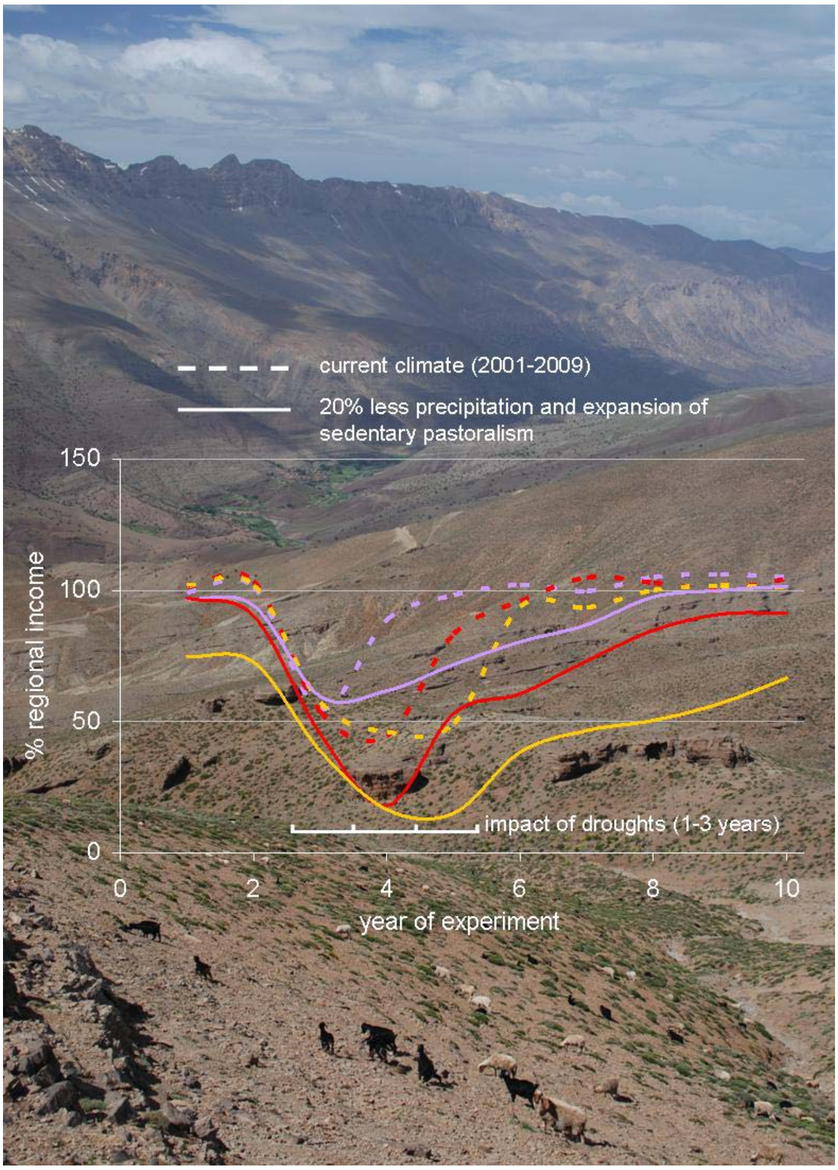

Korbinian Peter Freier

Hamburg 2012

"[...], perhaps the herdsman is due respect for his capabilities of handling the vagaries of African environmental conditions. The traveler can always leave and go home. To the pastoralist, the herd is forever."

Andrew B. Smith, (*African Herders – Emergence of pastoral traditions*)

Abstract

Pastoralism is a major source of income in semi-arid subtropical areas. Climate change in the 21st century will likely affect livelihood security in these areas through reduced average rainfall and increased frequency of droughts. This thesis investigates a pastoral land use system in semi-arid Morocco by means of transdisciplinary modelling. The aim of this thesis is to provide insights into the dynamics of the socio-ecological system and to clarify options for adaptation to environmental changes.

In a first study, a qualitative approach is used to clarify predictability of reactions of mobile pastoralists towards reduced rainfall. It is assumed that pastoralists' choices are based on availability of specific resources and on expectations of wellbeing which are associated to alternative livelihood options. A methodology is developed based on partial order theory which investigates if the pastoralists have clear preferences concerning alternatives, or if they are undecided and contingent decisions are likely. Thereby, a mathematically formal basis for the concept of historical contingency is developed. The analysis shows that 38% of pastoralists would opt for "sedentarity and localized pastoralism" as an alternative strategy under scarcity of precipitation, which would increase pressure on scarce resources such as arable land and irrigation water. Unclear preferences are given for 25% of the pastoralists, indicating a certain degree of unpredictability. The share of unclear preferences is increased by a policy scenario of enhanced access to education and capital. At the same time, such a scenario enables the activation of a broader set of alternatives and reduces the adoption of "sedentarity and localized pastoralism" as the dominant alternative.

A land use decision model is created for further studies, to quantitatively assess impacts of climate change and an increased frequency of droughts on pastoralism. The model includes a Markov chain meta-model of a biophysical soil-vegetation model. This enables including vegetation dynamics into a model of human decision making.

The land use decision model is applied in a first step to sedentary pastoralism for a village in the southern slopes of the High Atlas. The dynamic representation of vegetation leads to a higher resolution of system properties. The impacts of droughts (33% less precipitation) influence the system still up to four years after the end of the drought and have pronounced effects on income generation even when precipitation levels are back to average levels (57% decrease in income). Intense grazing in the surroundings of oases increases water availability for irrigated agriculture in the model.

In a second step, the land use decision model is regionalized to investigate effects of climate change on sedentary and mobile pastoralism. Sedentary herds are constrained

to pastures around settlements, while mobile herds are able to migrate seasonally between different types of pastures (transhumance). The model shows for different scenarios that climate change, as projected for the 21st century, will reduce income from pastoralism on average by 15-37%. The reduction is more pronounced for sedentary pastoralism (23-39%) than for mobile pastoralism (8-31%). The dynamical properties of the model reveal that under future climatic conditions an increased share of mobile pastoralism is able to buffer impacts from droughts on income generation by 11% and increases resilience of the livestock system. Destocking during droughts becomes more important under reduced average precipitation, which supports criticism of fodder subsidies during droughts. Encouragement of sedentarization as done by many governments in semi-arid regions is demonstrated to be counterproductive for adaptation to climate change.

Integrating the results of the presented studies into a broader perspective, a further study within this thesis investigates climate change impacts on agriculture and social implications in North Africa with focus on Morocco. It is identified that climate change is likely to contribute to social inequality and conflict. Especially policies of maximizing primary agricultural productivity risk achieving short term objectives by amplifying future problems such as productivity losses due to severe salinization of soils, groundwater depletion, and rangeland degradation. Shocks in income generation and food supply due to droughts become more pronounced under maximization strategies. Therefore it is recommended to focus agricultural policy on income stabilization rather than on maximization. Additionally it can be shown with the land use decision model that replacing firewood as dominant source of energy in rural areas by electricity offers the opportunity to reduce pressure on rangeland vegetation to an extent which compensates impacts from climate change on sedentary pastoralism.

Zusammenfassung

Extensive Weidewirtschaft spielt in subtropischen Trockengebieten eine maßgebliche Rolle für das Einkommen ländlicher Haushalte. Abnehmende Niederschläge und ein vermehrtes Auftreten von Dürren werden mit großer Wahrscheinlichkeit im 21. Jahrhundert zu einer geringeren Einkommenssicherheit in diesen Gebieten führen. Das Ziel der vorliegenden Doktorarbeit ist es, anhand von Modellen die Dynamiken eines Weidewirtschaftssystems im südlichen Marokko zu verstehen und Anpassungsstrategien an die erwarteten Umweltveränderungen herauszuarbeiten.

Um Reaktionen von nomadischen Viehhaltern bezüglich verringerter Niederschlagsmengen abzuschätzen, wird eine Methode zu Analyse von Interviews entwickelt, die auf der Theorie partieller Ordnungen basiert. Der entwickelte Algorithmus bietet dabei ein neuartiges formales mathematisches Konzept zur Erfassung von historischer Kontingenz an. Die Analyse von 16 Interviews mit nomadischen Viehhaltern ergibt, dass 38% von ihnen sich für "Sesshaftigkeit und lokale Viehhaltung" entscheiden, falls ihr Lebensunterhalt durch verringerte Niederschläge gefährdet wird. Die Sesshaftigkeit würde dabei allerdings den Druck auf knappe Ressourcen wie Ackerland und Grundwasser erhöhen. 25% der Viehhalter zeigen keine klaren Präferenzen, was auf einen gewissen Grad von Unvorhersagbarkeit hindeutet (Kontingenz). Die Analyse der Interviews zeigt zudem, dass die Reaktionen der Viehhalter noch weniger vorhersagbar werden, falls das Bildungsniveau erhöht und die Verfügbarkeit von finanziellen Mitteln verbessert wird. Allerdings würden derartige Maßnahmen den Viehhaltern ein breiteres Angebot an alternativen Strategien zum Lebensunterhalt ermöglichen und damit die Abhängigkeit von der dominanten Alternative "Sesshaftigkeit und lokale Viehhaltung" verringern.

Um die Auswirkung von klimatischen Veränderungen in Süd-Marokko quantitativ zu untersuchen, wird ein Landnutzungs-Modell entworfen. Das Modell berücksichtigt biophysikalische Prozesse, stochastisches Klima und dynamische menschliche Nutzung, insbesondere vorausschauendes Verhalten von Viehhaltern. Die Dynamik der Steppenvegetation wird in dem Landnutzungsmodell durch eine Markov-Kette abgebildet.

In einem ersten Schritt wird das Modell dann auf eine Fallstudie mit sesshaften Viehhaltern in den südlichen Ausläufern des Hohen Atlas angewendet. Dabei bewirkt das dynamische Verhalten der Vegetation in dem Modell, dass Systemeigenschaften detailliert dargestellt werden. Dürren mit 33% weniger Niederschlag führen in einer Simulation dazu, dass der Vegetationszustand und die Nutzung bis zu vier Jahre nach dem Ende der Dürre immer noch den Einfluss des geringeren Niederschlags zeigen.

Das Einkommen aus Viehhaltung ist zudem selbst nach dem Ende der Dürre bis zu 57% geringer als in durchschnittlichen Jahren. Beweidung in der Umgebung von Oasen bewirkt in dem Modell außerdem ein erhöhtes Wasserangebot für den Bewässerungsfeldbau.

In einem weiteren Schritt wird das Modell auf einem regionalen Maßstab angewendet, um den Effekt von Klimaänderungen auf sesshafte und nomadische Viehhaltung zu untersuchen. Dabei werden in dem Modell sesshafte Herden auf die Umgebung von Siedlungen beschränkt, während sich nomadische Herden saisonal zwischen verschiedenen Typen von Weidegebieten bewegen können (Transhumanz). Das Modell zeigt für unterschiedliche Szenarien, dass Einkommen aus der Weidewirtschaft durch die zu erwartenden Klimaänderungen um 15-37% abnehmen werden. Dabei müssen sesshafte Viehhalter größere Verluste hinnehmen (23-39%) als nomadische Viehhalter (8-31%). In dem Modell bewirkt eine Förderung von nomadischer Viehhaltung, dass die negativen Auswirkungen von zukünftigen Dürren auf das Einkommen um 11% verringert werden. Außerdem wird die Widerstandsfähigkeit des Weidewirtschafts-Systems insgesamt erhöht. Die drastische Reduktion von Viehbeständen während Dürren wird für eine nachhaltige Nutzung der Steppen-Vegetation umso wichtiger, je geringer das durchschnittliche Niederschlagsniveau ist. Damit bestätigt das Modell die Kritik an Futtersubventionen während Dürreperioden. Die Ergebnisse des Modells belegen, dass die staatliche Förderung von Sesshaftigkeit ehemals nomadischer Viehhalter in Trockengebieten contra-produktiv im Sinne einer Anpassung an den Klimawandel ist.

Eine weitere Studie dieser Doktorarbeit nützt die Ergebnisse aus den vorgestellten Teilen, um sie in einen Gesamtzusammenhang mit anderen nordafrikanischen Ländern zu stellen und sozio-ökonomische Konsequenzen des erwarteten Klimawandels zu untersuchen. Die erwarteten klimatischen Veränderungen haben dabei das deutliche Potential, zu sozialer Ungleichheit und Konflikten beizutragen. Maßnahmen, die bisher darauf abzielten die Primärproduktion der Landwirtschaft zu maximieren, riskieren kurzfristige Ziele zu erreichen, indem sie gleichzeitig langfristig negative Auswirkungen des Klimawandels verstärken, wie zum Beispiel Versalzung von Ackerböden, Grundwasserknappheit und Degradation von Steppenböden und Steppenvegetation. Daher wird empfohlen, den zukünftigen Schwerpunkt der Agrarpolitik auf die Stabilisierung der Produktion zu legen um die Auswirkungen von Dürren abzumildern. Das Landnutzungsmodell zeigt außerdem, dass die Verwendung von Strom anstelle von Feuerholz in ländlichen Gebieten den Druck auf die Steppenvegetation soweit verringern kann, dass die Auswirkungen der erwarteten Klimaänderungen auf sesshafte Herden kompensiert werden können.

Contents

CHAPTER 1 - INTRODUCTION

Chapter 1

Introduction

At the beginning of the 21st century, human society faces unprecedented challenges: population growth is expected to continue beyond the middle of the century (Lutz *et al.*, 2001); resource demands as well as environmental impacts of human society have partially surpassed planetary boundaries (Rockström *et al.*, 2009); and climate change is likely[1] to cause considerable disturbances of ecological and land use systems (IPCC, 2007a). Given these challenges, it remains open if human society will be able to sustain the current level of global wellbeing.

Investigating possibilities of choosing a safe route for human society into the future, one is confronted with highly interrelated, complex structures in the earth-system. For instance, human land use causes many environmental impacts, ranging from local to global scales. Land use is fundamental to social wellbeing, and it influences future options of human prosperity. But at the same time, environmental conditions and social wellbeing influence human land use. Approaches, which have not sufficiently taken into account the complexity of such interrelated structures, very often failed to improve human conditions (e.g. Scott, 1998).

To address problems which are summarized under the notion of global change, it is therefore necessary to apply transdisciplinary approaches (e.g. Reusswig & Schellnhuber, 1998). However, science is traditionally organized within disciplines, having their own terminologies, methods, and modelling concepts. Systems which belong to more than one scientific sphere are therefore until now difficult to investigate and to model. Socio-ecological systems, such as land use systems, belong to such a category. They cover disciplinary characteristics of anthropology, economy, geography, soil science, ecology, climatology, and mechanical engineering, to mention but a few. The question arises of how to investigate, understand, and model such systems.

1.1 Why semi-arid Morocco?

Drylands cover roughly 41% of the Earth's land surface and accommodate about one third of the world's total population. Approximately 90% of drylands are located in

[1] The Forth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) describes an outcome as "likely" if the probability of its occurrence is greater than 66%.

developing countries (Millennium Ecosystem Assessment, 2005). In those areas, pastoralism contributes a major share of income and secures livelihoods of up to 30% of the population (Gertel & Breuer, 2007; Thornton *et al.*, 2009).

During the course of the 21st century, precipitation will likely decrease by approximately 20% in many dryland areas (IPCC, 2007b), where population growth is among the highest in the world (Millennium Ecosystem Assessment, 2005). To which extend these changes will affect pastoral systems and livelihood security in dryland areas is not well investigated since global and regional models of grazing mostly struggle to integrate many of the systems' dynamic properties such as rainfall variability, vegetation dynamics, and human management (Diaz *et al.*, 2007; Thornton *et al.*, 2009). It is therefore of interest to develop models of pastoralism which are able to integrate ecological properties as well as human decision making. However, to be able to calibrate and validate such models, a reliable data basis from case studies is indispensible.

The character of the land use system in southern Morocco is representative for many dryland areas around the world: it is likely to face a reduction of rainfall by 10-30% during the 21st century (Born *et al.*, 2008a; Hertig & Jacobeit, 2008c; Paeth *et al.*, 2009); pastoralism is seen as the major economic activity for 14% of the male population (Breuer, 2007a); and more than 90% of the area can be considered as rangelands which are mainly used for extensive grazing by sheep and goats. Additionally, rangelands provide firewood which serves as primary energy source for heating and cooking. Annual population growth rates in southern Morocco amount to 0.8% to 3.1% (Rössler *et al.*, 2010a) and livelihood strategies as well as land use practices have changed considerably during the last decades (Davis, 2006; Rachik, 2007). Given the climatic and socio-economic changes, the future development of the land use system is uncertain. Is it possible to derive from climate projections possible development pathways of this system?

This thesis aims to answer that question through integrated scientific assessment based on transdisciplinary modelling of a pastoral land use system in southern Morocco. In this region, two research projects have been active between 2001 and 2009, which have focussed on climatic, hydrologic, and biodiversity issues (BIOTA Maroc, 2011; IMPETUS, 2011). The extensive empirical data basis created by these projects offers the opportunity to identify options for adaptation of a pastoral land use system to environmental changes as projected for the 21st century.

1.2 Outline of Thesis

In this thesis, I present four studies, in which impacts from environmental and socio-economic changes in a pastoral land use system of semi-arid Morocco are analyzed.

All four studies address their research questions in a transdisciplinary way, either by coupling environmental models to models of human decision making (chapter 2, 4 and 5), or by working problem-oriented, cutting through disciplinary boundaries (chapters 3 and 4). In this way I present a thorough scientific assessment of a socio-ecological system which is very likely facing considerable alterations in future climatic conditions. Recommending future pathways which avoid unfortunate outcomes for society in semi-arid Morocco is the major objective of this thesis.

To approach this research question, the necessary arguments are elaborated on in four main chapters. New modelling methodologies are developed and applied to case studies in four self-containing investigations. Finally, a general conclusion is drawn based on the insights which have been gathered.

In chapter 2, a mathematical model is created which couples vegetation dynamics, livestock growth and farsighted human decision making in a computational feasible manner. The model establishes the basis of further analyses in chapters 4 and 5. Based on a similar coupling of a land use model with a soil-carbon model (Schneider, 2007), a Markov chain is used as a core element to create a meta-model of a detailed soil-vegetation model, the Environmental Policy Impact Calculator (EPIC, Williams *et al.*, 1989). This meta-model is then included into a land use decision model. Thereby, a dynamical coupling of a biophysical model with a model of farsighted human decision making is demonstrated. The model is then tested by a case study of sedentary pastoralism around a village in southern Morocco. In this case study, the focus is set on identifying the impacts from severe droughts on income security, as well as on the influence of pastoralism on hydrologic properties of the rangelands. This chapter has been published in 2011 in similar form in the peer-reviewed journal of *Agriculture, Ecosystems and Environment*[2].

A more qualitative approach is used for assessing the predictability of future livelihood strategies of pastoralists. In chapter 3, a method is developed based on partial order theory to evaluate interviews which have been performed with pastoralists in the research region in 2009. Within these interviews, pastoralists have been asked to establish rankings of resource necessities and expectations of wellbeing regarding different alternative livelihood options. The analysis focuses on the most likely alternative livelihood strategies of today's pastoralists if precipitation is getting to scarce to pursue traditional pastoralism. It is additionally assessed if the choice itself is predictable or if it is undetermined. The methodology we develop enables us to investigate options of influencing the pastoralists' choices through policy interventions such as increasing the educational level or enhancing the access to

[2] Freier KP, Schneider UA, Finckh M (2011) Dynamic interactions between vegetation and land-use in semi-arid Morocco: Using a Markov process for modelling rangelands under climate change. *Agriculture, Ecosystems &Environment* 140 (3-4) 462-472, DOI: 10.1016/j.agee.2011.01.011

financial resources. A similar form of chapter 3 has been accepted by *Technological Forecasting and Social Change*[3].

In chapter 4, a broader perspective is taken on climate change impacts in North Africa with focus on Morocco. Bringing together perspectives from climate science, conflict research, and environmental sciences, policy options are assessed which are able to contribute to climate change adaptation. This chapter is using own modelling experiments as well as an extensive literature review. Especially the agriculture part of chapter 4 is building on insights gathered from the studies presented in chapter 2 and 3. A similar form of the study as presented in chapter 4 has been re-submitted after revision to the journal of *Regional Environmental Change*[4].

Since sedentarization of former mobile pastoralists is currently encouraged by new lifestyles as well as by many governmental initiatives in semi-arid areas, it is of interest to which degree this development influences impacts from climate change. In chapter 5, this question is addressed by studying the differences between mobile pastoralism (transhumance) and sedentary pastoralism concerning the impacts from reduced average precipitation and droughts. The model which has been described in chapter 2 is expanded to cover a regional scale of about 3400 km^2. Additionally, seasonal migration of transhumant herds within different types of pastures is introduced into the land use decision model. Using scenario analyses of different shares of transhumant pastoralism, the effects of increased sedentary pastoralism are analysed. The contents of chapter 5 have been submitted in similar form to the peer-reviewed journal of *Global Environmental Change*[5].

Bringing together the results from the four described studies, the summary and conclusion in chapter 6 addresses the main objective of this thesis: How to adapt a pastoral land use system in southern Morocco to the environmental changes as projected for the 21st century?

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[3] Freier KP, Brüggemann R, Scheffran J, Finckh M, Schneider UA (2011) Climate change and predictability of future behaviour of transhumant pastoralists in semi-arid Morocco. *Technological Forecasting & Social Change*, DOI: 10.1016/j.techfore.2011.07.003

[4] Schilling JP, Freier KP, Hertig E, Scheffran J (2011): Climate change, vulnerability and adaptation in North Africa with focus on Morocco.

[5] Freier KP, Finckh M, Schneider UA (2011): Adaptation to new climate by an old strategy? Modelling transhumant pastoralism in semi-arid Morocco.

Chapter 2

Dynamic interactions between vegetation and land use in semi-arid Morocco: Using a Markov process for modelling rangelands under climate change [6]

Integrated scientific assessments of semi-arid agro-ecosystems with mathematical models are challenging because of computational constraints. These constraints arise from exponentially increasing decision options due to dynamic interactions between the biophysical states of rangeland vegetation and farsighted decisions taken by pastoral stakeholders. This study applies a methodology that integrates these interactions in a computationally feasible manner. We equip a dynamic land use decision model with a detailed representation of biophysical processes by using a Markov chain meta-model of EPIC (Environmental Policy Impact Calculator). Using separate Markov chains for different weather scenarios, we investigate the economic and ecological impacts of droughts on rangeland management in southern Morocco. The drought simulations (two years with 33% less precipitation) show a decrease in profits from pastoralism by up to 57%. Pastoral land use of the rangeland in our model increases surface runoff by 20%, doubles infiltration, and thus influences irrigation agriculture. The economic and ecological impacts of drought in our simulation go substantially beyond its meteorological time horizon.

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[6] This chapter has been published in similar form as: Freier KP, Schneider UA, Finckh M (2011) Dynamic interactions between vegetation and land-use in semi-arid Morocco: Using a Markov process for modelling rangelands under climate change. *Agriculture, Ecosystems & Environment* 140 (3-4) 462-472, DOI: 10.1016/j.agee.2011.01.011; more than 95% of the work of this chapter has been done by Korbinian P Freier.

2.1 Introduction

Pastoralism is a dominant land use in semi-arid and arid areas. These areas occupy 41% of the world's land surface and are inhabited by more than two billion people (Millennium Ecosystem Assessment, 2005). However, in several large-scale economic assessments of global change, semi-arid areas have been found to not play an important role because the overall impacts of climate change are accounted for mostly in terms of the percentage of global gross domestic product (GDP, e.g. Tol, 2009), and drylands have the lowest GDP per capita (UNCCD, 2007). Hence, the socio-economic effects of climate change in these areas are at present of no great influence in large-scale economic models and the resolution of system properties is low. Furthermore, grazing is not generally considered as part of dynamic global vegetation models (Diaz *et al.*, 2007). Nevertheless, especially in developing countries, pastoralism is a major source of income for large parts of the population (Gertel & Breuer, 2007). At the same time, the social impact of climate change for people living in semi-arid areas has the potential to be quite substantial, since 90% of the affected areas are located in developing countries (Millennium Ecosystem Assessment, 2005), and highest infant mortality rates are reported from drylands (UNCCD, 2007). The conflict in the Sudanese Darfur, which can be traced back in part to changes in a pastoral agroecosystem, exemplifies the impacts climate change can have on society (Prunier, 2005). Hence, investigating the effects of climate change in these areas is of great importance.

To adequately assess the influence of climate change on large-scale agro-ecosystems and society, mathematical models can be used. However, these often require very high levels of computational effort, in particular for the combined representation of vegetation dynamics and decision-making. If human decision-making is farsighted, the number of possible land management plans and related vegetation states can quickly lead to the so-called "curse of dimensionality" (Bellman, 1961), where the computational effort is exponentially related to the number of considered time periods. To overcome this problem, large-scale land use models use either a static representation of biophysical properties, such as biomass growth, or myopic decision-making, such as prescribed scenarios or exclusion of inter-temporal planning (Lambin *et al.*, 2000; Schaldach & Priess, 2008).

The aim of this study is to quantify the implications of droughts in a medium-scale Moroccan pastoral agroecosystem. We approach this by estimating the changes in profits from pastoral activities of rural households. In addition, we also assess the relationships between land use intensity and local hydrological and biophysical properties, including the infiltration of water into the groundwater, surface runoff, evapotranspiration (ETP), and albedo. These biophysical parameters might have further implications for land use decisions since, for example, altered hydrological properties can affect downstream oasis agriculture.

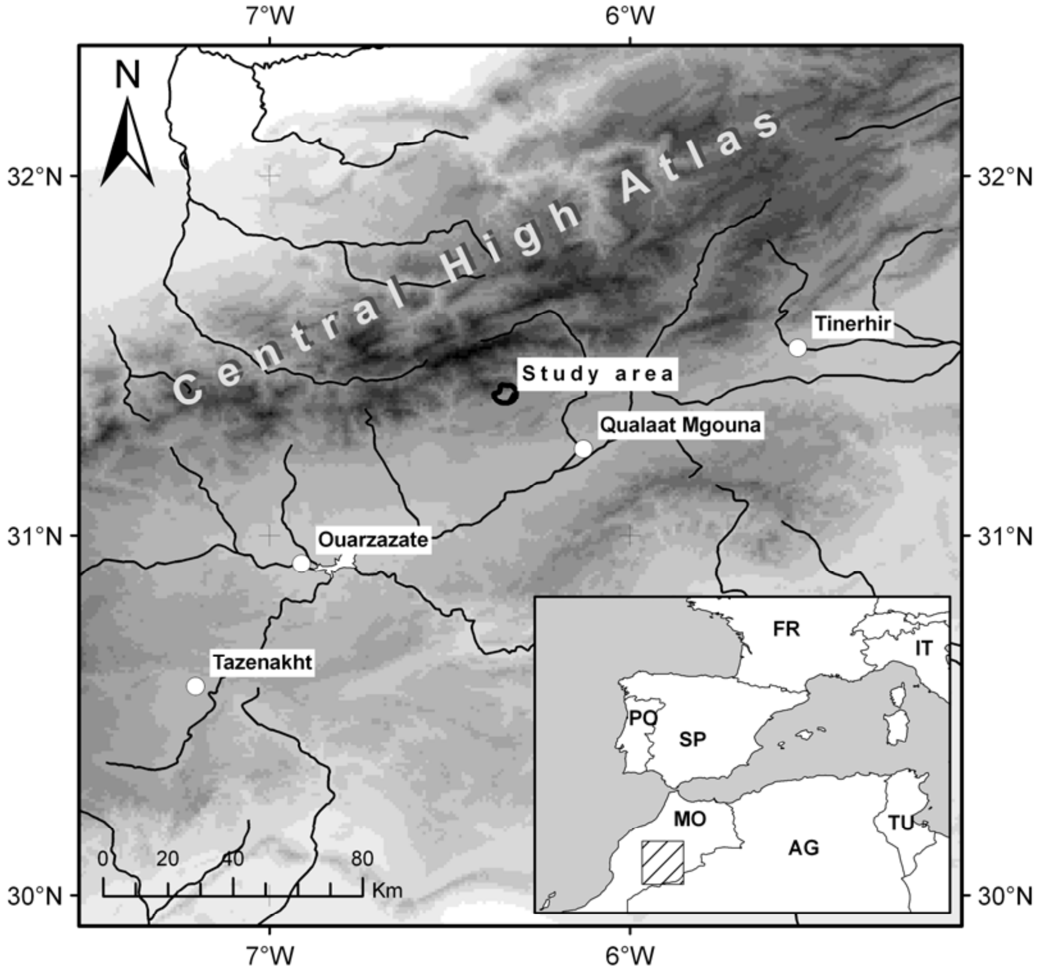

Figure 2.1: Location of the study area situated in the Drâa-river catchment, depicted on the map by the bold black boundary line. Lighter black lines represent rivers.

To address these aims, we develop an augmented mathematical land use decision model (LDM) that combines a dynamic representation of vegetation with farsighted, profit-oriented decision-making. In this way, it is hoped that our research will help bridge the scientific gap between those existing models that address either the detailed representation of farsighted decision-making on the one hand, or concentrate on describing accurately the biophysical vegetation dynamics on the other. We use a Markov chain to integrate into our LDM the results of an elaborated biophysical soil-vegetation model, as well as parts of its dynamic properties. The applied method is suitable for use at large scales, and for a more adequate representation of dryland agro-ecosystems in global LDMs, such as GLOBIOM (Havlík *et al.*, 2010).

2.2 Methodology

2.2.1 Study site and setup

The study site is located in the Moroccan province of Ouarzazate, on the southern slopes of the High Atlas mountain range (Figure 2.1). The region is characterized by a semi-arid to arid climate and a strong precipitation gradient (200 mm to more than 700 mm per year), which exists because of a similarly steep altitudinal gradient (Schulz & Judex, 2008). Climate projections for this region differ greatly and indicate large uncertainty in the direction of precipitation development (Born *et al.*, 2008a; Huebener & Kerschgens, 2007; Sillmann & Roeckner, 2008). Precipitation is currently the limiting factor for agricultural activities in this region, and a likely scenario for the future is characterized by increased water scarcity and increased inter-annual variability of precipitation. To cope with variable precipitation levels and a low average value, a mixed system of irrigation agriculture in river oases and livestock grazing on natural rangelands is traditionally used to secure livelihoods (Barrow & Hicham, 2000). Traditional livestock grazing takes the form of transhumance, where the variability in rainfall is mitigated by the seasonal mobility of pastoralists. However, developments in recent decades and expectations of the herders indicate that this traditional system is changing more and more towards the use of sedentary flocks (Breuer, 2007a; Davis, 2006; Freier *et al.*, 2011a, see chapter 3).

For this study, we develop an augmented LDM on a landscape level. The data for parameterization, calibration and validation of the model were collected in the surroundings of the rural village of Taoujgalt (6.322203° W, 31.38994° N). The village is situated approximately 100 km north of the provincial capital Ouarzazate and consists of 37 households (El Moudden, 2004). The mean annual temperature is 14 °C, and annual precipitation (2001–2008) is relatively variable at 270 ± 70 mm. The parent material for the soil is Jurassic limestone and red siltstones (couches rouges) covered by Calcisols. Rangelands are dominated by *Artemisia herba-alba* – *Stipa parviflora* steppes. Meteorological data are taken from the recordings of a meteorological station of the IMPETUS project, situated 2 km from the village (Schulz *et al.*, 2010). Similarly, vegetation data are used, which have been recorded annually by the BIOTA project on permanent monitoring plots inside and outside an exclosure experiment (BIOTA Maroc, 2011). Soil and surface properties of the study region are retrieved from the IMPETUS database (IMPETUS, 2011). The pastures surrounding the settlement are located at altitudes of between 1800 and 2400 m above sea level. Our simulations relate to the pastures around the village, which are in reach for the sedentary livestock (goats and sheep). The livestock are kept in stables overnight in the village, and the ranges of livestock herds, as determined by collar data, does not exceed more than 3 km and 400 m in altitude per day (Mahler, 2010). In total, the investigated area covers 2500 hectares.

2.2.2 The land use decision model (LDM)

Bioeconomic LDMs are used to assess the economic and ecologic impacts of land use changes, environmental developments and relevant policies (Janssen & van Ittersum, 2007). These models are applied at very different scales, ranging from the plot level to global studies. For the present study, we developed a LDM to depict extensive grazing management in a semi-arid area under variable precipitation conditions. The agricultural activities simulated by the model include a range of different intensities of grazing and a constant demand of firewood.

General structure

Our LDM is a mathematical optimization model that jointly depicts farsighted land use decision-making, livestock, and biophysical vegetation dynamics. The biophysical vegetation dynamics are derived from simulations using the Environmental Policy Impact Calculator [EPIC (Williams *et al.*, 1989)]. We parameterize EPIC with local monitoring data from the study site and include it as a Markov chain meta-model into the LDM. The model uses homogenous response units (HRU, Skalsky *et al.*, 2008) to portray different land qualities, which aggregate raster-based GIS data to avoid repeated calculations of spatial units with similar physical properties (soil type, slope, and altitude).

To model human decision-making it is necessary to make certain behavioural assumptions. Following a utilitarian approach, we assume people are rational and make their strategic decisions based on a maximization of utility. In aggregated agricultural assessments (landscape to global), it has been shown that the assumption of profit maximization mostly holds (Lambin *et al.*, 2000). Therefore, the objective function of our LDM is formulated as given in Eq. 2.1.

$$Max \sum_{t,l,c} (Ns_{t,l,c} \cdot p_{t,l,c}) \qquad 2.1$$

where $Ns_{t,l,c}$ is the number of livestock sold in year t and p is the corresponding producer price on the local market. The livestock in our model includes two species (index l: goats and sheep) and three age classes (index c: less than one year old, 1–2 years old, and more than 2 years old). The price is not constant over time, as livestock producer prices in Morocco are usually lower during droughts (Hazell *et al.*, 2001; Skees *et al.*, 2001). $Ns_{t,l,c}$ needs to be non-negative, and for simplicity we assume that selling takes place at the end of the year. The total number of animals at the end of year t equals the sum of animals sold and animals kept for the following year (Eq. 2.2).

$$Ne_{t,l,c} = Nb_{(t+1),l,c} + Ns_{t,l,c} \quad \forall\ t,l,c \qquad 2.2$$

where $Ne_{t,l,c}$ is the number of animals at the end of a year t and $Nb_{t,l,c}$ is the number of animals at the beginning of the following year $t+1$.

The number of animals per year is subject to various constraints, as represented in general by Eq. 2.3.

$$\sum_{l,c} (Ne_{t,l,c} \cdot a_{l,c,j}) \leq b_{t,l,c,j} \quad \forall\ t,j \qquad 2.3$$

where $b_{t,l,c,j}$ are j times t different constraints on the number of animals, which may be different for each livestock and age class. Technical coefficients ($a_{l,c,j}$) relate the livestock variables $Ne_{t,l,c}$ to the individual constraints, which include resource endowments such as the maximum availability of fodder for the animals.

The general structure of the livestock growth module is given in Eq. 2.4.

$$\sum_{c} Nb_{t,l,c} \cdot g_{t,l,c,\hat{c}} \geq Ne_{t,l,\hat{c}} \quad \forall\ t,l,\hat{c} \qquad 2.4$$

where the factor $g_{t,l,c,\hat{c}}$ maps the number of living animals at the beginning of each year onto the number of animals at the end of the year. The indices c and $\hat{c}$ separate the "source" and "destination" of age classes. For instance, the source age classes for lambs are all mature age classes, and the source age class for the one-year-olds is the previous year's lambs. The factor $g_{t,l,c,\hat{c}}$ includes reproduction and survival rates of the livestock and is calculated by several other equations. The livestock growth rate is limited by the availability and quality of fodder. If fodder is scarce, $g_{t,l,c}$ declines because energetic needs of remaining ewes need to be fulfilled. If fodder is too scarce to fulfil the basic energy demands of the animals, growth stops entirely and animals must be sold to prevent starvation. Thus, the growth module is still linear technically, but behaves like a typical sigmoid growth function. Goats and sheep are treated separately because in relation to body weight, the maximum dry-matter consumption of goats is up to 40% higher than for sheep. This makes it possible for goats to tolerate a diet with lower energy content (Le Houerou, 1980).

An important class of variables in the LDM are land use variables, which indicate the land use management within the individual HRUs (intensity and pattern of grazing and firewood collection). The land use variables control the removed biomass within a HRU, as given in Eq. 2.5.

$$\sum_{m,s} X_{t,HRU,m,s} \cdot EPIC\_yield_{HRU,m,s} = RB_{t,HRU} \quad \forall t, HRU \qquad 2.5$$

where $X_{t,HRU,m,s}$ are the land use variables with m possible management alternatives and s possible vegetation states. The states of vegetation are needed to represent the dynamic behaviour of vegetation. $EPIC\_yield_{HRU,m,s}$ is the productivity data per unit area of a HRU dependent of management and state and is precalculated by the EPIC model. The parameter $RB_{t,HRU}$ represents the total amount of removed biomass (dry-matter), which is gathered from a HRU in year t by applying management m. This removed biomass includes fodder for livestock and firewood for households. The fodder is one of the j constraining factors $b_{t,l,c,j}$ of Eq. 2.3. For every HRU the sum of land use variables has to equal the area of the HRU, i.e. a HRU can be subdivided into a maximum of s times m sub-units. Since HRUs are the smallest spatial units in our LDM, these sub-units cannot be localized spatially.

Planning horizon and recursivity

A dynamic optimization program simultaneously determines the optimal decisions for all considered time steps t (Eq. 2.1). The solution can be interpreted as the optimal trajectory for a decision maker to achieve the highest utility over the entire planning horizon T. When simulating an agroecosystem, one needs to consider that strategic decision-making is normally constrained to a certain finite time horizon. Furthermore, decision-making is influenced at all time steps by updated information. For instance, future weather conditions can only be estimated, while for the current year decisions are based on actual precipitation and temperature. To incorporate this feature into our model, we use a mixed recursive-dynamic specification, similar to that developed by Barbier and Bergeron (2001).

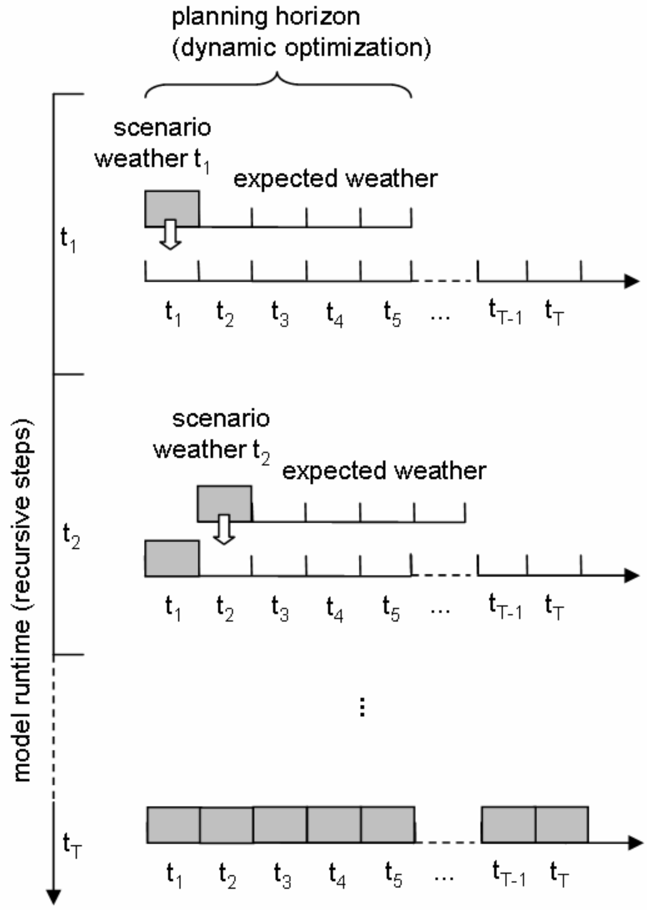

Figure 2.2: Mixed recursive-dynamic LDM with a planning horizon of five years. The indices t_1 to t_T represent individual years of the entire model runtime. Grey boxes represent the results of the first years of dynamic optimization, which are used as initial conditions for the optimization in the next time step and represent the final results of the recursive model.

Figure 2.2 depicts the recursive-dynamic setup, where a forward-looking planning horizon of 5 years is used. As shown in the top part of Figure 2.2, the optimization of the first recursive step t_1 is calculated based on initial data. A weather scenario is prescribed for the first year of the optimization, while some expected weather is used for the remaining years of the planning horizon. After calculating the optimal combination of land use options, the results of the first year of the optimization are recorded. Parts of the results, such as the numbers of livestock (Eq. 2.2) and the values of all land use variables (Eq. 2.5) are used to initiate the model at the next recursive step t_2 (Figure 2.2, middle). Specifically, the combined impacts of each year's management and weather regime is used recursively to update the initial vegetation state and herd size for the following year's planning process. This procedure is repeated for every year of the entire model runtime (Figure 2.2, bottom).

In economic models, discounting future profits expresses the time preferences of decision makers (for example, a sheep now is more valuable than a sheep in ten years). The higher the discounting rate the less future profits or losses are taken into account, i.e. the more myopic the behaviour. In our model, a shortening of the planning horizon to two years results in a less farsighted behaviour of the model, as the state of vegetation in the third year and beyond is no longer accounted for in the model. A longer planning horizon, on the other hand, leads to a more sustainable behaviour, as in this case the model will take more care for the future wellbeing of its resource base. Hence, adjusting the length of the planning horizon in our dynamic-recursive LDM is similar in its effect to the widely applied discounting of profits in dynamic LDMs. Keeping things simple, we do not use an additional discounting of the profits in our optimization procedure, since it is difficult to assess which discounting rate the pastoralists are using within a planning horizon. Instead, the model is calibrated to observed time preferences by manually adjusting the length of the planning horizon (see "Model parameterization and calibration", p. 29).

To prevent unrealistic activity planning in the last year of each optimization, we use terminal values for the livestock. These values represent the benefits of livestock remaining beyond the end of the model's planning horizon. We parameterize terminal values by averaging shadow prices of livestock of a model run with a 20-year planning horizon.

2.2.3 Vegetation dynamics

In representing extensive grazing in semi-arid rangelands, the main dynamic entities in our model are livestock and vegetation. Both are linked and controlled by biophysical constraints and human management. Capturing the dynamics of vegetation and livestock, as well as their interactions under different climate scenarios, is our main interest in developing this model. Hence, the fodder endowment in our LDM is not an exogenous parameter, but instead depends on management and the weather of current and previous years. The variable used as a proxy for the state of vegetation is above ground plant material (AGPM) in tons per hectare. AGPM is an explicit parameter in the EPIC model, is frequently measured in field experiments, and reflects the productivity of pastures under certain weather and management regimes (Navarro *et al.*, 2006; Schlecht *et al.*, 2009; Wiegand *et al.*, 2004). The fraction of AGPM utilized for fodder and firewood corresponds to the removed biomass of pastures. The longer a herd stays in an area and the bigger the herd, the more fodder they consume and the less AGPM they leave at the end of the season. Since productivity of a pasture is correlated to AGPM, the fodder consumption and firewood extraction of one year influences the productivity of the pasture in the following year. Adequate representation of this relationship in LDMs causes a computational problem similar to that described by Schneider (2007) for carbon sequestration. In particular, to maximize the utility from land use decisions over a multi-period planning horizon (Eq. 2.1), the dynamic model has to find the optimal management trajectory with corresponding states of vegetation. For example, if a farmer could choose between 10 alternative grazing intensities in each year, he would face 10 alternatives in year one, 10^2 combinations of current and future land use alternatives over two years, 10^3 over three years, and so forth. It is easy to see how an approach which includes every possible trajectory as an individual choice can become computationally very expensive. For example, suppose a dynamic model depicts six regions, two soil types, two livestock classes, three livestock cohorts, 10 different grazing intensities, and five time periods. The total number of possible decision paths would equal $12 \cdot 60^5$ ($\sim 9 \cdot 10^9$) alternatives. Such a dynamic decision model would require a huge amount of calculations, even though it is not yet that big. In addition, for every possible management decision path, one would have to compute the biophysical impacts upon vegetation with EPIC.

To overcome these computational hurdles, we classify discrete states of vegetation and calculate future states by a given current state and a transition probability between old and new states (Markov process). We assume that this property holds true in our context, i.e. that the impacts of past management and climate are sufficiently contained in the current state of vegetation expressed as AGPM. In this way, we reduce the necessary computational effort by several orders of magnitude. At the same time, we are able to include biophysical simulation results and dynamic properties of EPIC into the augmented LDM. This technique, referred to as "meta-modelling" (Wei *et al.*, 2009), is described in the following section.

EPIC simulations

To address the requirements of a Markov chain formulation of dynamic properties of vegetation, we use a state index *s* for the land use variable $X_{t,HRU,m,s}$ (Eq. 2.5). The state index *s* represents different discrete states of AGPM. The transition probabilities between the individual AGPM states are derived from vegetation development functions calculated beforehand by EPIC. These calculations are carried out for all soil types, weather scenarios, and alternative managements (grazing pattern and intensity). In our case, we start from an existing set of plant parameters in EPIC called "rangeland" developed for semi-arid areas in the United States. The default rangeland parameterization is adapted to observed values in our study region regarding plant growth height, maximum leaf area index (LAI), and the necessary heat units to reach plant maturity. Furthermore, we prescribe soil and terrain properties (slope, altitude) and weather (from meteorological data). The management impact is given as a set of arbitrary variations in grazing intensities and number of grazing days per year, which covers a range of theoretically possible intensities. The EPIC simulations are automatically prepared and executed using a PYTHON-based program. To investigate different weather conditions, we use a precipitation scenario according to the observed average for the period 2002–2008 as a basic scenario, which we will refer to hereafter as "average weather". To investigate droughts and to validate our model with observed data, we use years from the period 2002-2008 which show dryer- or wetter-than-average precipitation.

To establish the vegetation development functions for the computation of state transition probabilities, each EPIC simulation starts with two extreme initial conditions: i) a minimum AGPM value of zero; and ii) a maximum AGPM value, in our case the value after 15 years of zero grazing management. All EPIC simulations span a 15-year horizon under constant management to ensure that the model comes close to a steady state for a certain regime. Since EPIC uses a random daily weather generator, based on the monthly averages for observed meteorological data, we use at least 20 ensemble runs to calculate state transition probabilities. The ensemble runs of EPIC are averaged and standard deviations calculated. Figure 2.3 shows the simulated AGPM values for two different management options under 2002–2008 average precipitation. The observed variability of AGPM is classified into 12 states. For each state, climate and management, parameters such as average value and standard deviation of plant transpiration, surface runoff, and LAI are written to a data file for subsequent usage in the augmented LDM.

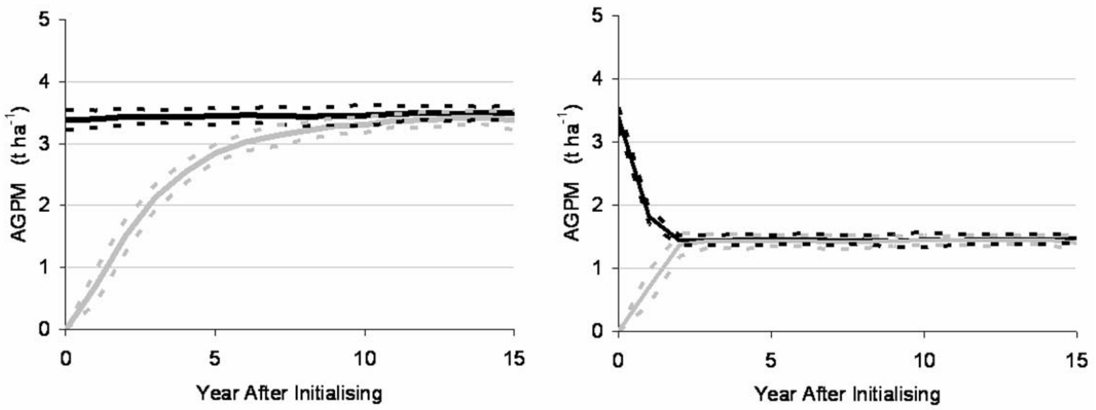

Figure 2.3: Results of the EPIC ensemble runs (n=20) for zero grazing management (left) and medium intensity grazing management (right). *AGPM* is the above ground plant material at the end of the year in t ·ha^{-1}. Black solid lines represent the results of initializing with the maximum *AGPM* values, grey solid lines of initializing with a zero *AGPM*, and dotted lines depict the interval of standard deviation for the correspondingly colored ensemble runs.

State transition probabilities

The vegetation development functions from the EPIC simulations (Figure 2.3) are approximated by polynomial functions between the initial state and the steady state. Beyond the steady state, constant values are used. To transform the polynomial functions into transition probabilities for Markov chains, the parameter space for AGPM is classified into 12 states (the same states as used to record plant transpiration, LAI etc.). The transition probabilities are arranged within a transition probability matrix (TPM), where the initial state corresponds to rows and the subsequent state after one time step to columns (Table 2.1). Such a TPM is established for each HRU, management and weather regime. Each cell contains the probability of a particular transition and lies between 0 and 1. The row sum in the TPM has to equal one since the system is conservative.

Table 2.1: Example of a vegetation state transition probability matrix for a given HRU, management and climate regime (rows: old state, columns: new state).

	State 1	State 2	State 3	…	State 12
State 1	0	0.65	0.35	…	0
State 2	0	0	1	…	0
…	…	…		…	
State 12	0	0	0	…	0

The determination of transition probabilities is illustrated by Figure 2.4 for the case of transitions from state 1 to follow-on states. The black polynomial starting at the origin describes a development function of AGPM (y-axis) for a certain regime as calculated by EPIC. It passes the state boundaries at certain points in time. For both the lower and upper boundary of state 1 (grey and black arrows, left part), we determine the point on the polynomial that is reached after exactly one year (grey and black arrows, right). The probabilities of the transitions are calculated by comparing the share of individual new states to the range covered by all new states together. Thus, for all possible starting points within state 1 (filled square, 100%), the new state after one time step will be within the range depicted by the shaded squares covering a portion of state 2 and state 3. The specific probability of reaching either state 2 or state 3 from state 1 is proportional to the shares of the shaded square that lies below (shaded grey square) or above (shaded black square) the boundary between state 2 and state 3, respectively. In our example, starting from state 1, 65% of the vegetation will be in state 2 after one year and 35% will be in state 3. The result of this calculation is then written into the TPM (Table 2.1). The described procedure is then repeated to calculate the transition probabilities between all 12 states for all HRUs, managements and climate regimes. More details on the numerical computation of the TPM are given in Schneider (2007).

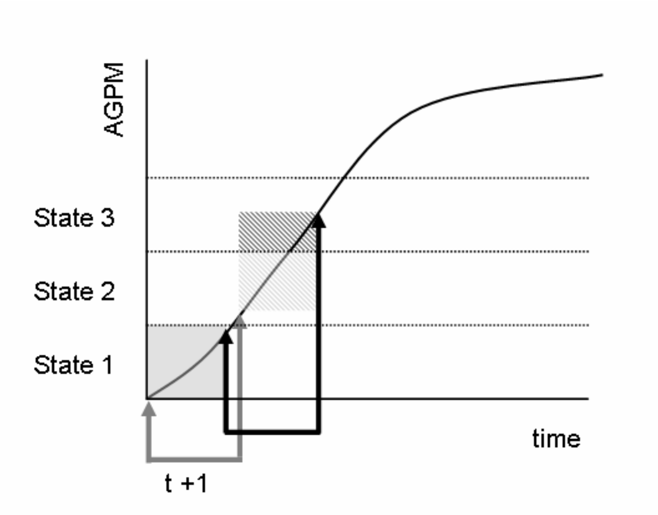

Figure 2.4: Determination of transition probabilities between states of AGPM for a given HRU, management and climate regime. AGPM is displayed against time. Grey arrowed lines measure one time step starting from the lower boundary of vegetation state 1, and black arrowed lines measure one time step starting from the upper boundary of vegetation state 1. Heights of the shaded squares indicate the range of possible vegetation states after one time step.

Integration into the LDM

To include the dynamic interaction between land management and vegetation, the TPM is used in an inter-temporal balancing equation of vegetation states (Eq. 2.6). This equation assures that vegetation states are influenced by past weather and management.

$$\sum_{m} X_{t,HRU,m,s} = \sum_{m,\hat{s}} \left(X_{t-1,HRU,m,\hat{s}} \cdot TPM_{t-1,m,\hat{s}\rightarrow s} \right) \quad \forall \; t, HRU, s \qquad 2.6$$

where $X_{t,HRU,m,s}$ are the land use variables, s is the index for the classified states of vegetation, and m the applied management (grazing intensity and pattern). The index for the states of land use variables in the period $t-1$ is given by $\hat{s}$. $TPM_{t-1,m,\hat{s}\rightarrow s}$ is the TPM, which describes all transitions from old states $\hat{s}$ to new states s given the applied management m. It is time-dependent since it is specific for the weather scenario chosen in each year.

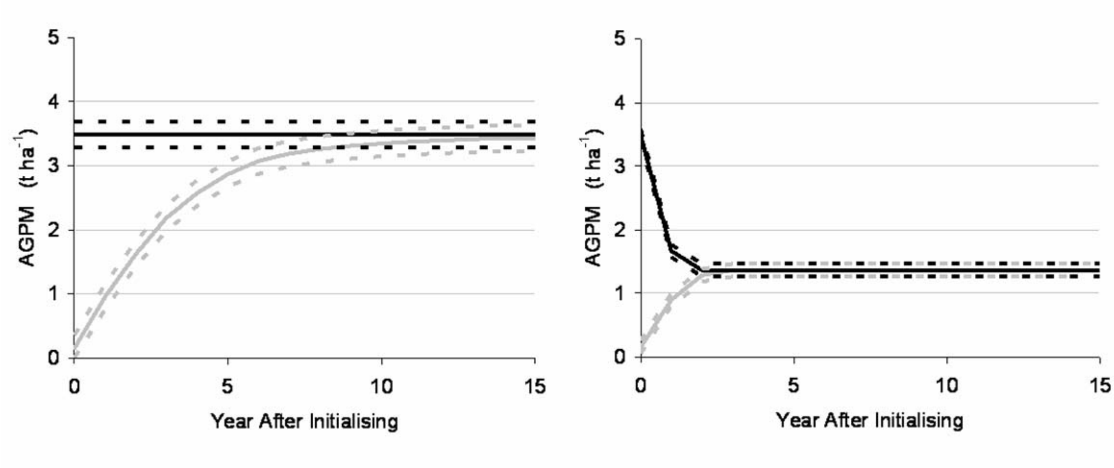

Figure 2.5: AGPM trajectories simulated with our augmented LDM using transition probability matrices. For comparability with EPIC results (Figure 2.3), we forced zero grazing management (left) and medium grazing management (right) over 15 years starting from both minimum and maximum AGPM values. Dotted lines give the 90 percent confidence intervals derived from the EPIC deviations.

By using Eq. 2.6, our augmented LDM is able to approximate the dynamics of vegetation as simulated by the EPIC model, since vegetation is influenced by past management and past weather events. An example is given in Figure 2.5, where we display some AGPM values from our augmented LDM against time. We use the same constant management intensities and weather as for the EPIC example in Figure 2.3. It is immediately evident that the graphs in Figure 2.5 are virtually the same as those in Figure 2.3, which demonstrates the correct implementation of the Markov chain in our augmented LDM. The accuracy of the reproduction of the EPIC results is determined by the number of classes chosen to characterize the state space. The more states chosen, the more accurate the Markov chain representation. By using 12 sates, the correlation with the EPIC output is very high, with $R^2 > 0.99$ (except for the steady state segments, where the correlation is affected more by the chosen class-width).

2.2.4 Model parameterization and calibration

Both the EPIC model and our augmented LDM are parameterized with observed data. Most data were made available by the IMPETUS project (Schulz & Judex, 2008) and the BIOTA Maroc project (Finckh *et al.*, 2007), which were active in the region of our study site in the period 2001–2009. A summary of the data sources for parameterization is provided in Table 2.2.

Table 2.2: Parameters and data sources used for EPIC and the augmented LDM.

Model	Parameters	Source
EPIC	Soil: carbon, texture, bulk density, depth, pH, coarse fragment, $CaCO_3$ content	IMPETUS database (IMPETUS, 2010)
	Elevation, slope	IMPETUS database (IMPETUS, 2010)
	Vegetation: above ground plant material (AGPM), leaf area index (LAI), heat units, growth height, rooting depth	BIOTA-Maroc Database (Finckh *et al.*, 2010) and Baumann (2009)
EPIC/LDM	Meteorological data (monthly averages): Maximum temperature, minimum temperature, precipitation, relative humidity, solar radiation, wind velocity	IMPETUS database (IMPETUS, 2010)
LDM	Livestock: prolificacy, fertility, live weights, energy consumption, energy consumption for pregnancy and lactation, survival rates, survival rates for new born, maximum daily dry-matter consumption	Boudiab (1981), Guessous *et al.* (1989), Hossaini-Hilali and Benlamlih (1995), Hossaini-Hilali and Mouslih (2002), Kamphues *et al.* (2004), Le Houerou (1980)
	Energy content of vegetation	Le Houerou (1980), Heneidy (1996) and Bryl (2009)
	Luzerne production in oasis	Kirscht (2008), El Moudden (2004), Hayek *et al.* (2009)
	Household consumption of firewood	El Moudden (2004)
	Price data for livestock	Own fieldwork, livestock Market at Ait'Toumert, May 2009

The EPIC model is parameterized with observed field data on soil properties, plant growth height, rooting depth, LAI, and the necessary heat units for the plants to reach maturity. Using zero grazing management, the model is calibrated to match the observed value of 3.2 t per ha AGPM in 2008 after eight years of livestock exclosure (Baumann, 2009; pers. comm. Akasbi). For calibrating the EPIC output to the observed AGPM value, we use the plant population density as a tuning parameter (since EPIC does not calculate plant population dynamics). Data for calibration are retrieved from the monitoring database of the BIOTA-Maroc project (BIOTA Maroc, 2011). To calculate the TPMs with EPIC, five HRUs are established for the study site, which are characterized by three slope classes (less than 5%, 5–15%, and more than 15%) and two altitude ranges (less than 2000 m and 2000–2400 m).

Weather scenarios for the augmented LDM are generated from observed daily data of the period 2002–2008. The mean annual precipitation (MAP) of "average weather" is 270 mm. For validation of our model, we calculate TPMs with reduced or increased mean precipitation corresponding to the observed values for the individual years. To address our research questions, we use a 33% reduction of precipitation (which corresponds to 180 mm MAP) for simulating a two-year drought. We prescribe the actual sequence of weather scenarios to be used by our augmented LDM in a separate weather file.

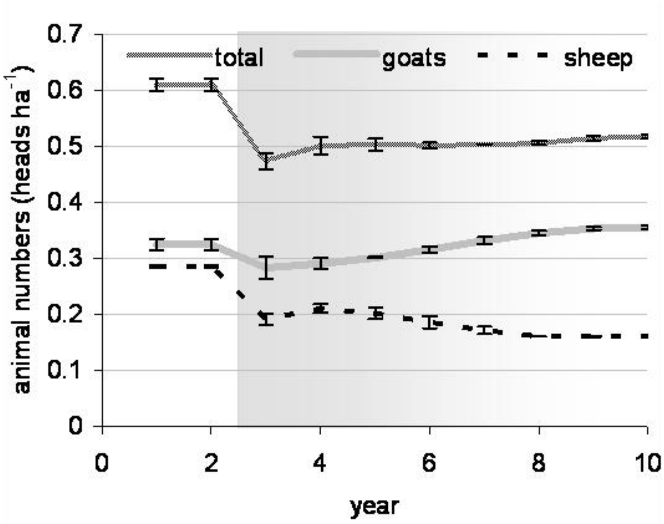

Figure 2.6: Stocking rates (at the beginning of a season) and composition of flocks for average weather with 270 mm precipitation (years 1 and 2) and 180 mm precipitation (later). Error bars indicate 90% confidence intervals over ensemble simulations (n = 6).

The specification of the objective function and the length of the planning horizon are the only tuning parameters outside of EPIC in our augmented LDM, which are used to match observed AGPM results under grazing and flock composition.

The specification of the objective function in the augmented LDM poses a two-fold challenge. First, we need to assume the objective(s) that drive farmers' decisions, i.e. concerning the stocking rates of their animals. Possible preferences may include individual objectives such as the maximization of annual profits or utility from the size of livestock herds, but also their combinations. Second, we need to assume the farmers' planning horizon and expectations about weather conditions for the years ahead. Since we want to model aggregated behaviour of pastoralists, we do not base the decision-making in our model on a survey of individuals, but instead try to calibrate our objective function by hand and compare the output to observed behaviour. The model output, for example concerning the different mixing ratios of sheep and goats in the flocks, is very sensitive to the expected weather in the following year(s). For instance, if a sequence of dry years is always expected, sheep are slowly disappearing. On the other hand, the conditions of the pastures (i.e. AGPM states) are influenced little by flock composition in our model and thus can be interpreted well independently of it. Hence, we chose our utility function and the length of the planning horizon manually in a way to a) fit results of the model to observed values of AGPM for the year 2009 under applied grazing and average weather (2002–2008 average); and b) fit to observed livestock compositions of the flocks as reported in a census (Schulz & Judex, 2008).

Satisfying a) and b), we use a maximization of profits over a five-year horizon as specification of the objective function. Furthermore, within the planning horizon, a "real" weather, as described by the weather file, is taken for the first year of optimization. The same weather is then expected under dynamic optimization for years two and three. For years four and five average weather is expected, i.e. the seven-year average. To show the sensitivity of flock composition in our model to weather shifts, we display the reaction of animal numbers *Nb* to a shift from average weather to a scenario of 33% less precipitation (Figure 2.6). The shift to a dryer weather regime (from year 3 on) leads to lower stocking rates and the composition of the flock changes towards more goats. This agrees well with observations from dryer areas adjacent to our study site (Heidecke & Roth, 2008).

However, to match observations, we had to introduce two further constraints in our model. First, as fuel for cooking and heating is collected by the people of Taoujgalt from the surrounding pastures, we introduce an additional demand for biomass (taken from low quality fodder). This demand is parameterized based on household data and the average origin of firewood (El Moudden, 2004). Second, following empirical evidence by Le Houerou (1980), our model does not permit sheep production on a pure browse diet because the energy content of fodder plants is insufficient, especially for the high energy demand of gestation and lactation. Therefore, to match observations, we introduce the possibility of using Lucerne produced in the oasis as additional fodder. This modification makes it possible for the model to simulate lamb production. The parameterization for the production of Lucerne is taken from the average crop mix in the region (Kirscht, 2008) and the cultivated area in the oasis. Price data for our augmented LDM were gathered from informal interviews performed in May 2009 at the livestock market in Ait'Toumert, which is the closest market to our study site. Average local prices for one-year-old sheep and goats in good years are 60 € and 40 € per head, respectively. During droughts, prices are on average 50% lower than during good years.

2.2.5 Validation of the model

The LDM is validated against a time series of observed AGPM data from the study site. Figure 2.7 shows the precipitation values for every year in the period 2002–2009, data which are used as an external weather scenario file for our augmented LDM. Figure 2.8 shows the results of our model for AGPM with zero grazing management and measured values of AGPM from the BIOTA project at fenced sites, which excluded grazing. Figure 2.9 compares results from our augmented LDM with grazing management and corresponding values from the BIOTA database, which were measured outside the fence.

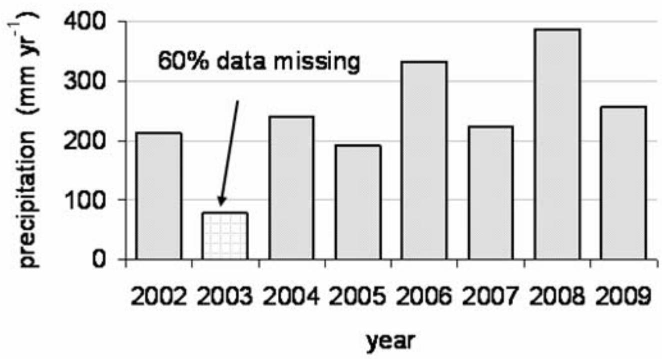

Figure 2.7: Measured precipitation at the study site, used as an external weather file in the augmented LDM.

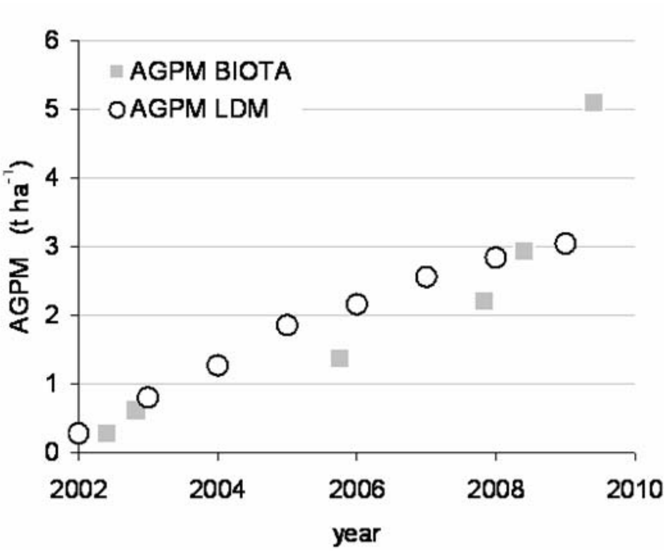

Figure 2.8: AGPM under zero grazing management. Comparison of observed (BIOTA) and modeled values (LDM).

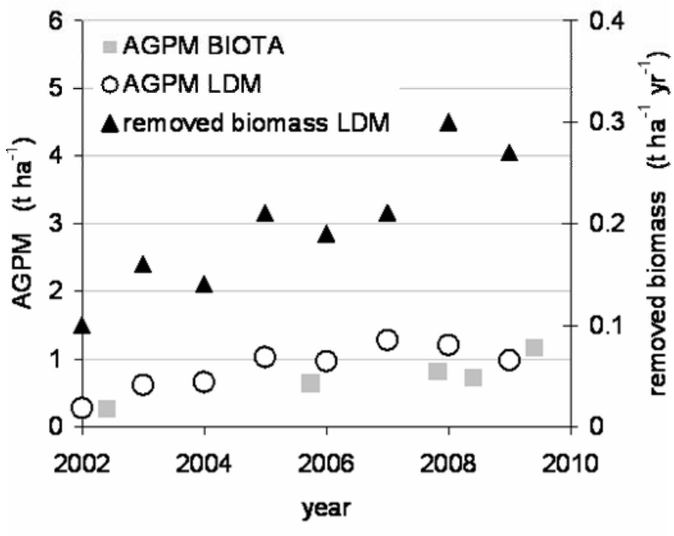

Figure 2.9: AGPM with grazing. Comparison of observed (BIOTA) and modeled values (LDM). The amount of removed biomass as calculated by the LDM is given on a secondary x-axis (to the right).

As seen in Figure 2.8 and Figure 2.9, our model fits relatively well to the observed values of AGPM. However, the model performs better at sites with grazing than at sites without grazing; in particular, the most recent value of AGPM under zero grazing (summer 2009) deviates notably from modelled results. This might be due to the fact that plant population dynamics are not included. As data from the BIOTA Maroc project reveal, the relatively wet winter of 2008/2009 has led to a 12% increase in plants per square meter. EPIC and the meta-model of it are not capable of simulating plant population dynamics automatically, which is a clear limitation of the model. However, we achieve a relatively good fit from our model for the remaining years and especially under grazed conditions. Furthermore, the quite low AGPM values under grazing for 2006 and 2008 indicate, both for the model and for the observations, a delayed impact of the low precipitation years 2005 and 2007. This reflects the appropriateness of including vegetation dynamics into our augmented LDM.

The simulated results for stocking rates from our augmented LDM can be compared to empirical livestock data. A census conducted in early summer of 2009 revealed a stocking rate of 0.5 heads per hectare in the area around Taoujgalt, which is close to the lower boundary of our estimates (0.6–0.96). Since there was no evidence of institutional regulation of animal numbers, the deviation may be due to the fact that only herds from the village were included and counted. However, mobile (transhumant) pastoralists pass the region several times a year and substantially increase stocking rates during these times. A regional agricultural census for the investigated area revealed a huge variation of between 1 and 60 heads per hectare (Heidecke & Roth, 2008). As our simulations show, the upper section of this range may not be realistic.

2.3 Simulation Results

To investigate the effects of drought in the agroecosystem of interest, we simulate two years with 33% less precipitation. The overall time horizon is ten years, with years 4 and 5 experiencing the drought. The remainder years are simulated with average weather. We use an ensemble of six model runs to separate the effects of droughts from the effects of the model's initial state. The 90% confidence intervals of the individual runs are shown by error bars in Figure 2.10 to Figure 2.12.

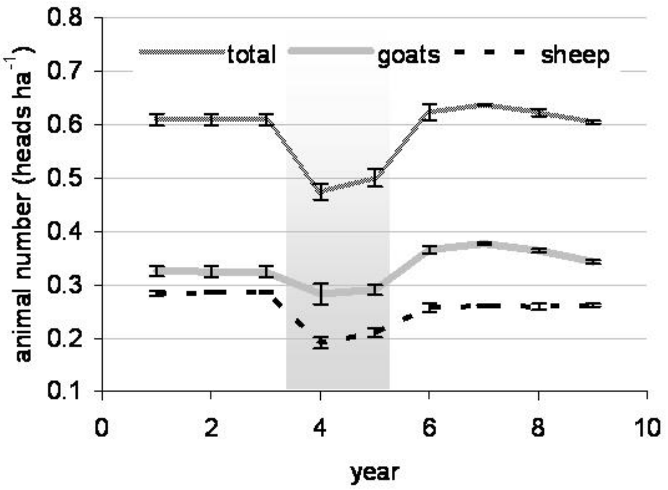

Figure 2.10: Stocking rates as given by our augmented LDM. Drought is simulated in years 4 and 5. Error bars indicate 90% confidence intervals over the ensemble simulations (n = 6).

The augmented LDM simulations show with average weather conditions an optimal stocking rate of 0.6 (± 0.01) animals per hectare at the beginning, and 0.96 (± 0.01) at the end of a grazing season. The stocking rates for the beginning of a season are displayed in Figure 2.10. The resulting AGPM under average weather is on average 0.60 (± 0.04) t ha^{-1} (Figure 2.11). Total biomass consumption of grazing livestock averages 0.42 (± 0.02) t ha^{-1} yr^{-1} DM (Figure 2.11). At the beginning of the drought in year 4, stocking rates are reduced by 20% (Figure 2.10). During the first year of the drought, the model projects more animal sales than usual because the drought is expected to last longer than one year. However, because prices decrease by about

50% in years with low precipitation, the profit from sold livestock drops by 25% (Figure 2.12).

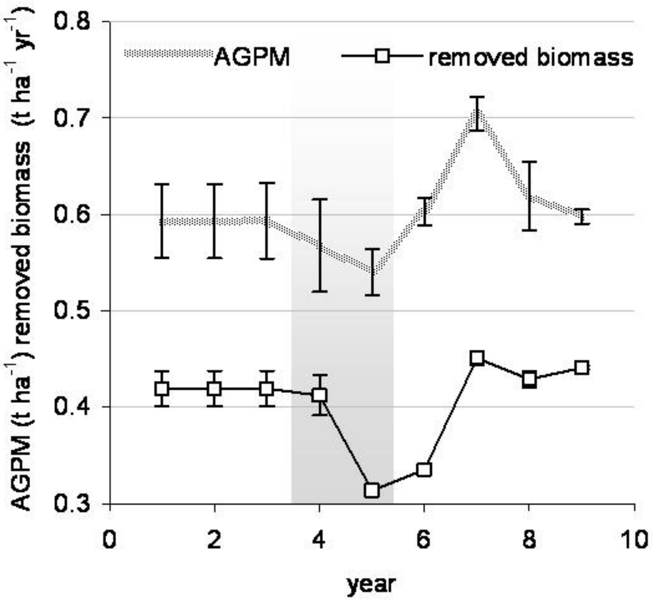

Figure 2.11: AGPM and removed biomass as given by our augmented LDM. Drought is simulated in years 4 and 5. Error bars indicate 90% confidence intervals over the ensemble simulations (n = 6).

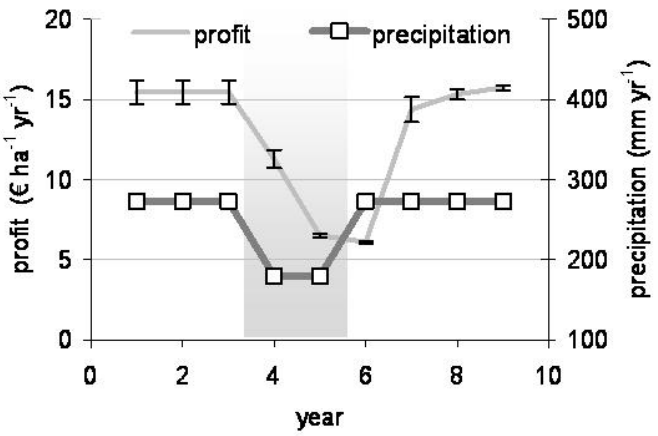

Figure 2.12: Relationship between precipitation and income as calculated by our augmented LDM. Drought is simulated in years 4 and 5. Error bars indicate 90% confidence intervals over ensemble simulations (n = 6).

In the second year of the drought, the profits decrease further to 43% of normal values (Figure 2.12). This is due to low prices in the second year of the drought and a low potential for removing biomass from pastures, which reaches a minimum of about 0.3 tones per hectare and year (Figure 2.11). The simulation of reduced precipitation leads to economic and ecological impacts, which go substantially beyond the meteorological time horizon of the drought. For instance, even though precipitation is back to normal levels and animal prices are high in year 6, removed biomass of the pasture and profits remain at low levels (Figure 2.11 and Figure 2.12).

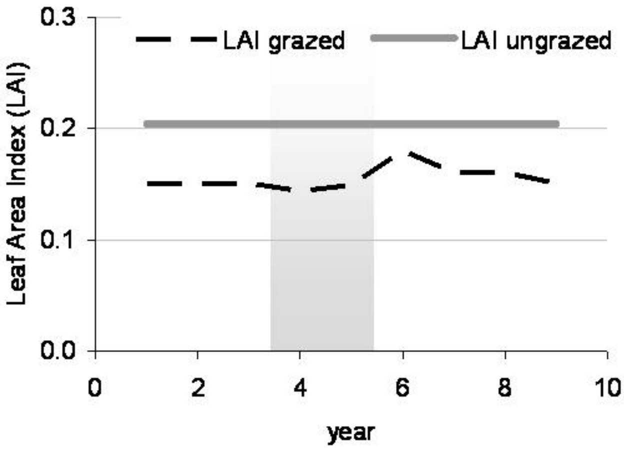

Figure 2.13: Leaf area index under the assumption of a two-year drought (years 4 and 5) with grazing (dashed, black line) and without (grey, solid). The six ensemble simulations do not show deviations in this parameter.

The model results also indicate that continued grazing in areas affected by a drought may lead to substantial variation in LAI over the years (Figure 2.13). Since LAI is an important factor for local climatic processes, this implies the existence of dynamic interactions between human management, droughts, and radiative properties of the steppes.

The pastures studied in our research are situated within the catchment of the oasis of Taoujgalt. Therefore, it is of interest how hydrological properties of the landscape are affected by human management under given weather scenarios. As we are unable to calibrate our model output with observed data, we instead refer to relative differences in our results (Figure 2.14 - Figure 2.16). Evapotranspiration (ETP; Figure 2.14) is almost unaffected by grazing in our augmented LDM. The model indicates very high rates of evaporation, and therefore the effect of grazing on plant transpiration is of less significance to changes in total ETP. However, under average weather conditions, groundwater recharge of grazed pastures is 20% higher than the recharge of abandoned pastures (Figure 2.15). During a drought, the simulated infiltration with grazing is still higher than without. The most pronounced effect of human management is shown by our model as being surface runoff. This parameter doubles relative to fully developed vegetation if grazing is applied (Figure 2.16). During drought, surface runoff is heavily reduced, with the influence of human management further enhancing the decrease. It can be seen from Figure 2.14 to Figure 2.16 that human management is in general less important to hydrological properties of the landscape than precipitation. However, human management is important for infiltration and surface runoff, which further influences the availability of irrigation water in the oasis.

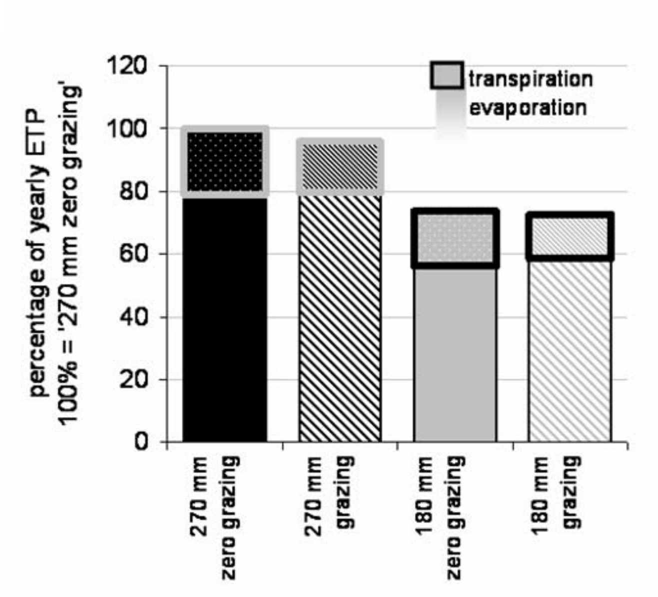

Figure 2.14: Simulated total annual ETP as the sum of plant transpiration (framed, upper part) and evaporation (lower part of bar). Average weather (270 mm annual precipitation) and 33% reduction of precipitation are investigated (180 mm).

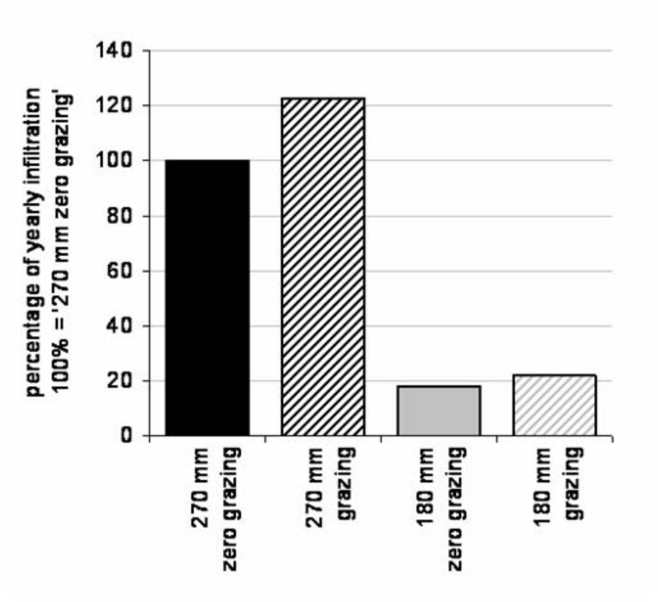

Figure 2.15: Simulated total annual groundwater recharge (infiltration). Average weather (270 mm annual precipitation) and 33% reduction of precipitation are investigated (180 mm).

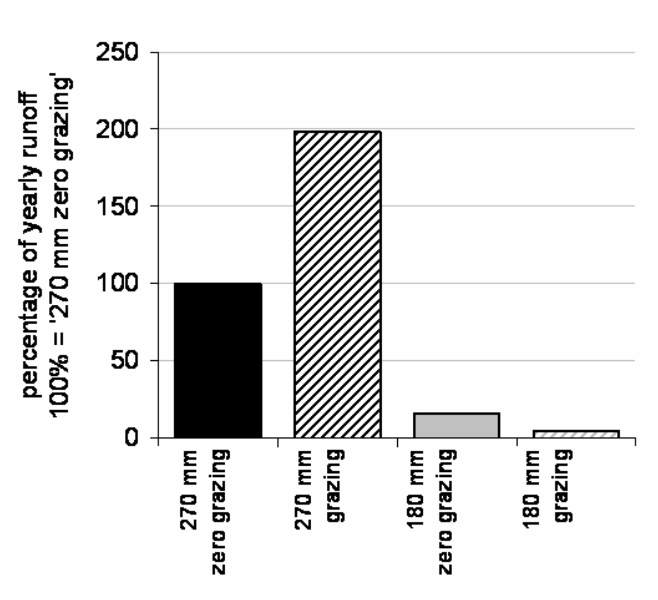

Figure 2.16: Simulated total annual surface runoff. Average weather (270 mm annual precipitation) and 33% reduction of precipitation are investigated (180 mm).

2.4 Discussion

The Markov-chain-based integration of EPIC into an economic LDM has succeeded in providing a more accurate picture of the complex land use system dynamics than the two modelling components alone. However, the reduction of EPIC to a single-state-variable-based Markov chain is not cost-free. We assume that the entire land management history of a certain site is fully captured by the value of a single state variable, namely AGPM. In reality, the grazing and precipitation history affects many other factors, including species composition, plant morphology, plant population density, and soil structure. The impact on these other factors is not considered explicitly in our augmented LDM, and thus biases our results. To overcome this deficiency, one could introduce more state variables at the expense of increased computation and calibration requirements. Furthermore, we assume that transitions do not occur between different vegetation types, and we justify that by the observation that pastoral agro-ecosystems, especially in the Mediterranean, are characterized by a long and continuous grazing history. Therefore, transitions between different vegetation types are limited (Diaz *et al.*, 2007; Navarro *et al.*, 2006). For this reason, we use only a single state variable and calibrate the model against measured AGPM data. This represents a compromise between simplicity of the model and accuracy of the model output, as given in Figure 2.7 to Figure 2.9.

The major advantage of our augmented LDM is the joint representation of farsighted decision-making and vegetation dynamics, even though both components are simplified. The combined modelling of human decision-making and environmental processes leads to new insights. For instance, in a transdisciplinary study for southern Morocco, de Jong *et al.* (2008) demonstrated a conceptual model of the importance of human land use management for evaluating the impact of climate change. In their study, the authors exogenously prescribed land use management. Our augmented LDM provides quantitative results on human impacts on hydrological parameters under altered climate, while using land use management as an internal variable. Thus, using Markov-chain-based replications of biophysical models within economic models increases the explanatory power of such models. Due to non-exponential computational requirements over explicit time periods, the method can be used for regional models (see chapter 5).

The results from applying our augmented LDM to investigate a Moroccan agroecosystem demonstrate clearly the importance of dynamic vegetation for evaluating the socio-economic effects of droughts with mathematical models. As a comparison between Figure 2.10 and Figure 2.11 shows, the stocking rates of goats and sheep themselves are not sufficient to explain the drought-induced changes in AGPM values. Hence, the interplay between stocking rates and dynamic vegetation must be responsible for the observation of longer-lasting effects of a drought on parameters such as profit and AGPM (Figure 2.12 and Figure 2.11).

Concerning the social effects of droughts, a close look at the results of our augmented LDM demonstrates the problem of increasing long-term social inequality, i.e. making poorer farmers poorer and richer farmers richer. Since we use only one aggregated agent for the entire village of Taoujgalt, the model has the option to suspend livestock selling in the year after the drought (Figure 2.12) to restock the pastures and apply optimal management. However, disaggregating the model to a higher resolution of agents would make it possible to include poor and rich farmers, i.e. farmers with few animals and farmers with lots of animals. At a certain threshold of animal numbers, poorer farmers would be forced to sell a substantial part of their herd after the drought to sustain their livelihoods. In this way, their future profits would be reduced due to delayed restocking. Wealthier farmers, on the other hand, might take advantage of this situation, since restocking after droughts for them is facilitated because of proportionally lower subsistence needs. After collective destocking during droughts, rangeland vegetation reaches high values of AGPM when precipitation returns to average levels (see Figure 2.11). Richer farmer are then in a better position to take advantage of that "fodder peak". Hence, the dynamics displayed by our model demonstrate the polarizing effect of droughts (Zimmermann & Carter, 2003).

A more detailed representation of farmers in our augmented LDM could make it additionally possible to better investigate the social impacts of droughts in semi-arid areas. Instead of calculating the loss of GDP, a further developed LDM could in this way assess the risk of impoverishment of rural people. Furthermore, land use policy options can be investigated, which reduce the risk of emerging social inequality due to repeated occurrence of droughts.

Surface water runoff and groundwater recharge in our augmented LDM are influenced by land use decisions in ways that fit with experimental studies (Le Maitre *et al.*, 2007; e.g. Murphy *et al.*, 2004). In our model, during normal years, livestock husbandry increases water availability for downstream oasis agriculture. This might be an important influence of landscape management on irrigation agriculture: the observation of relatively high grazing pressure around oases could be attributed to the evolutionary success of coupling high intensity grazing with concentrated irrigation agriculture. Therefore, an agricultural decision model for such regions should depict this relationship. Similarly, climate-relevant parameters such as LAI are influenced by human management (25% less under grazing management in our model), which certainly has implications for regional climate and predictions of it.

2.5 Conclusion

The methodology presented in this paper allows a computationally feasible integration of a complex biophysical model into an economic LDM. The dynamic interactions between land management and vegetation in semi-arid areas can be more accurately depicted. The Markov-chain-based approximation of the biophysical impacts reduces drastically the computational requirements compared to a direct coupling with explicit land use management trajectories. By using separate Markov chains for different weather scenarios, locations, and management regimes, we are able to investigate the economic and environmental effects of a drought, including the likely adaptation of management.

Our simulations show that a 33% decrease in precipitation reduces profits from pastoralism by up to 57%, although losses in the first year can be kept at relatively low levels. Through the inclusion of a dynamic vegetation module, the relationship between precipitation and profits in our model becomes history-dependent, i.e. the impact of reduced precipitation on profits depends on the grazing management of previous years. Furthermore, our model results indicate that, for the studied agroecosystem, human land use increases surface runoff and infiltration to the groundwater relative to undisturbed conditions, but decreases LAI. This shows the importance of including physical relationships into socio-economic models, or vice-versa, including human management adaptation into biophysical models. The exclusion or exogenous specification of land use management can bias the results and conclusions of agroecological and climate models. The insights from our interdisciplinary modelling approach emphasize the need for ecological long-term monitoring campaigns to be able to parameterize and validate bio-economic land use models.

Acknowledgements

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Chapter 3

Assessing the predictability of future livelihood strategies of transhumant pastoralists [7]

This study assesses the predictability of future livelihood strategies of transhumant pastoralists in semi-arid Morocco. A decrease in precipitation due to climate change will likely threaten their traditional livelihood strategy. We examine whether the pastoralists explicitly prefer certain alternative strategies or if their reactions will be contingent. Our analysis uses standardised interviews focussing on two aspects: Firstly, which resources are necessary for the pastoralists to be able to choose a livelihood strategy? Secondly, to what degree are expectations of wellbeing satisfied by alternative strategies? To assign levels of predictability to all investigated strategies, we analyze the interviews using simple methods of partial order theory. We find that under perceived precipitation scarcity, 38% of pastoralists would explicitly opt for sedentarity and localized pastoralism as alternative strategy. Unclear preferences are given for 25% of the cases. Considering a policy scenario of enhanced access to education and capital, our analysis indicates commercial pastoralism as dominant alternative. However, such a scenario would increase the share of unclear preferences to 43%, which increases the likelihood of a contingent development. The method we propose can be considered as a mathematical basis for the concept of historical contingency.

[7] A similar version of this chapter is going to be published as: Freier KP, Brüggemann R, Scheffran J, Finckh M, Schneider UA: Climate change and predictability of future behaviour of transhumant pastoralists in semi-arid Morocco. *Technological Forecasting and Social Change* DOI: 10.1016/j.techfore.2011.07.003
More than 90% of the work of this chapter has been done by Korbinian P Freier.

3.1 Introduction

In our study we assess the predictability of future livelihood strategies of transhumant pastoralists in semi-arid Morocco. The region of interest is likely to experience considerable alterations in precipitation during the 21st century (Born *et al.*, 2008a), leading to modifications of livelihood strategies and agricultural techniques. The extent to which livelihood strategies will be modified is unclear, since socio-ecological systems are traditionally considered as very difficult to predict. Reasons for poor predictability are a high complexity of internal structures and involvement of partly unpredictable human agency (e.g. Berkes, 1999; Crane, 2010).

Given these constraints on predictability, social sciences mostly investigate socio-ecological systems from a historical perspective. Random events, which strongly impact the subsequent development of these systems, are considered as so-called historical contingencies which lead to path-dependence (Bennett & Elman, 2006; Beyer, 2010; Goldstone, 1998; Mahoney, 2000). Historical contingencies are seen as an irreducible gap in the causal narrative (Bennett & Elman, 2006) and therefore principally prevent valid predictions about socio-ecological systems.

In contrast to social sciences, physical sciences are very much oriented towards giving predictions. If natural processes are sufficiently understood, limits to predictions within physical models arise mainly from deficiencies in measurement accuracy. For example, chaotic systems can be regarded to a certain extent as unpredictable, since infinitesimal deviations in initial conditions can completely alter future states. In such systems, accuracy of predictions decreases towards a certain time-horizon. After that time-horizon an exact calculation of future states is unfeasible (Lorenz, 1963). Lack of predictability also relates to concepts of inherent randomness (Regan *et al.*, 2002) or deep uncertainty (Walker *et al.*, 2010), where predictability is restricted because the system is irreducible to a deterministic one. Despite these principal limits, physical assessments of socio-ecological systems aim at giving valid predictions to enable rational decision making by actors within the system or by agents which control boundary conditions. However, it is disputable whether or to which degree socio-ecological systems can be described by contemporary physical concepts (Hauhs & Lange, 2008; Rosen, 1991).

Considering these different perspectives of social and physical sciences, an integrated assessment of socio-ecological systems holds considerable challenges for the scientific community. For instance, decision making within such systems, which has relied too much on physically motivated predictions, often has failed due to excessive confidence in such predictions (Scott, 1998). On the other hand, using only a historical perspective for planning is not able to include new social and environmental situations such as technological advances and climate change. Planning and rational decision making is therefore mainly constrained to adaptive methods which are designed to be able to include unforeseen elements during the run of their implementation (Walker *et al.*, 2010). However, adaptation of societies to altered environmental conditions may require early investments. For the planning and realization of these investments, decision makers benefit from knowing the degree to which a specific socio-ecological system can be considered as predictable and how the predictability changes in response to technological and environmental developments.

Here, we present and apply a mathematically formalized way of investigating the predictability of future livelihood options of a pastoral society in southern Morocco. We assume that contingency mainly arises from the pastoralists' decisions. For instance, facing decreasing precipitation, pastoralists will behave more predictable if they have clear preferences about alternative agricultural techniques and alternative livelihood strategies. To assess the level of predictability of the pastoralists' decisions, we use standardized interviews based on a multi-criteria ranking to analyze the background of relevant preferences of the pastoralists. Predictable parts of expected behaviour will than be separated from unpredictable ones by using simple methods of partial order theory.

3.2 Methods

3.2.1 Study region and research questions

Fieldwork for our study was performed in summer 2009 in the upper Drâa catchment in the High Atlas Mountains of southern Morocco (Ouarzazate Province). Being part of the Moroccan "migration belt", 65% of households in the Drâa valley depend on remittances from migrants (Rössler *et al.*, 2010b). The region is characterized by a semi-arid to arid climate (Schulz & Judex, 2008). Traditional agricultural techniques allow coping with low average values of precipitation together with a high variability, by using a mixed system of irrigation agriculture and transhumant livestock grazing (Barrow & Hicham, 2000). Transhumant pastoralism mitigates variability in rainfall by seasonal mobility of herds on collective rangelands. The access to collective lands (*agdal*) used by tribal and intertribal groups as well as the opening and closing dates of pastures are fixed by the pastoralists at a local level (Rössler *et al.*, 2010a). After new livelihood options became available, 42% of households using formerly transhumant pastoralism have changed within the last decades towards the usage of sedentary flocks combined with the use of additional fodder from non-rangeland sources (Breuer, 2007b; Davis, 2006; Rachik, 2007). Within families, parts of the remittances from migrants are used to "subsidize" pastoral activities (Rössler *et al.*, 2010b).

Regional climate projections for the Drâa catchment differ greatly and indicate large uncertainty in the direction and magnitude of precipitation change (Born *et al.*, 2008a; Huebener & Kerschgens, 2007; Sillmann & Roeckner, 2008). Those discrepancies lead to different projections of the regional risks of climate change in the region (Scheffran, 2009; Schilling *et al.*, 2011). Dryer conditions in the future, however, are a highly probable scenario and might substantially affect livelihood options within the socio-ecological system.

Hence, the research questions we are interested in our case study are:

What alternative livelihood strategies are probable to be chosen by the pastoralists provided that scarcity of precipitation makes it impossible to pursue the current strategy of transhumant pastoralism?

Is it possible to assign a certain probability to these alternative livelihood strategies or is contingency realistic?

Do the outcome and its predictability depend on the availability of other resources besides precipitation?

Table 3.1: Strategies considered in the survey

Strategy	Short name
Traditional transhumance	TRAD
Sedentarity and localized pastoralism	SED
Commercialize pastoralism	COMM
Local engagement in tourism	TOUR
Working in urban centres (within Morocco)	CITIES
Working abroad	ABROAD

3.2.2 Interviews

In our study region we interviewed 25 transhumant pastoralists in Berber language (*tajlheit*) by using interpreters. Interviews were based on a formalized questionnaire (see Appendix 1, p. 135). Language skills and interview expertise of the interpreters made it possible to bridge the intercultural gap, concerning, for instance, problems like the meaning of "happiness".

Our interview partners belonged to tribal fractions of the Ait Toumert, Ait Zekri, Ait M'rauwn and Ait M'goun, who occupy comparable stripwise north-south oriented territories down from high mountain zones into the southern forelands. The main purpose of the interviews was to assess the resource requirements and expectations of the local land users associated with six alternative strategies. The considered strategies are based on Breuer (2007a) and are given with abbreviations in Table 3.1.

Traditional transhumance (TRAD) is the livelihood strategy which all of our interview partners pursued at the time of the interview. To distinguish TRAD from other techniques of pastoralism we introduced the strategies "sedentarity and localized pastoralism" (SED) and "commercial pastoralism" (COMM).

As Rachik (2007) shows, SED appeared as an alternative livelihood strategy for transhumant pastoralists after the droughts in the 1970s. At that time, the government introduced forage supplements which enabled new options beyond TRAD.

A more recent development is the emergence of COMM as pastoral livelihood strategy in the region: It describes the use of additional fodder sources, for instance through financial help of migrants or by selling animals of large herds in a non-subsistence way. Furthermore, the financial resources created by COMM make it feasible for the herders to use trucks during times of fodder scarcity to displace the flock to remote areas (Breuer, 2007a).

The local engagement in tourism (TOUR) is a non-pastoral livelihood strategy which is getting more and more relevant in the region. Furthermore, migration is an important alternative livelihood strategy (Rössler *et al.*, 2010b), both nationally to urban centres (CITIES) and internationally, mostly to Europe (ABROAD).

In the interviews, the transhumant pastoralists were asked to establish a ranking of these strategies concerning their demand for resources and their potential for satisfying certain personal expectations of wellbeing such as prestige, happiness and income. A summary of the resource and expectation categories is shown in Table 3.2. The ranking of strategies was established through sequential comparison. For example, the interview partners were asked which strategy they think of being most dependent on sufficient precipitation. When they answered for example TRAD, the following question was "which strategy requires less precipitation than TRAD?" and so on. It was possible for the interview partner to mention that several strategies do not significantly differ in their dependency on certain resources. The same scheme was applied to the expectations.

The quality of the interviews was mainly influenced in two ways: Firstly, we used five interviews to experiment and to ensure that our interview partners adequately understood our questions. Therefore, the first five interviews are of lower value than the latter ones. Secondly, the quality was influenced by the pastoralists' time and willingness to finish the interviews. At the end, among the 25 interviews performed, we consider 16 suitable for further evaluation (see Appendix 2, p. 136).

Table 3.2: Types of resources and expectations considered

Resources	Description
Precipitation	Dependency of the strategy on rainfall
Capital	Capital needed for investments (at the beginning or during the course of the strategy)
Experience	Non-educational knowledge needed to perform this strategy
Education	Educational level (school) needed to perform this strategy
Expectations	
Prestige	Social position associated with the strategy
Income	Monetary income from this livelihood strategy
Happiness	Would you feel happy with using this strategy, regardless of income and prestige?

3.2.3 Rationale of evaluation

The method we use in this study does explicitly include the possibility of contingent decision making which enables us to identify indicators for non-deterministic behaviour. The distinctive element in this approach is that we use the concept of incomparability, which is a typical methodological element in partial order theory (e.g. Bruggemann & Patil, 2010).

To clarify our rationale, we start with a small example. Suppose we have two techniques or strategies *A* and *B*. As a result of an interview, both strategies are assigned rank scores for a set of two attributes *r1* and *r2* and are written as *A*[1,0] and *B*[0,1]. This notation means that strategy *A* is higher ranked concerning attribute *r1* but strategy *B* is higher ranked by attribute *r2*. We do not use a weighting factor for the individual attributes to create a definite overall ranking, which would imply a subjective intervention by the analyst. Instead, we keep this incomparability and create a partial order with respect to the different attributes.

Now, let us assume a third strategy *C* exists. As result of the interview, we have *C*[2,2]. This means, C is ranked higher than *A* and *B* for both attributes and thus, can be definitely ranked higher than both. Figure 3.1 displays the partial order established from *A*, *B* and *C* graphically using the Hasse diagram technique (HDT, see Bruggemann *et al.*, 2001; Bruggemann & Voigt, 2008).

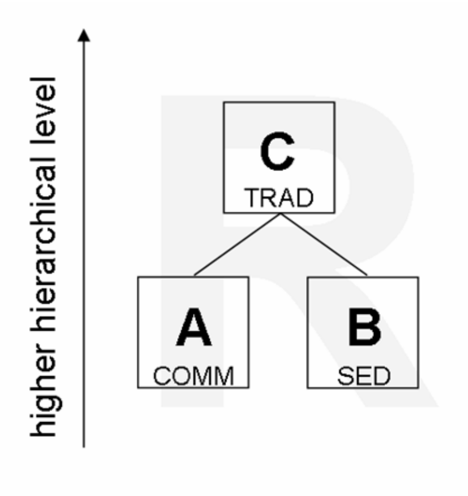

Figure 3.1: Partial order for ranking strategies *A*, *B*, and *C* with respect to resource attributes *r1* and *r2* (Resources-Partial Order: R-PO)

We want to combine two aspects in our investigation: On the one hand, we postulate that the strategies chosen by the land users are dependent on the availability of resources. This availability can be interpreted as a necessary condition: Only if fulfilled, the strategy can be chosen at all. On the other hand, the available strategies are linked to certain subjective expectations of the transhumant pastoralists. For instance, a strategy which is feasible but not at all appreciated will only be chosen if there are no preferred alternatives available. Thus, as observed, expectations and norms dominate decisions on several alternative livelihood strategies (e.g. Crane, 2010; Nielsen & Reenberg, 2010; Wilk, 2006).

To address the two described factors of resources and expectations in our analysis, we separate partial orders of resources (R-PO) from partial orders of expectations (E-PO). This is done for every single interview.

We can now investigate what will happen if resource availability for a land user changes. To illustrate this, let us consider the small example from above. Assume strategies *A*, *B*, and *C* are the pastoral strategies COMM, SED, and TRAD, respectively. To pursue the strategies, the attributes *r1* (experience) and *r2* (precipitation) are necessary resources. Figure 3.1 displays the resource necessities by ordering *A*, *B* and *C* concerning to their attributes *r1* and *r2*. Clearly, TRAD needs the most resources, SED and COMM are incomparable.

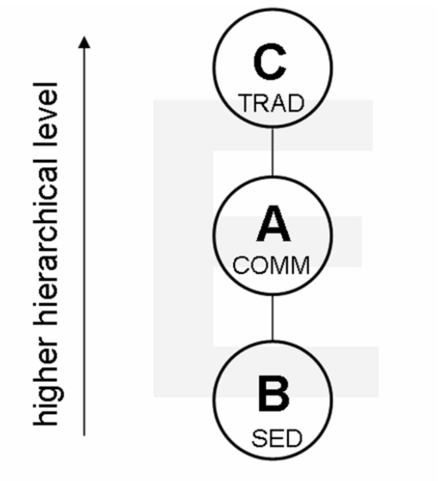

Figure 3.2: Partial order for ranking strategies *A*, *B* and *C* with respect to expectation attributes *e1* and *e2* (Expectations-Partial Order: E-PO)

Let us now assume two attributes for expectations (*e1* and *e2*) which represent income and prestige. Suppose an expectation ranking of TRAD[1,1], COMM[1,0] and SED[0,0]. That means both income and prestige are expected by the interviewed person to be lowest by pursuing SED. Let us further assume that there is no clear utility weighting between income and prestige and that the interviewed person is currently engaged in TRAD. Figure 3.2 shows that TRAD is preferred with regard to all expectations.

Let us now consider a situation where the amount of precipitation is decreased. The resulting amount of precipitation should be at least infinitesimally lower than the requirement of TRAD but higher than that for COMM and SED. By this way of reduction, we do not assume a certain threshold of reduction in rainfall. Instead, we investigate on a semi-quantitative basis what happens if a transhumant pastoralist will experience a reduction in rainfall which forces him to abandon the traditional livelihood strategy. What will be the most probable reaction of our interviewed person under this setting?

From the individual values for *r1* and *r2* in the R-PO we can conclude that both strategies COMM and SED are feasible alternatives. COMM and SED are therefore called real successors of TRAD because their critical attribute *r2* (dependency on precipitation) is really smaller than that attribute for TRAD. All other attributes are equal or less. Next, we combine the outcome of the R-PO evaluation with the partial order of the expectations by assuming a priority of the latter (for a full mathematical analysis of combining partially ordered sets, see Rademaker *et al.*, 2008). Looking at the E-PO (Figure 3.2), we find COMM preferred over SED. So the definite outcome of this situation will be that the interviewed person shifts to strategy COMM. We call such a situation deterministic because there is no alternative visible.

However, under a different structure of E-POs different outcomes are possible. Figure 3.3 illustrates two alternative E-POs. The left structure represents a case where options *A* and *B* are equivalent concerning their attributes *e1* and *e2*, i.e. both attributes show the same level. Another situation is shown on the right structure of Figure 3.3: *A* and *B* are incomparable, because one expectation attribute of *A* is higher, one is less than the attribute of *B*. We term both situations as non-deterministic because no clear preference can be given.

In standard rational decision making, non-deterministic situations are often resolved by introducing attribute weights and then forming an overall utility value which creates a definite ranking. However, creating such a ranking often reduces the objectivity of the result, especially for situations where it is hard to define an empirical weighting system. In our methodology, we avoid weighting and carry incomparability and equivalency throughout the evaluation. Even more: By explicitly considering the possibility of choice, we allow our investigated actors to entail historical contingencies. A non-deterministic situation, indicated by incomparability or equivalency in expectations, may therefore be regarded as a condensation nucleus for historical contingency. We consider this formal description of historical contingency from an *ex ante* perspective as the essential innovative element of our methodology.

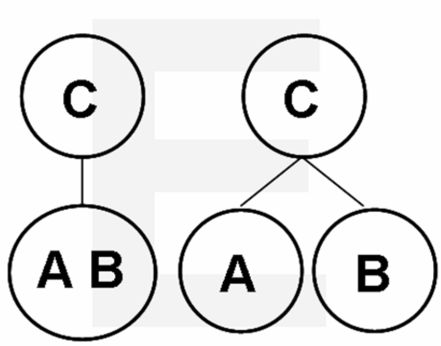

Figure 3.3: Partial order of alternative expectations for *A* and *B* equivalent (left), and for *A* and *B* incomparable (right) concerning attributes *e1* and *e2*

The above example describes the general algorithm we use to evaluate interviews of *N* Moroccan pastoralists. For the E-PO, we include the concept of non-determinism and determinism. Incomparabilities in the R-PO are not relevant for the classification of results because expectation is dominant: For instance, if there are two strategies incomparable concerning their resources, this poses no problem if one of them is preferred in E-PO. Only, if they are incomparable in the E-PO as well, they are treated as non-deterministic.

The only special case we have to consider is that there are no successors in E-PO at all, because either possible alternatives do not exist or we did not ask for them. Since our interviews do not reveal any information about possible missing strategies, we decided to count interviews without alternative options separately (addressed as "no alternative" in the final statistics).

After employing the above-described method, we obtain one of four possible outcomes for each individual interview:

a) no alternative strategy (no real successor in the R-PO) or

b) one or more real successor strategies concerning the R-PO with

b1) definite ranking in the E- PO

b2) equivalent ranking in the E- PO

b3) incomparable ranking in the E- PO

Both options, b2) and b3) are regarded as non-deterministic because the agents of the system show no clear preference concerning alternative strategies.

The frequency of the considered strategies as outcome of the evaluations is counted and the occurrence relative to the number of interviews computed. Finally, for definite results, in Equation (3.1) we calculate the Shannon index (SH, Shannon, 1948) to describe the distribution of outcomes.

$$SH = -\sum_i p_i \cdot \log_2 p_i \qquad with \quad p_i = \frac{n_i}{N} \tag{3.1}$$

where p_i is the relative frequency of strategy *i* within *N* interviews (n_i is the absolute occurrence). The *SH* is commonly used to characterize diversity of data and the Evenness of the Shannon index is the *SH* normalized by its possible maximum ($\log_2[N]$). The minimum evenness value of 0 indicates that only one strategy occurs in the results, whereas the maximum evenness value of 1 indicates an equal distribution of preferred strategies.

3.2.4 Algorithm and application to our interviews

The procedure of our algorithm can be summarized as follows:

1. There are *r* attributes of resources, *e* attributes of expectations and *i* strategies (see Table 3.1 and Table 3.2)
2. Choose a strategy i_x (the strategy, which is performed at the moment)
3. Choose a resource attribute r_x of i_x, which will change in an evaluation scenario. Because i_x is currently used, r_x must be available in sufficient quantities for i_x. For instance, r_x may be the estimated amount of precipitation per year. In the scenarios, r_x decreases to levels insufficient to carry out i_x.
4. Select one of the *N* interviews
5. Use the R-PO to find all strategies *SR*, which are real successors for i_x concerning the change in r_x. Because the new level of r_x is too low for i_x, the remaining strategies must rely less on r_x. All other attributes of remaining strategies are equal or less.
6. Find the preferred strategy of *SR* in the E-PO. If *SR* is empty, terminate evaluation of the interview.
7. Repeat step 4 to 6 for all *N* interviews and apply Equ. (3.1) for definite outcomes.
8. If desired, increase the availability of one resource (e.g. capital) in the currently performed strategy such that other real successors than in the base scenario become feasible. Repeat step 1 to 7

To clarify this algorithm, we now describe in detail the evaluation of one individual interview of our survey. This example corresponds to the R-PO and E-PO in Figure 3.4, where squares vertically represent the level of the considered resource and expectation attributes. The higher an "attribute tower", the higher a strategy is ranked by this attribute. TRAD is considered as currently pursued strategy, denoted as i_x in the algorithm above. Precipitation p is considered as attribute r_x from the algorithm above (grey squares in Figure 3.4).

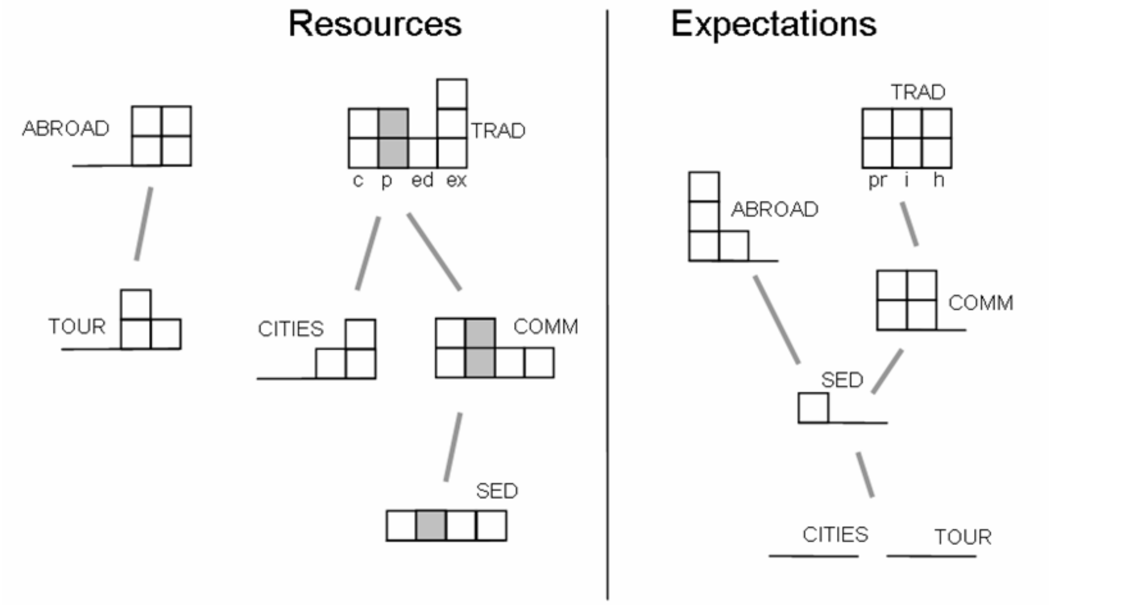

Figure 3.4: Resource-Partial Order (left) and Expectations-Partial Order (right) created from one of our interviews. Upper case terms denote livelihood strategies as given in Table 3.1. The squares vertically represent the attributes of resources and expectations indicated by lower case letters. Resources: c = capital; p = precipitation; ed = education; ex = experience; Expectations: pr = prestige; i = income; h = happiness (Table 3.2)

To investigate the reactions to reduced average rainfall, precipitation in our analysis is semi-quantitatively reduced to such an extent that TRAD becomes unfeasible for the transhumant pastoralist. As mentioned, the term “semi-quantitatively” indicates that we do not quantify a specific threshold in millimetres of rainfall. We only examine, what will happen if the pastoralist gives up TRAD due to a subjectively perceived scarcity of precipitation. Looking at the R-PO (Figure 3.4, left), we find that SED and CITIES are real successors of TRAD under less precipitation, since the grey "tower" is smaller for SED and not existent at all for CITIES. COMM is not feasible because it requires the same ordinal level of precipitation as TRAD does and therefore it is not a real successor in this specific case. The evaluation of the interview additionally shows that ABROAD and TOUR would require a higher level of education from the interviewed person than currently available. Taking this result to the E-PO (Figure 3.4, right), we find that SED is preferred, because it satisfies a higher level of prestige than CITIES. Hence, we have a definite outcome (SED), which is added to the final statistics of deterministic outcomes.

A non-deterministic outcome of our evaluation would have been achieved if both TOUR and CITIES would have been real successors to TRAD because these two strategies are equivalent in the E-PO. Such a result would have been added to the final statistics of equivalent outcomes.

For the scenario of less precipitation, one might also investigate, what would happen if the availability of several other resources is increased. For example, if the current level of available education (ed) would be increased by one unit (figuratively increasing the "tower" of this attribute in the currently pursued strategy TRAD), the real successors for TRAD would be SED, CITIES, ABROAD and TOUR (R-PO in Figure 3.4). Taking this result to the dominating E-PO, one would find the strategy ABROAD as unique definite outcome, because it is ranked higher than all other real successors.

3.3 Results

In our evaluation, we examine all 16 interviews on the impact of less precipitation (base scenario). To investigate possible policy options, we additionally examine the same precipitation scenario together with an experimentally higher availability of education and capital.

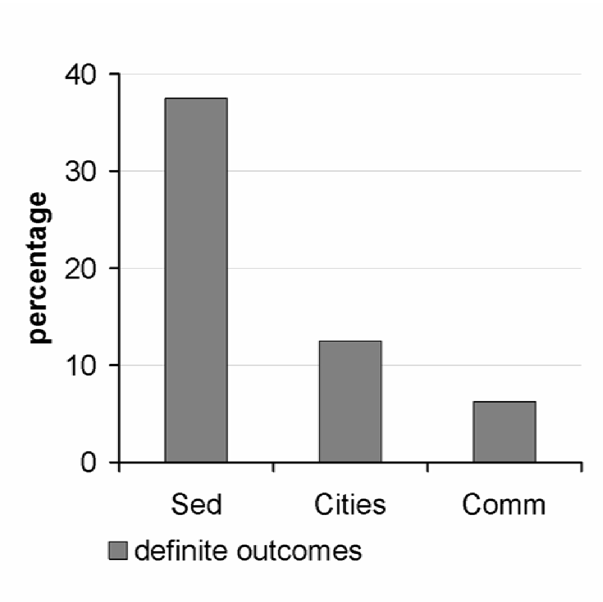

Figure 3.5: Occurrence of successor strategies as definite outcome. The availability of water was reduced to an extent that traditional transhumance is no longer feasible. Evenness = 0.39

3.3.1 Decreased precipitation

Decreasing the amount of precipitation yields a 38% probability in our model that a transhumant pastoralist will definitely adopt SED as new livelihood strategy (Figure 3.5). Together, for 56% of our investigated interviews we are able to assign definite outcomes. Other definite outcomes include CITIES with a probability of 13% and COMM with a probability of 6%.

A considerable proportion of the interviews (25%) did not lead to a definite successor livelihood strategy (Figure 3.6). In these interviews, pastoralists turned out to be undecided or indifferent between SED, COMM, CITIES, TOUR and ABROAD. If these pastoralists were forced to abandon traditional transhumance, we would not be able to assign a probability for them choosing a certain successor strategy. We conclude from this that the real outcome for them under reduced precipitation is non-deterministic.

The evenness of the Shannon index in Figure 3.6 equals 0.39 and implies that SED is a clearly dominating successor strategy for the projected development. For 19% of our interviews our method can not find any feasible alternative livelihood strategy.

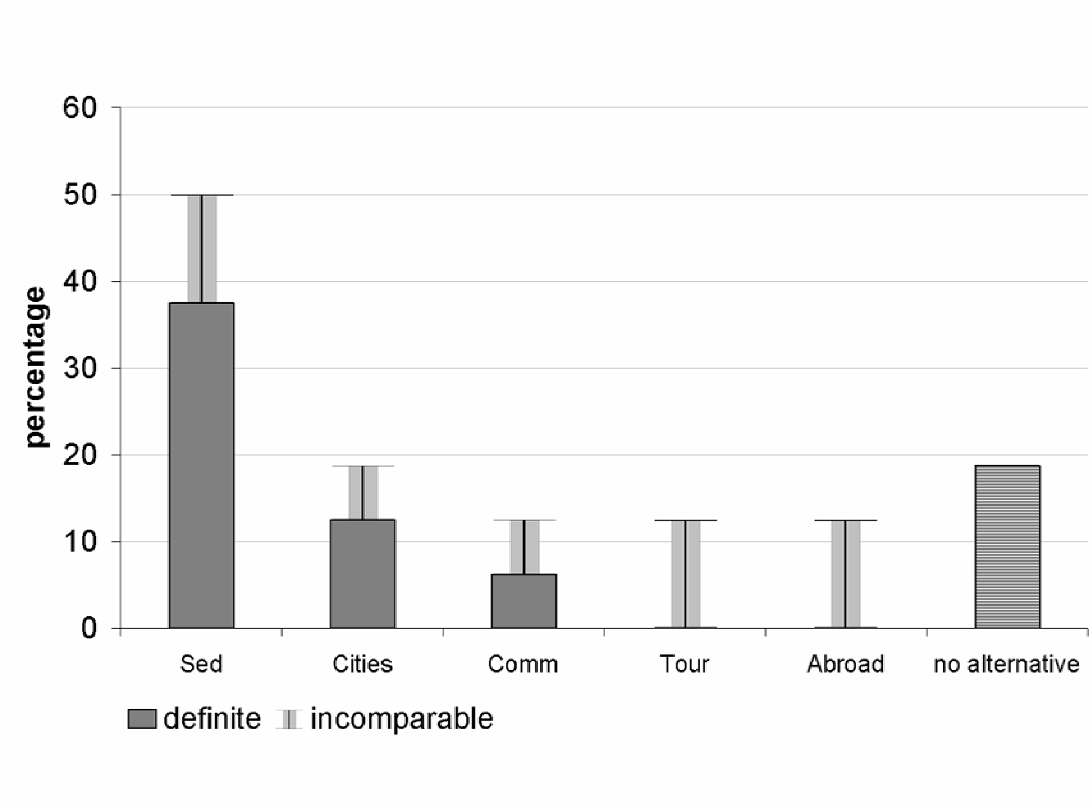

Figure 3.6: Abundance of alternative livelihood strategies for the case of ***reduced precipitation*** (n = 16). 25% of the interviews have non-deterministic outcomes

3.3.2 Enhanced capital and education

In addition to the base scenario of reduced precipitation, we investigate the impacts of enhanced endowments of key resources such as the level of education and the availability of investment capital (for instance small loans or remittances). The effects of an enhanced availability of these resources are quite pronounced.

The effect of an increased availability of capital is shown in Figure 3.7. Under this assumption, the probability of adopting COMM as successor strategy increases from 6% in the base scenario to 25%. The probability of choosing SED decreases from 38% to 25%. Furthermore, the level of non-deterministic results increases to 31% and is 6% higher than in the base scenario. However, in contrast to the base scenario, there is only one pastoralist, who does not see a feasible successor strategy at all under the considered circumstances.

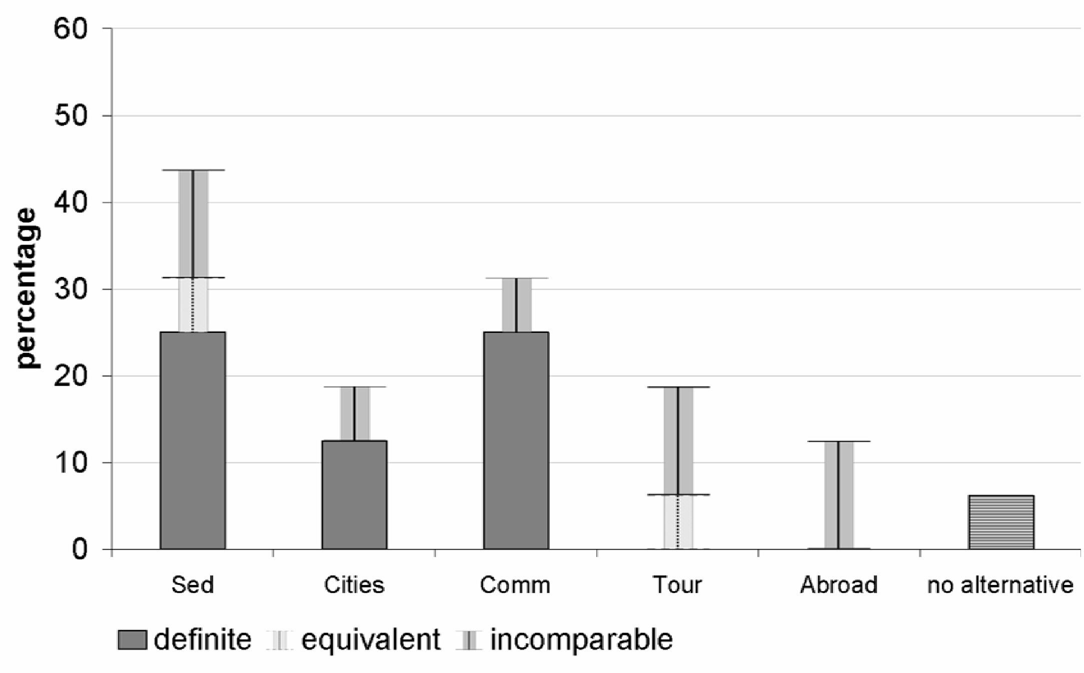

Figure 3.7: Abundance of alternative livelihood strategies for ***higher availability of capital*** and reduced precipitation (n = 16). 31% of the interviews show non-deterministic outcomes. Evenness = 0.45

Figure 3.8 shows the results for the combination of reduced precipitation and a higher level of education. In this scenario setup, only CITIES, COMM, and ABROAD are within the set of definite strategies with a combined probability of

25%. The majority of results (56%) have non-deterministic outcomes where probabilities cannot be assigned. As in the base scenario, for 19% of the transhumant pastoralists an alternative livelihood cannot be found at all.

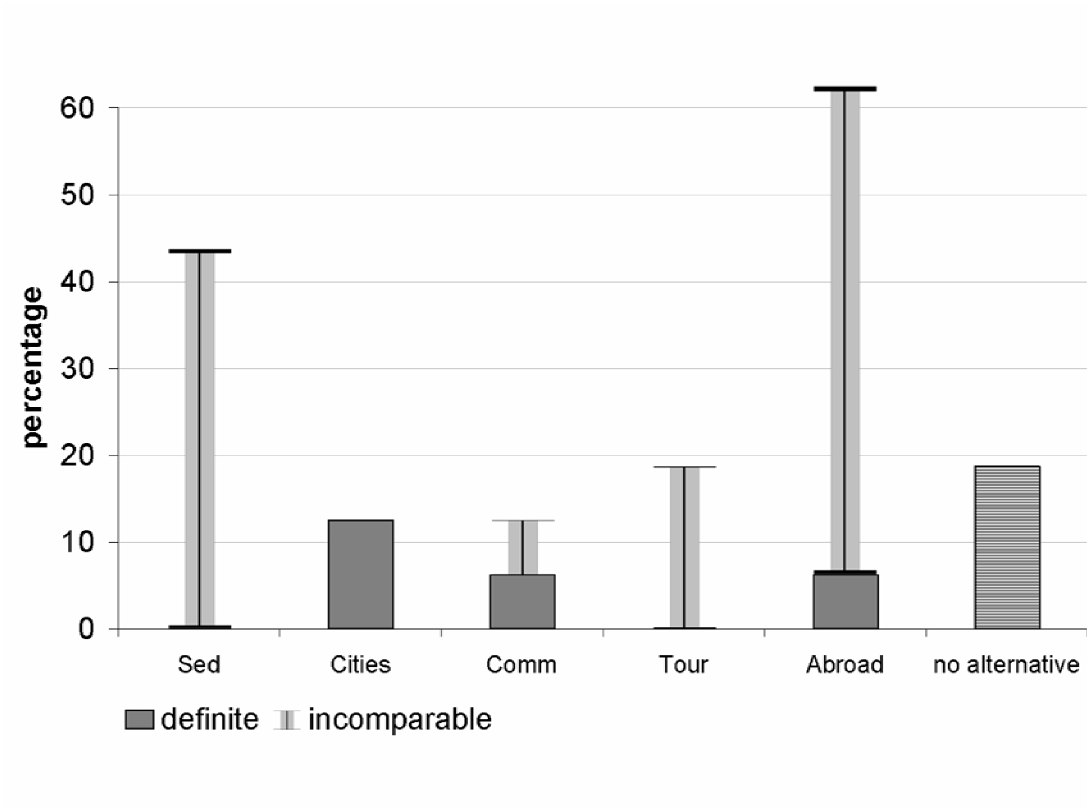

Figure 3.8: Abundance of alternative livelihood strategies for a ***higher level of education*** and reduced precipitation (n = 16). 56 % of the interviews have non-deterministic results. Evenness = 0.75

Finally, we analyze reduced precipitation together with increases in both, education and availability of capital. Results are shown in Figure 3.9. Obviously, the values in Figure 3.9 are not just a simple linear combination of the previous results. The availability of both resources makes it now feasible that four livelihood strategies are considered as definite alternative strategies. The resulting diversity (Evenness = 0.58) is higher than for all previous scenarios. Under the combined setup, only 6% of the interviewed pastoralists would choose SED as alternative. This value for SED is in clear contrast to 37% in the base scenario (Figure 3.6) and 28% in the increased capital scenario (Figure 3.7). Similarly as in the increased capital scenario, 25% of answers indicate commercial pastoralism as definite successor strategy. Still, 43% of outcomes are unpredictable. Only for one interview we can not find a feasible successor livelihood strategy.

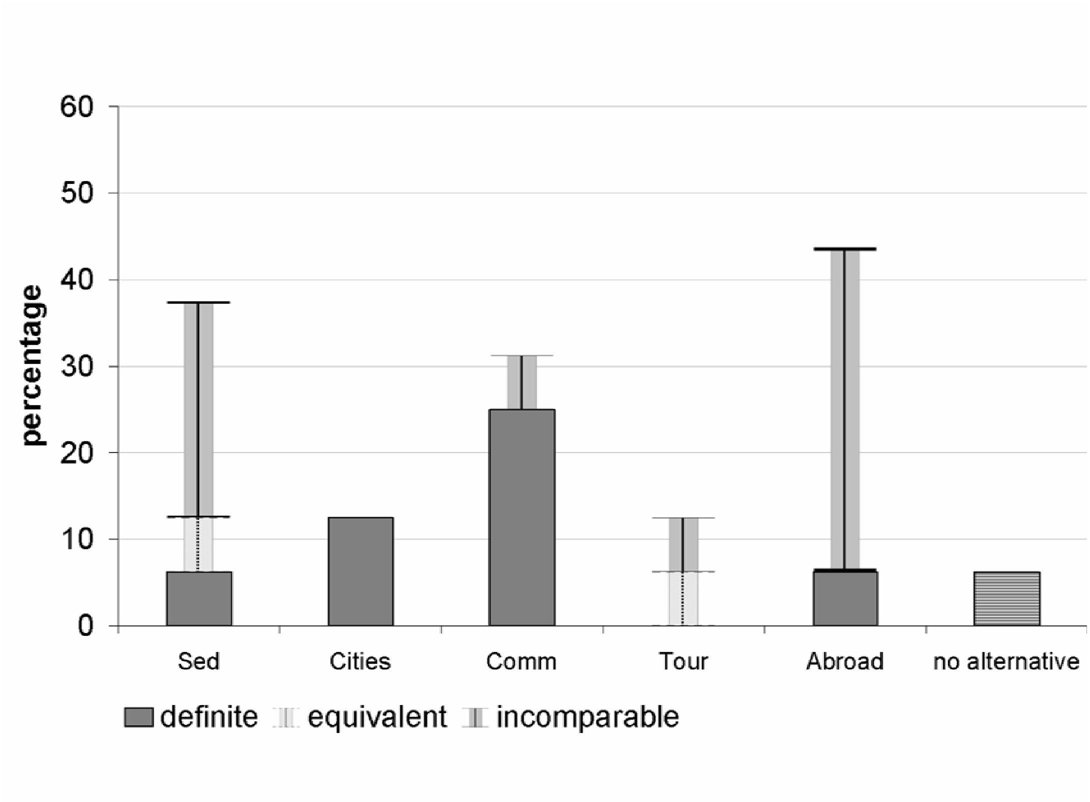

Figure 3.9: Abundance of alternative livelihood strategies for ***higher availability of education and capital,*** and reduced precipitation (n = 16). 43 % of the interviews have non-deterministic results. Evenness = 0.58

3.4 Discussion

3.4.1 Methodology

The presented analysis may be scrutinized in a fourfold manner: Firstly, one might ask what is new and cannot or has not been examined with existing methods? Secondly, are there explicit or implicit assumptions hidden behind the method? Thirdly, how to validate the model? Fourthly, are there non-trivial insights generated through the results?

Concerning the first point, the novel aspect of our method is to distinguish between predictable and unpredictable outcomes in mathematical formal terms and describing possible points of contingency *ex ante*. Therewith, we bridge concepts of natural and social sciences. We believe that existing multi-criteria analyses (MCA) mostly aim at a final, objectively clear ranking (e.g. Brans & Vincke, 1985; Geldermann & Rentz, 2001; Koo & O'Connell, 2006; Strassert & Prato, 2002) but do not distinguish between deterministic and non-deterministic structures. Instead of describing a ranking of different options like other MCA's do, we elaborate a statement about future decision pathways. Within the same setup, we investigate possibilities of altering the outcome of the analysis and the level of predictability by altered resource endowments. Thus, our analysis based on simple elements of the theory of partially ordered sets aims much more at system properties than traditional MCA. In contrast to a survey, where the alternatives used under certain conditions are directly solicited, our model leaves the option of later choices and allows to investigate easily which attributes play an important role in determining (or un-determining) the outcome.

Concerning the second question of hidden assumptions, firstly, we suppose that there are no trade-offs possible between the chosen attributes like precipitation and capital. Nonetheless, we tried to capture only those attributes of resources and expectations, which are not easily replaced by one another. For example, a sedentary farmer could "replace" water by capital by installing a motorized water pump. For a nomadic pastoralist moving through vast areas, this is not suitable. We tried to capture possible trade-offs as discrete strategies. For instance, the case of trading livestock for additional fodder to a higher degree than usual is addressed in COMM.

As second assumption, we consider the interviewed pastoralists to have a profound knowledge about their current livelihood strategy as well as their alternatives, which might be imperfect. Our model may therefore only reveal the land users opinions and hopes. However, studies on human decision making (Klein, 1999; Wilk, 2006) and studies of observed choices of adaptation strategies from other pastoralist societies (Crane, 2010; Nielsen & Reenberg, 2010; Pedersen & Benjaminsen, 2008) suggest that subjective opinions often affect real decisions more than scientifically measured parameters.

Studies from social psychology and environmental sciences suggest further that expectations and perceptions of human beings may significantly change over time (Pinnegar & Engelhard, 2008; Welzer, 2009). The insights provided by our study are therefore primarily based on present conditions and perceptions and can only be considered as a snapshot of the actual situation. Possible dynamic feedbacks, for instance via impacts of successor strategies on land scarcity are, if at all, only included implicitly. If at some point pastoralists would change their livelihood strategy, their perceptions and expectations for this livelihood strategy will change, since a pursued livelihood is positively biased against alternatives due to psychologically motivated self-affirmation (Steele, 1988). Hence, our E-PO describes only the current situation and should be used only for assessing the very next step of the development of the socio-ecological system.

Besides these two major assumptions, the robustness of our study is limited by the small number of considered interviews. However, a statistical re-sampling analysis (Cirincione & Gurrieri, 1997) shows that a maximum error in our results of 15 to 20% is possible but only in the case of really extreme bimodal distributions of preferred strategies by the population. In realistic cases the error of our analysis should be much lower since we interviewed a quite homogenous population.

Concerning the third question, the validation of our model poses a difficult task. Our analysis is locally and temporally very specific - the answers of transhumant pastoralists would have been different 30 years ago and are likely different in other regions. Thus, our model can be validated on its own by observing the future development of livelihood strategies of transhumant pastoralists in the Drâa basin while simultaneously observing changes in precipitation regimes.

Comparing our model to similar studies which use different methods is another option for validation (Stirling, 2006): It has been shown that beginning from the droughts in the 70's, SED became the dominant livelihood strategy for transhumant pastoralists (Breuer, 2007b; Davis, 2006). Our results are therefore confirmed from a different perspective, although these studies take up a historical perspective and our study is directed towards future developments.

Another point on validation concerns the treatment of non-deterministic results. Popper shows that the falsification of our definite results is possible in principle if a sufficiently large number of transhumant pastoralists is considered (Popper, 1959). The model would be falsified, for example, if in the near future a substantial number of nomads would abandon their traditional livelihood and nobody would turn to SED but all would leave the country (ABROAD; see Figure 3.6). However, falsification becomes more difficult when we include the non-deterministic results. Our non-deterministic results are not entirely what Popper called chance, which he defined as "our knowledge does not suffice for prediction" (Popper, 1959, p. 69). Instead, it can be seen in a Bayesian perspective as a degree of plausibility of expected outcomes (Jaynes, 2003) or an indicator of deep uncertainty (Walker *et al.*, 2010).

For example, in the base scenario, we find a range of 12.5% of non-deterministic results concerning SED for all nomads abandoning their traditional livelihood. The non-deterministic results can be added to the deterministic ones and therefore, the overall frequency of SED as outcome covers a range from 37.5% to 50% (see Figure 3.6 and Table 3.3). Since we are able to put a number on that possible deviation, we are convinced it represents a useful non-trivial insight.

Table 3.3: Frequency of SED as preferred successor strategy for different scenarios

Scenario	definite abundance	maximum abundance (definite + non-deterministic results)
base scenario	38 %	50 %
access to capital	25 %	48 %
access to education	0 %	44 %
capital + education	6 %	38 %

3.4.2 Insights and applications

While unpredictabilities remain, at least 38% of the interviewed nomads would definitely opt for SED if precipitation decreases below the minimum threshold for traditional transhumance. This result may also reflect the development of different attitudes towards sedentarity on the part of nomads within the past 40 years (Rachik, 2007). However, SED is not necessarily a secure alternative since an increasing number of sedentary people in the Drâa region increases pressure on available arable land and ground water resources (Kirscht, 2008). Therefore, the real and perceived benefits of SED are likely to decrease.

If social planners would like to avoid a development which favours mainly SED, our model results can help to identify possible policy interventions: Considering the definite outcomes, a better access to education substantially decreases SED as preferred livelihood successor strategy (Table 3.3). However, a considerable degree of uncertainty is associated with that outcome. In an extreme case, non-deterministic outcomes for this scenario could turn into reality such that overall 44% of the transhumant pastoralists finally opt for SED. By considering that implication, our model shows that the scenario with a higher access to capital and education at the same time might be a more secure option. In this 'capital and education' scenario, only 38% would opt for SED as alternative in the most extreme case (non-deterministic and definite outcomes added) and only 6% would opt for it definitely. Additionally, four out of five livelihood options in this scenario would be definitely chosen by some pastoralists indicating a more diverse set of possible strategies (Figure 3.9).

Since our model only uses ordinal ranking, we cannot estimate how much capital should be invested in education to stimulate this development. However, we can say that if access to education and capital at the same time is increased relative to the current level, the socio-ecological system will move away from SED as a dominant alternative strategy.

Our method can be applied primarily to investigate social and socio-ecological systems, where human decisions represent a major influencing factor for future pathways. In many cases, it is highly uncertain which technological options or alternative livelihoods will be chosen by human actors under altered conditions. It has been shown repeatedly that human expectations and values heavily influence pathways of socio-ecological systems, even if the same environmental boundary conditions are considered (Crane, 2010; Nielsen & Reenberg, 2010; Thornton *et al.*, 2007; Wilk, 2006). Human behaviour therefore is often perceived as unpredictable and many development projects have failed due to overestimating predictable capacities of scientific analyses (Pedersen & Benjaminsen, 2008; Scott, 1998). Our method, which needs only a little bit more effort like a conventional survey, offers an adequate measure for better assessing predictability of human decisions beforehand.

3.5 Conclusions

We present a novel method to assess the predictability of future decision pathways of socio-ecological systems in a mathematically formalized way. For the application to semi-arid Morocco, we use 16 interviews of transhumant pastoralists. Due to the relatively small number of interviews, the explanatory power of our results might be limited. However, we can show that there are livelihood strategies which are definitely preferred over others by the pastoralists and that many pastoralists are undecided between possible alternatives. This indicates a relevant possibility of a contingent development in our investigated socio-ecological system for the case that precipitation will force the pastoralists giving up their traditional livelihood strategy.

In our analysis, we use the concept of historical contingency in a new manner for determining whether a future development of a system is to a certain degree predictable or not. We assume that unclear preferences with respect to possible alternatives in a decision situation are responsible for unpredictable human behaviour. Since humans are the key agents in most socio-ecological systems, we relate the predictability of the system to the predictability of human decision making. Using standardized interviews, in combination with simple elements of partial order theory, we show how clear preferences of our key agents can be separated from unclear ones. This allows us to deduce levels of predictability for a hypothesized future decision situation. Hence, our study shows how the important concept of contingency can be given a solid mathematical basis.

Acknowledgements

We want to thank all of our interview partners whose open-hearted hospitality we greatly appreciated. Second, we would like to thank the interpreters Redouane Ouhmouch and Abdelaziz Labdi for their professional work. We thank four anonymous reviewers, Jochem Marotzke, Dallas Murphy, and several students of the IMPRS-ESM Hamburg for their comments, which substantially improved the explanatory power of this chapter. From Michael Hauhs we picked up the idea of separating determinism from non-determinism. We thank the BIOTA-Maroc project team, whose expertise and infrastructure we used to perform this study (German Federal Ministry of Education and Research, Förderkennzeichen 01 LC 0601A).

Chapter 4

Climate change, vulnerability and adaptation in North Africa with focus on Morocco [8]

Our study links environmental impacts of climate change to major socio-economic and agricultural developments in North Africa. We jointly investigate climate projections, vulnerability, impacts, and options for adaptation. Precipitation in North Africa is likely to decrease between 10 and 20%, while temperatures are likely to rise between 2 and 3°C by 2050. This trend is most pronounced in the north-western parts of northern Africa as own model results suggest. Population is likely to grow by more than 50% until 2050. The combination of decreasing supply and increasing demand aggravates the stressed water situation in the region. We compare the vulnerabilities and conflict implications of climate change in Algeria, Egypt, Libya, Morocco, and Tunisia. The adaptive capacities vary strongly from state to state. Climate change will likely have the strongest effect on Morocco where the agricultural sector is of high importance for the country's economy and for 57% of poor people. Based on our comparison, we choose Morocco for a more detailed analysis of impacts and adaptation options. To increase resilience against climate change, agricultural policies should focus on conservation of soil quality, rangeland vegetation, and balanced groundwater usage, since prospects of further increasing primary agricultural productivity are limited. Therefore, an increase of added value should be a major objective. Our model results suggest a considerable potential of replacing the use of firewood by electric energy to sustain pastoral productivity. Failure to implement these policies increases the risk that climate change will contribute to inequality and instability in North Africa.

[8] A similar version of this chapter has been submitted after revision to *Regional Environmental Change* as: Schilling J, Freier KP, Hertig E, Scheffran J: Climate change, vulnerability and adaptation in North Africa with focus on Morocco; Leading author was Janpeter Schilling, Korbinian P Freier has contributed estimated 45% to the abstract, 45% to introduction, 90% to chapter 4.4 (Climate change impacts on agriculture and adaptation in Morocco) and 60% to the synthesis chapter 4.5.

4.1 Introduction

Climate change poses a significant challenge for North Africa, affecting and interacting with both environmental and anthropogenic systems in the region. Among the variables of interest are environmental degradation, agricultural productivity, food security, population growth and economic and societal (in-)stability. So far, the majority of research articles have focused on climate change and its interrelation with one or two of the aforementioned variables (e.g. Abou-Hadid, 2006; Agoumi, 2003; Beckouche *et al.*, 2010; Bekkoussa *et al.*, 2008; Brauch, 2010; Lhomme *et al.*, 2009; Meddi *et al.*, 2010; Mougou *et al.*, 2011).

The present article aims to draw a wider, although not exhaustive, picture of climatic and social changes in North Africa by integrating perspectives from climate science, social geography, conflict research, and environmental sciences. We jointly investigate some major interrelations between climate projections, vulnerability, impacts, policy responses and options for adaptation.

The starting point of our investigation is a description of the physical climate change as presently observed and its projections for the 21st century. We address the uncertainties of projections and their consequences for extreme events using own model runs as well as data from the literature (section 4.2).

Against this background, we give an overview of the vulnerability to climatic changes of the five North African states Algeria, Egypt, Libya, Morocco and Tunisia (see Figure 4.1). The overview servers two purposes: First, it allows us to discuss security concerns of climate change which have been raised even prior to the riots in Tunisia, Egypt and Libya in 2011 (see Iglesias *et al.*, 2010; Smith & Vivekananda, 2009; WBGU, 2007). Second, the overview enables us to identify countries which are particularly vulnerable to climate change and hence suitable for a further discussion. Morocco is particularly vulnerable, predominantly because of its high sensitivity to climatic changes and its limited adaptive capacities (section 4.3).

Focussing on Morocco, we assess the impacts of climate change on agriculture and society. It turns out that impacts of climate change can be aggravated by unsustainable policy responses and agricultural practices. Based on this finding, we investigate a set of adaptation options using data from local research projects. In addition, an own bio-economic model is used to explore the possibility of increasing resilience of pastoral livestock husbandry in semi-arid rangelands. One option is to replace firewood by other energy sources such as solar power (section 4.4). The insights from Morocco are supposed to reveal linkages between climate change, agricultural practices and socio-economic developments which are also relevant for adaptation in other North African countries.

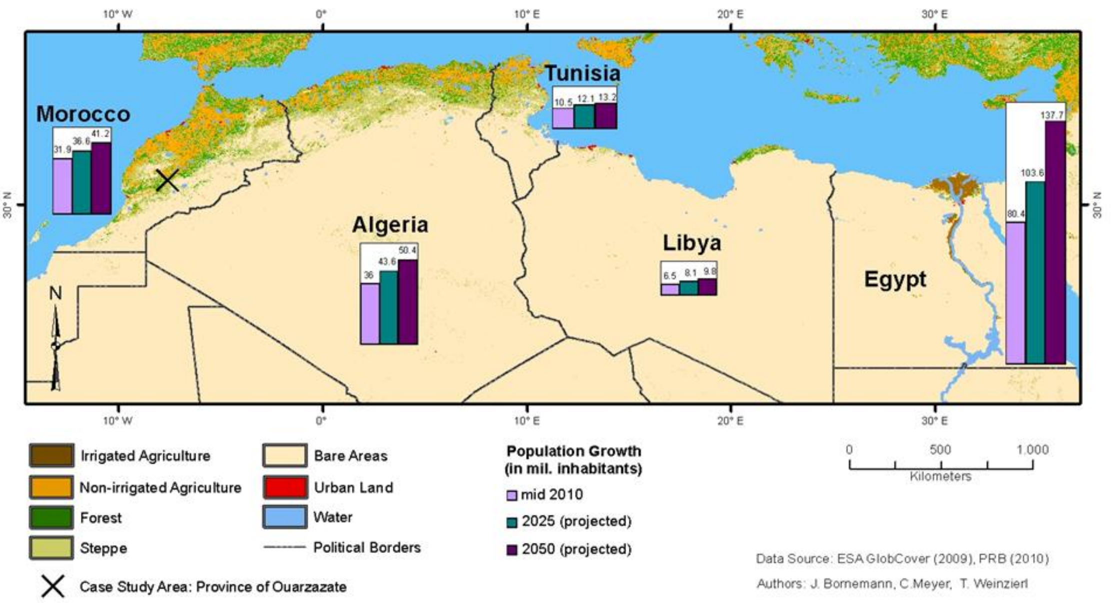

Figure 4.1: Land use and population growth in North Africa (own representation, based on: European Space Agency, 2010; PRB, 2010)

4.2 Climate change in North Africa[9]

4.2.1 Recent climate characteristics

Precipitation of North Africa is characterized by a wet season in winter and dry conditions in summer. The rainy season, which starts in October and lasts until April, has its maximum in the months from December to February (Endlicher, 2000; Lionello *et al.*, 2006). Additionally the whole region is characterized by high inter-annual precipitation variability. Thus, long-term mean precipitation, especially in the southern region of North Africa, reflects averages over many dry years and some relatively humid years.

A generalized overview of historical trends in the recent past and likely future trends under enhanced greenhouse warming conditions for temperature and precipitation in the North African countries is given in Table 4.1. For north-eastern Morocco and north-western Algeria, several studies point to below average annual rainfall rates which have prevailed since about the mid-1970s (Fink *et al.*, 2008; Hertig, 2004; Meddi *et al.*, 2010). Also for the southern parts of the Moroccan Atlantic coast as well as for the Atlas Mountains several periods of below average precipitation occurred in the second half of the 20th century in the winter season, for example in the period 1971 to 1975 and in the period 1979 to 1983, but also some positive

[9] Leading author of this chapter (4.2) has been Elke Hertig, University of Augsburg

anomalies can be found around the late 1980s and 1990s (Hertig, 2004). Due to the observed changes, a general tendency towards warmer and drier conditions can be found in the last decades for the above mentioned regions (Born *et al.*, 2008b; Gerstengarbe & Werner, 2007). In contrast to the predominantly negative precipitation evolution in the western parts of Northern Africa, no pronounced precipitation trends have been observed for the eastern regions such as north-eastern Algeria (Meddi & Talia, 2008), Mediterranean Tunisia (Hertig, 2004), central Tunisia (with some decadal variability, Kingumbi *et al.*, 2005), and the Mediterranean parts of Libya and Egypt (Hertig, 2004) during the last decades of the 20th century.

Table 4.1: Generalized overview of recent and likely climatic trends in North Africa

State	Recent trends		Future trends	
	temperature	precipitation	temperature	precipitation
Algeria	+	-	+	-
Egypt	+	o	+	-
Libya	+	o	+	-
Morocco	+	-	+	-
Tunisia	+	o	+	-

+ increase - decrease o no change

With respect to seasonal predictions, Born *et al.* (2010) find that the skill of simple statistical seasonal rainfall predictions is limited. Using multivariate statistical analyses, Hertig and Jacobeit (2010a; 2010b) show that precipitation in February in the Atlas Mountains of Morocco, regional temperatures in Algeria and Tunisia in the month of May, and December temperatures in the western parts of Northern Africa can be predicted by taking preceding sea surface temperature anomalies as predictors. Thus, it becomes evident that there is some skill regarding seasonal predictions of temperature and precipitation (see Slimani *et al.*, 2007 for Tunisia). In the scope of possible future enhancements of such predictions, they could become more important, especially in the context of the additional challenges due to climate change.

4.2.2 Future climate change

For Northern Africa climate change studies indicate that annual precipitation is likely to decrease during the course of the 21st century (Gibelin & Déqué, 2003; Giorgi & Bi, 2005; Rowell, 2005). According to the Regional Model REMO, precipitation in North Africa is likely to decrease between 10% and 20% until the year 2050 under SRES A1B scenario conditions (Paeth *et al.*, 2009). For winter precipitation, decreases are modelled by Räisänen *et al.* (2004), with an emphasis of strongest reductions on the Moroccan region. An assessment of precipitation changes within the IMPETUS project (An integrated approach to the efficient management of scarce water resources in West Africa) shows that Moroccan rainfall might be reduced in the period 2011-2050 between 5% (mountainous areas) and 30% in the southern regions for the SRES A1B scenario and by 5% and 20% for the B1 scenario (Christoph *et al.*, 2010). Projected precipitation decreases in winter are controlled by processes which involve a systematic shift of the cyclone tracks to a more polward position. This leads to drier conditions in North Africa. In summer a positive feedback with decreased soil moisture values has been considered. However, it has to be kept in mind that the exact spatial location of the polar front in a future warmer climate is still highly uncertain. Furthermore atmospheric humidity has to be taken into account because of the increased moisture holding capacity of the atmosphere under warmer conditions.

Precipitation

Statistical downscaling of precipitation for a region covering the western parts of Northern Africa shows rainfall increases in December/January of up to about 60 mm in the period 2071-2100 compared to the time period 1990-2019 (Figure 4.2). The results are based on assessments of precipitation changes under the moderate SRES B2 scenario assumptions using a statistical downscaling technique. A detailed description of the downscaling technique can be found in Hertig and Jacobeit (2008a). As can be seen from Figure 4.2, there are negative precipitation changes at the beginning of the rainy season in October/November. However, in high winter (December/January) substantial increases are estimated. A simulation with a local model within the IMPETUS project shows more intense precipitation events as a result of enhanced humidity advection (Christoph *et al.*, 2010). In the statistical assessment of the present paper, weak increases continue in some sub-areas in February/March (Figure 4.2). Thereafter, the whole region is affected by drier conditions in spring (April/May). The signal-to-noise-ratio (the rainfall difference of the two 30-year periods in relation to natural variability) of the precipitation reduction in spring is greater than one, indicating that the climate change signal is greater than the recent natural variability. A study by Palutikof and Wigley (1996) also estimates decreased rainfall south of the Mediterranean Sea during spring. Around this drier region, the north-western parts of northern Africa stand out as a region of most pronounced decreases in precipitation. This was also reported by Jacobeit (1994). Summarizing the results of the statistical downscaling, a shortening and at the same time an increase in rainfall amount of the wet season arises for the western parts of North Africa.

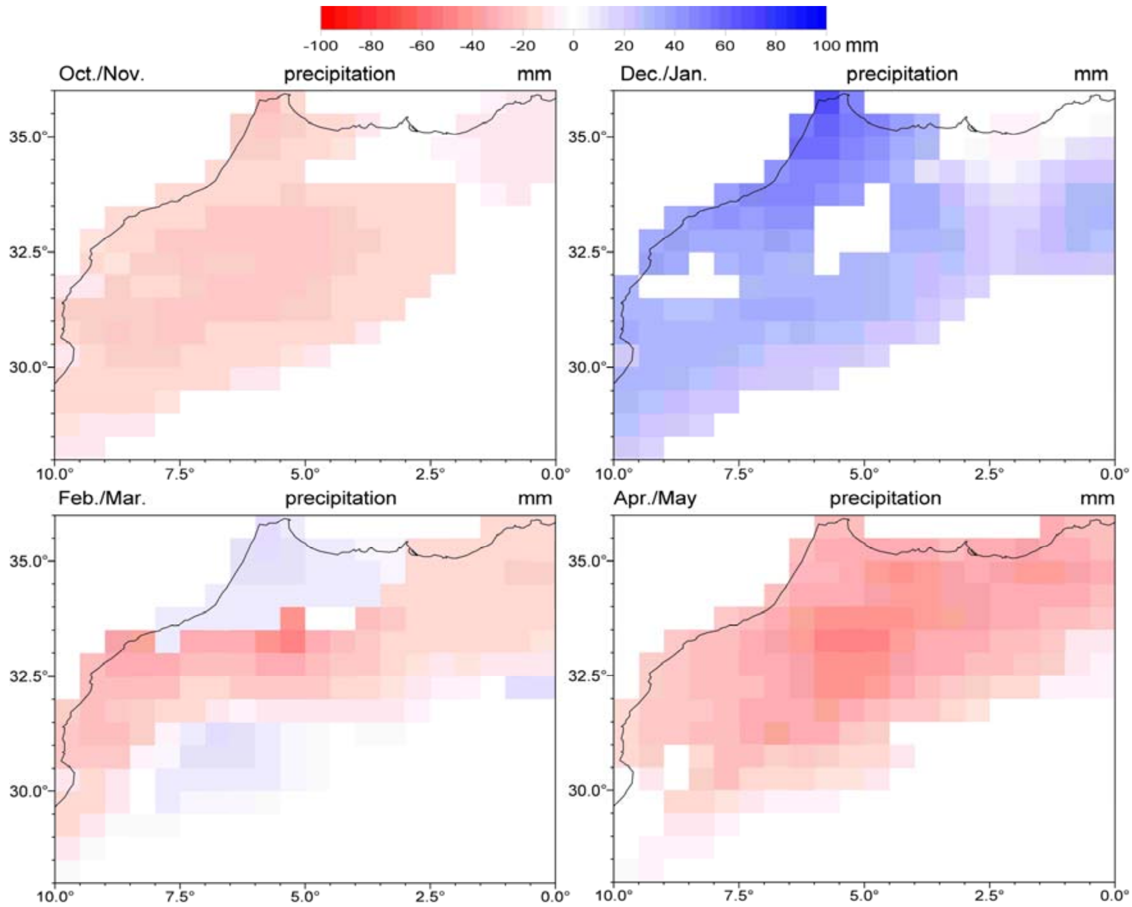

Figure 4.2: Changes of Mediterranean precipitation for the main rainy season from October to May according to statistical downscaling assessments using ECHAM4/OPYC3 predictors (1000hPa-/500hPa- geopotential heights and 1000hPa-specific humidity). Differences of the mean 2-month precipitation between the periods 2071-2100 and 1990-2019 in mm. Statistical downscaling technique: Canonical Correlation Analysis. Scenario: SRES-B2

Temperature

Regarding temperature the dynamical regional model REMO suggests a temperature rise in North Africa between 2 and 3°C by 2050 under A1B scenario conditions (Paeth *et al.*, 2009). The temperature rise for Morocco is estimated to 1.2°C in the SRES A1B and 1°C in the B1 scenario. Both scenarios yield a slightly more pronounced increase in the mountain region (Christoph *et al.*, 2010). An application of regional and global climate models by Patricola and Cook (2010) for Northern Africa shows a very strong warming of about 6°C over north-western Africa in the 21st century compared to the 20th century. Also, when looking at results from statistical downscaling by Hertig and Jacobeit (2008b), a temperature rise becomes visible for western North Africa. The temperature assessment indicates increases of mean temperature in all months of the year, with largest warming rates in summer

(June/July) and autumn (Oct./Nov.) of partly more than 4°C until the end of the 21st century. The lowest warming rate is assessed for the winter months December and January with values of up to about 1°C. Overall the spatial warming pattern has an emphasis on the mountainous areas of the Atlas Mountains, and weakens towards the coastal areas of the Atlantic Ocean and the Mediterranean Sea.

Extreme events

Concerning extremes, more precisely droughts, the risk of these events is likely to increase in Northern Africa. For Europe and western North Africa Räisänen *et al.* (2004) find that average precipitation reduction is associated with a reduced number of precipitation days rather than with reduced precipitation intensity. Voss *et al.* (2002) determine a significant prolongation of very long dry spells (10-year return values of annual maximum dry spells) in the period 2060-89 compared to 1970–99 for Northern Africa. A study of Beniston *et al.* (2003) also indicates considerable drying over western Mediterranean North Africa. The main features are reduced intensity of precipitation, and earlier onset and longer duration of drought (i.e. continuous period of days with no precipitation). This finding is in accordance with the study of Tebaldi *et al.* (2006) who also find a significant increase in dry days (defined as the annual maximum number of consecutive dry days).

Uncertainties

As the previous discussion already suggests, projections of future climate change for Africa exhibit considerable uncertainties. The IPCC concludes that it is necessary to improve the assessments for the African regions. The global general circulation models still have major difficulties over Africa, for example unrealistic climate variability in the Sahel zone or a southward displacement of the Atlantic inter-tropical convergence zone (Christensen *et al.*, 2007). In some projections, the greening of the Sahara is a possibility (see Claussen & Gayler , 1997; Claussen *et al.*, 2003; Vamborg *et al.*, 2011). Dynamical and statistical downscaling assessments also need major improvements for the African domain. For instance it is necessary to gain a better understanding of climate variability in this region, which involves the inclusion of specific feedback mechanisms, e.g. of the oceans and of land use change. In recent years more attention has been turned to this region as for example by the IMPETUS project or the CORDEX (Coordinated Regional Climate Downscaling Experiment) initiative, which tries to enhance regional climate change information especially for Africa.

4.3 Vulnerability of North Africa[10]

This section gives an overview of the vulnerability to climate change of five North African states, Algeria, Egypt, Libya, Morocco and Tunisia. So far, the concept of vulnerability lacks one generally accepted and precise definition (see Cutter, 2003; Füssel, 2007; Scheffran, 2010; Vincent, 2004). Yet, three elements of vulnerability can be identified as consistent throughout the literature: i) exposure to climate change, ii) sensitivity to climate change, and iii) adaptive capacity (Adger, 2006; Heltberg *et al.*, 2009; Smit & Wandel, 2006). These elements are reflected by the IPCC, who defines vulnerability as "a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC, 2007c:883). Exposure to climate change has been described in the previous section; sensitivity and adaptive capacity are subject of this section (see Figure 4.3).

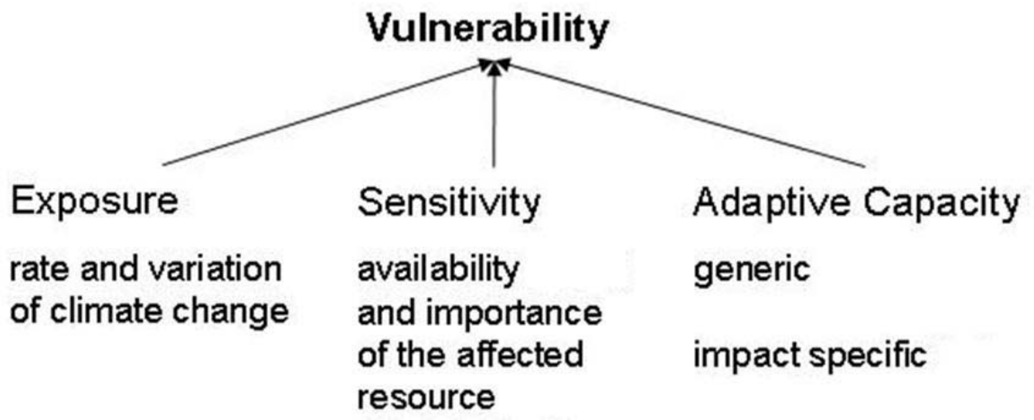

Figure 4.3: Elements of vulnerability (IPCC, 2007c)

With respect to the overview character of this section, the discussion of sensitivity focuses on agriculture which is most directly affected by climate change (Mougou *et al.*, 2011). The indicators used to analyze the sensitivity and the adaptive capacity were chosen based on recognition in the literature, consistency and availability. The resulting catalogue of indicators is similar to the one suggested by Brooks *et al.* (2005). The findings on sensitivity and adaptive capacity are then combined with the climate change exposure (section 4.2) to assess the vulnerability and to draw conclusions for potential conflict implications.

[10] Leading author of this chapter (4.3) has been Janpeter Schilling, University of Hamburg

4.3.1 Sensitivity

While closely related to exposure, sensitivity is "the degree to which a system is affected, either adversely or beneficially, by climate variability or change" (IPCC, 2007c:881). In the context of this paper we focus on the resource dimension of sensitivity as suggested by Barnett and Adger (2007). Referring to the sensitivity element of vulnerability, Barnett and Adger argue that the vulnerability of people "depends on the extent to which they are dependent on natural resources and ecosystem services [and] the extent to which the resources and services they rely on are sensitive to climate change" (Barnett & Adger, 2007:641). The following section therefore discusses the availability of the affected resources prior to the climate stimuli (see Adger, 1999) and the importance of the resource for the system.

Water availability

Water is the resource most directly and strongly affected by the described climatic changes. Higher temperatures and less (reliable) precipitations will likely decrease the overall availability of water in North Africa. Already, water is a scarce resource in the whole region. Depending on the index used, the North African countries are either termed stressed or scarce (Figure 4.4). According to the Hydrological Water Stress Index (HWSI) Algeria and Tunisia face the highest level of water scarcity while in Egypt and Morocco water is less scarce (Figure 4.4)[11]. If the human development is taken into account the situation seems to be less dramatic (see SWSI in Figure 4.4). The Social Water Scarcity Index (SWSI) indicates water stress in Egypt and Morocco and water scarcity in the remaining countries. Although the SWSI to some extent takes the social adaptive capacity of the affected society into account (see following sections), it does not say anything about other relevant factors such as the distribution or the quality of the water. In this respect, the Water Poverty Index (WPI) is more suitable as it is composed out of four indices on: water resources, access, capacity and environment (see Lawrence *et al.*, 2003). Even though the WPI should be seen as an "order-of-magnitude estimate" (World Resources Institute, 2008:213), it still partially reverses the statement of previously discussed indices. While both the HWSI and the SWSI characterize the water situation in Morocco to be comparatively less serious, the country is the water poorest according to the WPI (see Reversed Water Poverty Index (RWPI) in Figure 4.4).

[11] Libya has by far the lowest renewable water resources; 60 million m³ compared to the second lowest Morocco with 4.6 billion m³ in 2008 (FAO, 2010a). This causes its water indices (HWSI of 1050 and SWSI of 797) to lie way out of range. Additionally no water poverty index was available. Therefore Libya is excluded from the discussion of water indices.

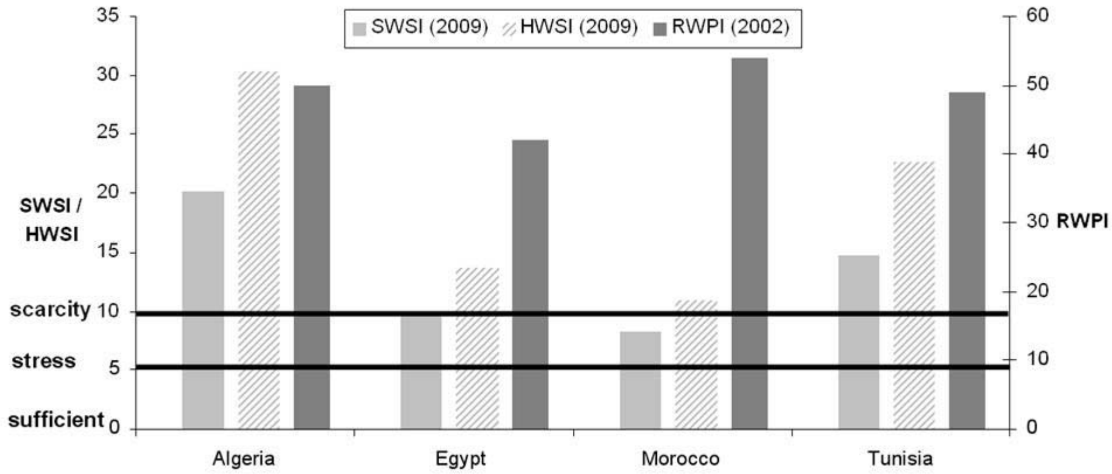

Figure 4.4: Comparison of water indices for North Africa (own calculations based on: FAO, 2010a; Ohlsson, 2000; World Resources Institute, 2008). The HWSI (Hydrological Water Stress Index) measures the number of hundreds of people per one million m³ of available renewable water. The Social Water Scarcity Index (SWSI) equals the HWSI divided by the HDI (see Table 4.1) and by a correction factor of 2 (Ohlsson, 2000). A SWSI or HWSI of 0 to 5 indicates sufficient water supply, a value above 5 and below 10 indicates water stress and values above 10 indicate water scarcity (see black lines). The Water Poverty Index (WPI) measures the impact of water scarcity and water provision on human populations (WRI). Its values lie between 0 and 100. High scores indicate a higher water provision. For the purpose of graphical representation the WPI has been reversed to the RWPI (Reversed Water Poverty Index) by subtracting the value for the WRI from 100. Hence, for the RWPI higher values indicate lower water provision. The categories (sufficient, stress and scarcity) only apply to the SWSI and the HWSI

Aside from the country specifics on the water supply side, all states share one common development on the demand side: significant population growth. Egypt is expected to see the strongest growth with an increase of 57 million people until 2050 (Figure 4.1). Algeria and Morocco could grow by more than 14 and 10 millions, respectively. The population growth of the smaller states Libya and Tunisia is also significant, especially in relative terms. Both the relative and absolute population growth will increase the demand for food and water on the national and regional scale. Interlinked with this development are the processes of urbanization and littoralization (concentration of population along the coast) which could lead to highly localized peaks in water and food demand.

Agricultural sector

The agricultural sector is in all North African countries by far the largest consumer of water, mostly reaching values above 80% (Table 4.2). It is therefore promising to look into the agricultural sector and its importance for the each country in more detail.

Except from Egypt's agricultural sector which is focused on the Nile, all other countries in North Africa depend almost entirely on precipitation as the main water source for agriculture (see Table 4.2, Figure 4.1 and Figure 4.4). The dependence on precipitation determines the impact of climate change on agricultural productivity. While the agricultural productivity can be increased under climate change conditions in Egypt, a decrease in productivity of almost 30% is projected for Algeria and Morocco, even if the use of carbon fertilization is considered (Cline, 2007 and Table 4.2). Without carbon fertilization the climate change impact increases by 10% (see also Lhomme *et al.*, 2009; Mougou *et al.*, 2011; Nelson *et al.*, 2009; Requier-Desjardins, 2010). The IPCC (2007c) estimates that in North Africa climate change will cause a loss in agriculture of between 0.4 and 1.3% of GDP by 2100.

Table 4.2: Agriculture and climate change impact in North Africa (Cline, 2007; FAO, 2010a; 2010b)

State	Percentage of water withdrawals used for agricultural purposes (2000)	Rain fed land as a percent of total agricultural area (2003)	Percent impact of climate change on agricultural productivity by 2080 (compared to 2003), without carbon fertilization	Percent impact of climate change on agricultural productivity by 2080 (compared to 2003), with carbon fertilization
Algeria	65	98.6	-36	-26.4
Egypt	86	0.1	11.3	28
Libya	83	97	NA	NA
Morocco	87	95.2	-39	-29.9
Tunisia	82	96	NA	NA

The importance of the agricultural sector for the economy varies strongly among the considered states. Table 4.3 shows the sectoral composition of GDP and labour force in North Africa. In Algeria and Libya the industry contributes most to the GDP, while in Egypt, Morocco and Tunisia the service sector is most important. Agriculture is in none of the countries the largest contributor to GDP. However, in Morocco the agricultural sector, reaching 17%, is significant for the GDP. This becomes even more evident when the occupational distribution across sectors is considered. Almost half of the working population in Morocco is employed in the agricultural sector (Table 4.3). Considering both GDP and employment, the importance of the agricultural sector in North Africa ranges from medium (Libya, Algeria) to high (Tunisia) and very high (Morocco, Egypt).

Table 4.3: Sectoral composition of GDP and labour force in North Africa (CIA, 2010)

	GDP (est. 2010)			Labor force (est.)		
State	Agriculture percentage	Industry percentage	Services percentage	Agriculture percentage	Industry percentage	Services percentage
Algeria	**8.3**	61.5	30.2	**14** (2003)	13.4	NA
Egypt	**13.5**	37.9	48.6	**32** (2001)	17	51
Libya	**2.6**	63.8	33.6	**17** (2004)	23	59
Morocco	**17.1**	31.6	51.4	**44.6** (2006)	19.8	35.5
Tunisia	**10.6**	34.6	54.8	**18.3** (2009)	31.9	49.8

In summary, water is the most affected resource by climate change in North Africa. Depending on the index used, the water situation is most severe in Libya and Algeria (physical water availability) or in Morocco (water poverty index). The dependency on water and its importance for the economy is highest in Morocco, making the country overall the most sensitive to climate change.

4.3.2 Adaptive capacity

According to the IPCC, the adaptive capacity of a society can be divided into generic and impact specific indicators. "Generic indicators include factors such as education, income and health. Indicators specific to a particular impact, such as drought or floods, may relate to institutions, knowledge and technology" (IPCC, 2007c:727). Using indicators suggested by the IPCC (2007c) and Adger (2006), this section compares the generic and impact specific adaptive capacities of Algeria, Egypt, Libya, Morocco and Tunisia.

Generic adaptive capacity

The generic adaptive capacity refers the capacity of a society to adapt to changes in general. Key determinants are economic resources, human development, health and education (2007). The absolute economic resources are largest in Egypt, followed by Algeria and the significantly weaker economies of Libya, Morocco and Tunisia (Table 4.4). When measured in per capita income as suggested by Adger (2006), the distribution of the economic power changes. Here, Libya ranks highest and Morocco lowest. For the individual adaptive capacity, it is important to consider not only the per capita income level but also its distribution among the households of a society. The highest levels of income inequality are found in Morocco and Tunisia (see Gini index in Table 4.4). According to the human development index Morocco shows the largest development deficit (Table 4.4).

Table 4.4: Generic indicators I: Income and human development in North Africa (UNDP, 2009)

State	GDP[1] in billion PPP[2] USD (2009 est.)	GDP per capita in PPP USD (2007)	GINI index[3] (average 1991-2007)	HDI[4] (2007)
Algeria	239.6	7740	35.3	0.754
Egypt	471.2	5329	32.1	0.703
Libya	95.88	14364	N/A	0.847
Morocco	91.84	4108	40.9	0.654
Tunisia	84.04	7520	40.8	0.769

[1] GDP: gross domestic product, [2] PPP: purchasing power parity, [3] the Gini index lies between 0 and 100. A value of 0 represents absolute equality and 100 absolute inequality. [4] HDI: Human development index

The health level of the North African countries lies above the average of the continent and below the European level. While the under-five mortality rate of Algeria and Morocco is comparably high among the considered countries, with values of 37 and 36 respectively (per 1000 live births) (Table 4.5), it is still low compared to the average value of 78 for the countries of the Eastern Mediterranean region (for a complete list of countries see WHO, 2010:176). The life expectancy at birth is around 70 years in all North African countries (WHO, 2010). Further, the percentage of undernourished population has not been critical over the past 20 years (FAO, 2010b). More than 90% of the rural population of the considered countries use improved drinking-water sources, except for Morocco where this share only accounts for 60% (Table 4.5).

Table 4.5: Generic indicators II: Health and education in North Africa (UNDP, 2009; WHO, 2010)

State	Under-five mortality rate (2008)[1]	Percentage of rural population using improved drinking-water sources (2008)	Education index (2007)[2]
Algeria	37	97	0.748
Egypt	23	98	0.697
Libya	17	NA	0.898
Morocco	36	60	0.574
Tunisia	21	94	0.772

[1] probability of dying by age 5 per 1000 live births, [2] the education index combines adult literacy rates and gross enrolment ratios

Overall, Morocco has the lowest generic adaptive capacity in North Africa. The country performs poorest in economic resources, human development, health and education. Prior to the outbreak of the war in 2011 (see for example Economist, 2011), Libya had the highest generic adaptive capacity in North Africa.

Impact specific adaptive capacity

The adaptive capacity, specific to an impact, is shaped by the performance of institutions and the availability of knowledge and technology. With respect to the performance of institutions and the region's overall development, the level of corruption has been identified as a "fundamental challenge" (Transparency International, 2008). Widespread corruption limits the efficient use of economic assets (see previous section) to cope with the effects of climate change (Transparency International, 2011). Within North Africa, all countries have "a serious corruption problem" (Transparency International, 2008) as none of the countries reaches the threshold score of 5. The level of corruption is lowest in Morocco and Tunisia (Table 4.6).

Table 4.6: Impact specific indicators: Corruption, knowledge and technology in North Africa (Schwab, 2010; Transparency International, 2010; World Bank, 2010)

State	Corruption perceptions index (2009) [1]	Knowledge index (2009) [2]	Technological readiness index (2010) [3]
Algeria	2.8	3.57 *	3.0
Egypt	2.8	4.24	3.3
Libya	2.5	N/A	2.9
Morocco	3.3	3.35	3.5
Tunisia	4.2	4.54	3.9

[1] the corruption perception index measures the perceived level of public-sector corruption. It is a "survey of surveys", based on 13 different expert and business surveys [2] the knowledge index is composed out of key variables on education, innovation, and innovation and communication technology, * incomplete data

The knowledge index suggested by the World Bank "measures a country's ability to generate, adopt and diffuse knowledge" (World Bank, 2009). As the index is composed out of different indicators on education, human resources, innovation, and information and communication technology, it interlinks with other impact specific and generic indicators (see previous section). Further, the index does not take indigenous knowledge into account which has been identified by several studies to be critical with respect to climate change adaptation (Ensor & Berger, 2009; Folke *et al.*, 2005; Pedersen & Benjaminsen, 2008). Still, the index allows for a general classification. In all five North African countries, the level of knowledge is lower than the Middle Eastern and North African average of 5.68 but significantly higher than the continents average of 2.72 (World Bank, 2009 and Table 4.6).

Closely interlinked with the level of knowledge is the level of technology. Based on the Technological Readiness index, Tunisia is the most advanced country while Libya marks the lower end (Table 4.6). The index combines several components such as foreign direct investments, availability of latest technologies and number of internet users. As the predictive skill of seasonal forecasts is growing, the availability of technology is particularly important to communicate information to farmers and pastoralist.

In general, the impact specific adaptive capacity of a country is more difficult to characterize than the generic adaptive capacity. This is mainly because institutions, knowledge and technology are broader categories than the ones used to define the general adaptive capacity. Fewer well-established indicators exist for the impact specific adaptive capacity. Especially the knowledge index is incomprehensive as it partially relies on incomplete data and is not available for Libya. Some conclusions can still be drawn. Tunisia scores best in all three categories (corruption, knowledge and technology). Morocco performs relatively well in terms of corruption and technology, whereas Libya shows the lowest values in these categories.

4.3.3 Comparison and conflict implications

In order to assess the vulnerability of a country or a region, it is necessary to discuss and visualize the three elements of vulnerability in a joint manner. Figure 4.5 pursues this aim, combining main indicators for the generic adaptive capacity (light grey shading) with main indicators for sensitivity (darker grey shading).[12] The figure relates the individual values of each country to the highest and lowest observed in North Africa. For reasons of graphical representation, the indicators representing the sensitivity towards climate change have been reversed to insensitivity. A greater plot area therefore indicates a higher generic adaptive capacity and a lower sensitivity.

Comparing the countries' plots, several aspects become apparent: A general weakness of the region is its high dependency on rain fed agriculture, which can be observed in all countries but Egypt. In Egypt the importance of agriculture for employment and GDP as well as the low per capita GDP are most critical. Algeria and Tunisia show a similar distribution of generic adaptive capacity and sensitivity. Their greatest strengths are the level of education and human development. These categories were best developed in Libya. Yet, Libya's adaptive capacity has suffered considerably from the violent conflict in 2011. Morocco has the smallest plot area, showing that it is the country with the lowest generic adaptive capacity and the highest sensitivity. The country's impact specific adaptive capacity is relatively better developed (see 3.2). However, the combination of high climate exposure, low generic adaptive capacity and high sensitivity makes Morocco the most vulnerable state in a vulnerable region.

[12] The impact specific adaptive capacity is not included because of its limitations discussed in 3.2. The water situation is not shown, since it is already displayed in Figure 4.

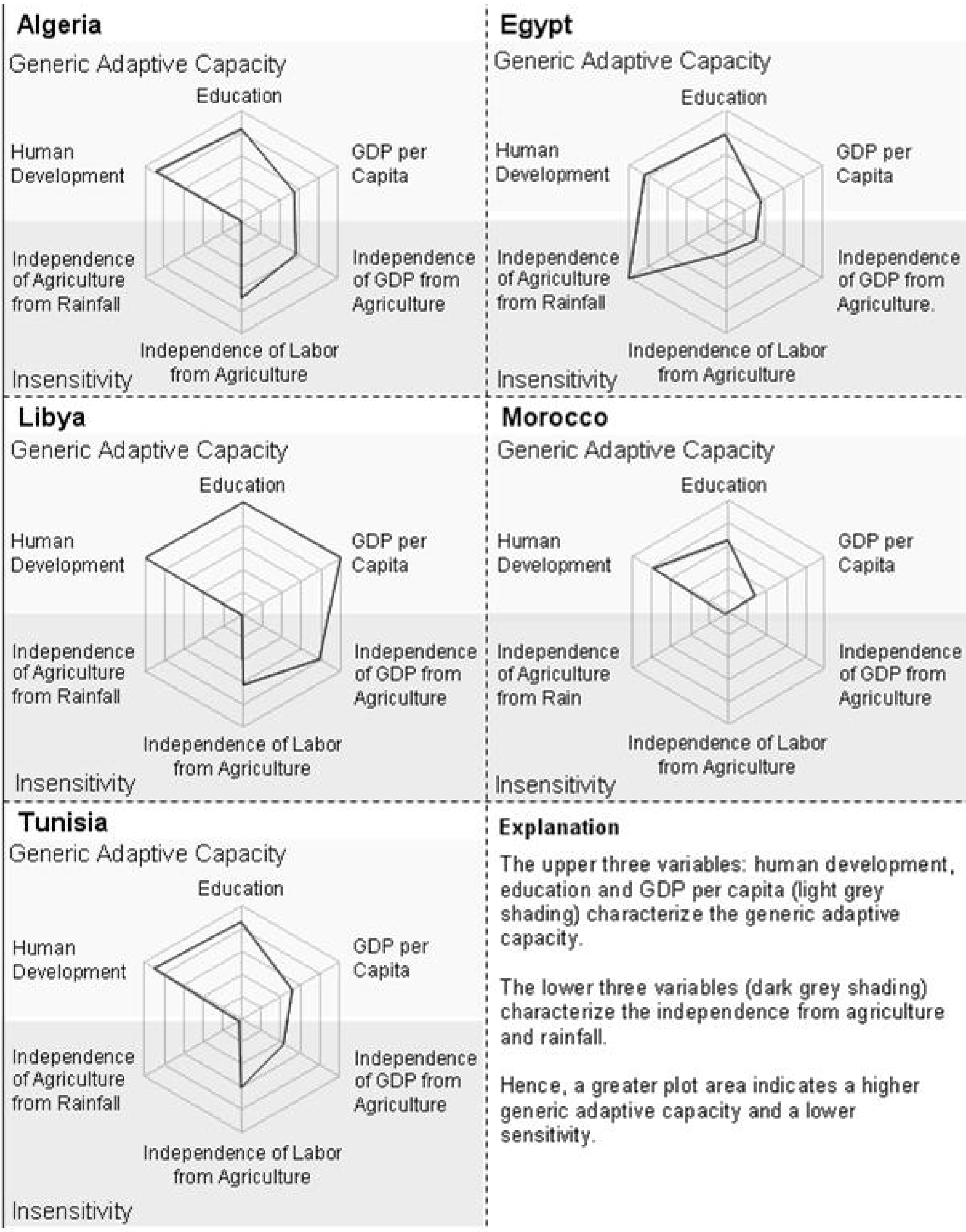

Figure 4.5: Generic adaptive capacity and insensitivity to climate change in North Africa (own calculations based on: CIA, 2010; FAO, 2010b; UNDP, 2009). For the upper three variables (human development, education and GDP per capita) the highest value in North Africa is set 100 and the other country values are calculated accordingly. The lower three variables (related to agriculture) are taken from Table 4.2 and Table 4.3 and reversed for graphical representation

This result is in line with Yohe *et al.* (2006) who apply a combined index of exposure and sensitivity to find a significant level of climate change vulnerability for Morocco and Tunisia (and a moderate level of vulnerability for the remaining countries). Sullivan and Huntingford (2009), using the climate vulnerability index (a composition of the previously discussed WPI and additional geographical factors), assess the vulnerability of the region to be medium high. Similar results are presented by Iglesias *et al.* (2009).

Conflict implications

Against the background of high vulnerability, increasing demand for food and water (driven by population growth) and the projected decline in agricultural productivity (driven by climate change), concerns have been raised about food and water security and its implications for conflict (Iglesias *et al.*, 2010; Scheffran & Battaglini, 2011).[13] Iglesias *et al.* (2010:165) see a "potential for more pronounced water conflicts of neighbouring countries" in North Africa. Smith and Vivekananda (2007:19) find a "high risk of political instability as a knock-on consequence of climate change" for Egypt, Libya and Morocco after assessing the factors of conflict, poverty, inequality, and governance. While no risk was identified for Tunisia, "a high risk of armed conflict as a knock-on consequence of climate change" is expected for Algeria (ibid.).

Homer-Dixon's environmental scarcity theory (Homer-Dixon, 1994; 1999) claims that environmental change likely leads to violent conflict when it is combined with population growth and unequal resource distribution. While our previous discussion has shown that water scarcity and population growth are characteristics of North Africa, unequal resource distribution is more difficult to capture.

In the context of environmental conflict theory, Morocco seems to be particularly conflict prone. Compared to the other North African countries, Morocco is also closest to meeting the criterion of low per capita income (see Table 4.1), which is often seen as a key factor for violent conflict (Collier *et al.*, 2003; Collier, 2007). According to Collier (2007), countries, which have experienced violent conflicts before, face a significantly higher risk of violence, especially within a 5 year post-conflict phase. In this regard Algeria, Egypt and most recently Libya are more conflict prone as they have experienced more conflicts in the recent two decades (Table 4.7). The application of Homer-Dixon's and Collier's conflict framework should not be misinterpreted as a simplification of the climate-conflict complex. Indeed, there are more factors such as ethnic diversity and political marginalization

[13] A general introduction to the security implications of climate change can be found in Barnett and Adger (2007), Nordås and Gleditsch (2007), WBGU (2007), Brzoska (2009); Brauch (2009), Webersik (2010), Scheffran and Battaglini (2011); Scheffran *et al.* (2011). Regarding implications for Africa see Brown and Crawford (2009).

(for Morocco see Rössler *et al.*, 2010a) that potentially contribute to conflict. However, the discussion of population growth, unequal resource distribution, per capita income and conflict history is a first attempt to assess the conflict sensitivity of a country.

Table 4.7: Armed conflicts in North Africa between 1998 and 2008 (PRIO, 2009b)

State	Number of conflicts 1989-2008	Dominant conflict intensity	Dominant conflict type
Algeria	18	minor armed conflicts and war	Internal armed conflict
Egypt	6	minor armed conflicts	Internal armed conflict
Libya	0		
Morocco	1	minor armed conflicts	Internal armed conflict
Tunisia	0		

Peace Research Institute Oslo (PRIO) uses the UCDP (Uppsala Conflict Database Program) definition of armed conflict: “a contested incompatibility that concerns government and/or territory where the use of armed force between two parties, of which at least one is the government of a state, results in at least 25 battle-related deaths” (PRIO, 2009a:1). An “internal armed conflict occurs between the government of a state and one or more internal opposition group(s) without intervention from other states” (ibid.). A conflict of minor intensity has between 25 and 999 battle-related deaths in a given year (PRIO, 2009a:7). Above this threshold a conflict is classified as “war” (ibid.)

In general, the assessment of potential conflict implications of climate change is a difficult task since there is neither a direct measurement of the resource distribution nor of small scale violent events (which would for instance capture food riots). PRIO’s definition of conflict for example requires at least 25 battle-related deaths and the state as one conflict party (see Table 4.7). These criteria exclude lower levels of violence as well as conflicts where the state is not directly involved.[14] Nevertheless the use of Homer-Dixon’s environmental scarcity theory and Collier’s conflict factors point to Morocco (unequal income distribution, high water poverty, comparatively low per capita income) and Algeria as well as Egypt (both high number of past conflicts, strong population growth) to being suitable for a more comprehensive analysis. Yet, Mougou *et al.* (2011) have shown that also Tunisia is promising in this regard.

To improve the understanding of the interrelations between climate change, conflict and adaptation, it is in any case necessary to leave the regional perspective and to look into one country in more detail.

[14] Increasing attention is being paid to data bases of low-level instability events (see Nardulli & Leetaru, 2010; Nardulli & Leetaru, 2011).

4.4 Climate change impacts on agriculture and adaptation in Morocco[15]

We focus in this section on Morocco because our analysis of vulnerability indicates Morocco as especially vulnerable to the effects of climate change. This focus allows us to discuss the impacts of climate change, its characteristics, developments, and socio-economic implications in more detail and with a closer look at the empirical data and policy options. Nonetheless, the conclusions drawn from this section can be related back to other North African countries to some degree, since their agricultural systems and expected climatic impacts are similar (Giannakopoulos *et al.*, 2009).

4.4.1 Traditional land use and recent developments

The main components of the Moroccan land use sector are farming and pastoral livestock husbandry, which have evolved for centuries under spatial and temporal fluctuations in precipitation (Barrow & Hicham, 2000). Farming is practised in the more fertile and humid locations, whereas pastoral livestock husbandry makes best use of marginal lands through extensive grazing of mainly sheep and goats. Traditionally, both components are combined which allows to buffer income shocks from droughts (Casciarri, 2006).

Farming

To ensure resilience in rain fed agriculture, which is used on more than 90% of the Moroccan arable land (Figure 4.1), special crop mixes and harvesting strategies are traditionally applied. For instance, barley is traditionally used instead of wheat, because barley needs less water and ripens faster, which increases the capability of resistance against water deficit (Kuhn *et al.*, 2010). Late planting of lentils makes best use of available water after late rains, recognizing shorter temporal fluctuations in rainfall (Lybbert *et al.*, 2009a), whereas fallow accumulates water on a yearly-timescale on arable land. A scattering of fields tries to avoid severe shocks by taking advantage of spatial variations in precipitation. An additional buffer is built up by stockpiling grain in good years (Skees *et al.*, 2001).

In the southern part of Morocco, the traditional adaptation of farming to a semi-arid to arid climate is the extended use of surface irrigation systems (‘*seguias*’) in the oases. Irrigated fields are additionally surrounded by trees such as apple, walnut, almond, olives, and date palms to use the percolating water as efficient as possible. This land use in the southern regions is combined with the aforementioned adaptation strategies (Barrow & Hicham, 2000; Rössler *et al.*, 2010a).

[15] Leading author of this chapter (4.4) has been Korbinian P. Freier, University of Hamburg

Since the middle of the 20th century, traditional agricultural strategies to cope with erratic and diverse precipitation patterns have changed substantially. The use of nitrogen fertilizer, mechanization, and the heavy use of irrigation (surface water and groundwater) were promoted in farming sector with the main objective of the government to increase cereal production and to expand cropland (Badraoui *et al.*, 2000; Davis, 2006). Especially the more drought prone wheat was supported by many governmental initiatives.

The new mode of agriculture allowed maximizing the production in years with sufficient rain, while it increased potential severity of droughts in dry years. The same is also observed for other North African countries (e.g. Latiri *et al.*, 2010). As Figure 4.6 shows, maximum yields and maximum harvested area in Morocco increased during the last 30 years, while the variability of both parameters increased as well. The agricultural model therefore can be characterized as a "higher-risk higher-stakes game" in comparison to the traditional one (Lybbert *et al.*, 2009b).

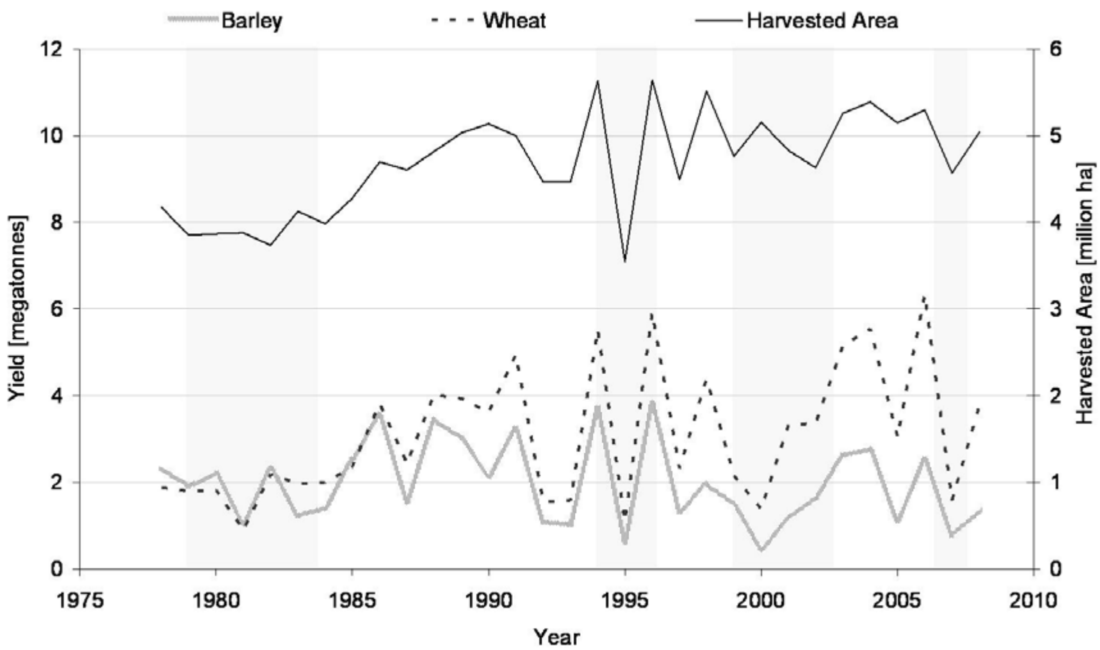

Figure 4.6: Harvested area and yields of barley and wheat in Morocco from 1978 to 2008. Drought periods are indicated with grey background (own representation based on: FAO, 2010b)

Despite a higher risk of crop failure, governmental programmes advocated this development to become more independent from cereal imports and to abate the exodus of people from rural areas. For instance, farmers were encouraged to declare property by ploughing former collective rangelands and establishing water pumps

(Davis, 2006). Additionally, the use of groundwater for irrigation is still free of any charge for the southern regions of Ouarzazate and Tafilalet (Badraoui *et al.*, 2000).

Surface-water management projects in Morocco, necessary for expansion of irrigated agriculture, relied in the past mostly on building large dams, which transferred the control over water resources from local owners to national authorities. This centralizing strategy had two effects: Traditional water management systems were devaluated while farmers did not perceive an improved supply with irrigation water. Thus, in combination with the trend of mechanization, farmers were encouraged to switch their irrigation systems from surface water to groundwater supply, where they control the access to a varying degree themselves (Heidecke *et al.*, 2010). This, in consequence, lead to a massive drop of groundwater tables in the past decades which in turn already lowered grain yields in some areas (Breuer 2007b; Fink *et al.*, 2010; Kuhn *et al.*, 2010). Additionally, inadequate irrigation always implies the risk of salinization, which can be increasingly observed in Morocco, where 35% of irrigated areas can be considered as saline (Badraoui *et al.*, 2000). In the southern province of Ouarzazate (IMPETUS project area, see Figure 4.1), even 80% of the soils are affected by salinization, 45% of them at a critical level (Davis, 2006).

Livestock husbandry

Within the sector of pastoral livestock husbandry, the most dominant traditional adaptation to droughts and precipitation irregularities is the wandering of herds according to precipitation patterns (transhumance). Traditionally, animals are slaughtered during times of fodder scarcity to prevent starvation even though prices are significantly lower during such periods (Hazell *et al.*, 2001; Skees *et al.*, 2001). Furthermore, reciprocal grazing arrangements with distant tribes as well as social networks are used to buffer income shocks caused by droughts (Hazell *et al.*, 2001; Kuhn *et al.*, 2010). A modern way of transhumance, in order to by-pass fodder scarcity, is the usage of trucks to transport the flocks to distant areas (Breuer, 2007a).

From the 1960s on, the government began to establish drought relief measures in the form of fodder subsidies and the rescheduling of loans. This practice turned transhumance from a necessity into an alternative and promoted tendencies of sedentarity and urbanization. Since close relations to governmental authorities ensured fodder supply, the policy of fodder subsidies enhanced fragmentation of tribal structures, which formerly controlled access to pastures (Rachik, 2007). While the interventions of the government reduced the catastrophic losses of livestock in recent droughts (see Figure 4.7), this policy made it possible to keep herd sizes at a higher level since the traditional de-stocking during droughts was drastically reduced.

Remittances of emigrants from Europe enabled the purchase of supplementary fodder as well (Kuhn *et al.*, 2010).

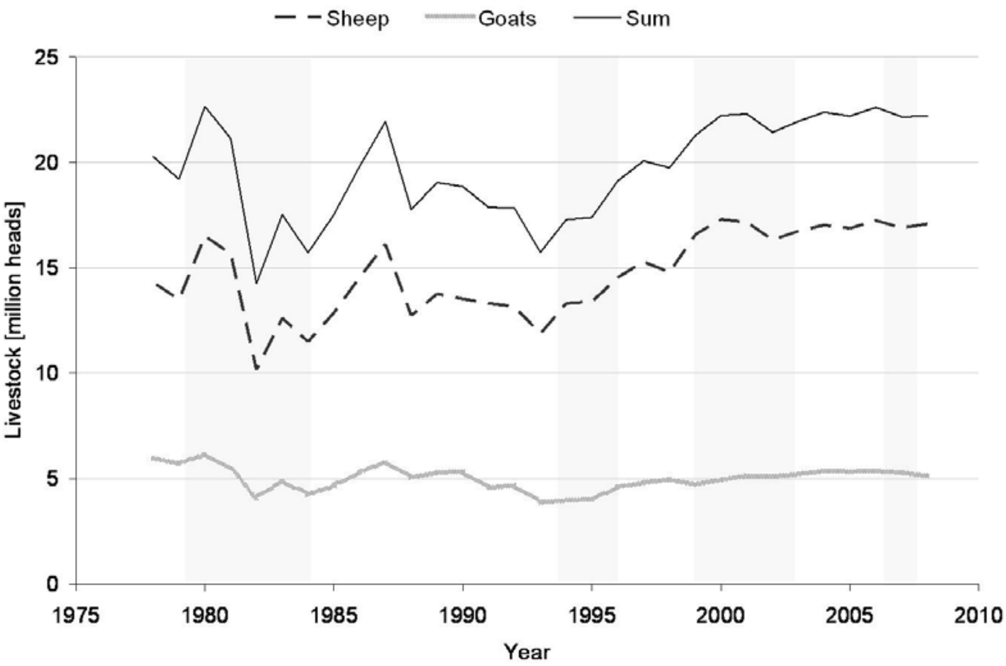

Figure 4.7: Numbers of livestock (sheep and goats) in Morocco in million heads from 1978 to 2008 (own representation based on: FAO, 2010b). Drought periods are indicated with grey background

Overall, fodder subsidies and remittances led to an increased grazing pressure in Moroccan rangelands over the past decades. Figure 4.7 shows the number of goats and sheep from 1978 till 2008. The numbers have to be seen in relation with the expansion of cropland which increased by about 25% since 1980 (see Figure 4.6). Hence, while precipitation was decreasing, livestock density increased. Additionally, in contrast to cereal production, the volatility of livestock numbers has decreased over the past decade mainly due to the stabilizing effect of fodder subsidies.

However, degradation of rangelands in Morocco is not only caused by high stocking rates, but also because of ploughing of marginal lands and an increasing demand in firewood for cooking and heating (Davis, 2006; El Moudden, 2004; Le Houerou, 1996). Particularly pastures with sufficient precipitation (>200 mm p.a.) and proximity to settlements are affected by degradation, since the human influence is decisive on these ecosystems (Finckh & Goldbach, 2010). On arid pastures, with precipitation below 200 mm, the anthropogenic influence is less pronounced, because vegetation of these ecosystems is mainly controlled by natural water scarcity (Finckh & Goldbach, 2010).

Besides husbandry of sheep and goats, the production of cow milk has become increasingly important, experiencing an increment in production by a factor of three within the past 30 years. Diary farming is well integrated into small scale farming, since for instance 85% of milk producers in the southern parts of the country have less than three cows (Maroc, 2008a). Because income from milk production is relatively stable, it is seen as an adequate measure for poverty reduction and income diversification. That is why the new Moroccan agricultural strategy is aiming at up to a doubling of milk production till 2020 (Maroc, 2008a), even though dairy farming in North Africa is expected to be negatively affected by climate change (Ben Salem & Bouraoui, 2009).

The traditional diversification of income sources in Morocco between farming and livestock keeping in rural households is currently developing into a "multi resource economy" (Casciarri, 2006). New options of livelihoods, such as engaging in wage labour, and national or international migration of household members allow a wider diversification of income sources (Rössler *et al.*, 2010b). In the southern province of Ouarzazate for instance (see Figure 4.1), already 44% of the working population are engaged in some sort of wage labour which decreases their dependency from agriculture and promotes sedentarity (Breuer, 2007a). Hence, 42% of former pastoral households gave up their mobility (Rachik, 2007).

Plan Maroc Vert

In 2008 the Moroccan government released a new agricultural strategy, called "Plan Maroc Vert" (PMV, Maroc, 2008b). Beside the objective of promoting "aggressively" (Maroc, 2008a) the productivity of the Moroccan agriculture, the PMV addresses climate change (Maroc, 2011), overexploitation of groundwater reserves, and alleviation of poverty. Main feature of the strategy is a distinction of two pillars: Pillar one is aiming at promoting a "modern agriculture, competitive, with a high added value and adapted to markets" (Maroc, 2008a:1). Pillar two is dedicated at "combating poverty through amelioration of agricultural revenues" of small scale farmers (ibid.). The PMV is accompanied by planned investments of 12-17 Billion Euros, whereby almost 90% of investments are dedicated to pillar one (Maroc, 2008b).

Measures to achieve an increase in agricultural productivity according to the PMV of up to 59% till 2020 are mainly: intensification of production techniques, extension of cropland, improvement of localized irrigation techniques and an improved processing of agricultural products (Maroc, 2008a). Furthermore, it is discussed that the decentralization of agricultural policy and a combination of governmental interventions with traditional resource management systems is a major achievement of the PMV, too (Toumi, 2008). In contrast to the previous agricultural policy, the priority is shifted from cereal production to production and processing of vegetables, citrus fruits and olives for a growing international market. For instance, the extension of crop areas and improvements in processing of olives are expected to increase the added value of olive products till 2020 by a factor of four (Maroc, 2008a). However, given the projections of climatic changes and their effects on agricultural productivity in North Africa (see section 4.3.2), it remains questionable if the ambitious goals of the PMV can be reached. Below, we will turn to the question, if the focus is set legitimately on an agriculture which is considered to serve as the "principle motor of national economic growth" in times of climate change (Maroc, 2011:7).

In summary, the current development of the Moroccan agriculture can be described by “mechanization, market orientation and specialization" for the farming sector, and “maximization” for the pastoral sector if sufficient capital is available. The question has to be raised now, how effective these measures were at coping with past droughts and what options exist for the future.

4.4.2 Impacts of climate change on agriculture and societal stability

In this section we will discuss expected impacts from climate change in Morocco on agriculture and implications on income security, social inequality, food security, and hence, societal (in-)stability. We concentrate on the impacts on agricultural production because, as shown in section 4.3, it is the main component which attributes to vulnerability of Morocco to climate change. Agriculture will be threatened by soil degradation as well as altered average conditions for plant growth. An increased frequency of droughts has already shown socio-economic impacts in the past.

Soil degradation and yield losses

Soil erosion in general threatens the possibility of North African countries to adapt to climatic changes (e.g. Iglesias *et al.*, 2010; Requier-Desjardins, 2010). Already 75% of arable lands in Morocco are affected by erosion (Maroc, 2011). However, concerning projections on erosion, future land use is decisive concerning projections on erosion rates (e.g. Kosmas *et al.*, 1997). As shown in section two, peak rainfall rates are not expected to increase for the north western part of Morocco. Thus, in this area, erosion rates will largely depend on land use practices. In contrast, projected extremes in daily rainfall in the Atlas Mountains will be able to increase erosion rates of fertile lands. For instance, under present-day land use, climate change would increase erosion from rangelands in southern Morocco until 2050 by 25% (Linstädter *et al.*, 2010). In the worst case, with more intense livestock grazing and increased firewood collection which is likely due to population pressure, erosion in this area might even increase by up to 45%. However, also a decrease of erosion by 30% is possible under the assumption of less intense livestock grazing and less firewood collection. Thus, in general, human influence on erosivity superposes the effects of altered precipitation in Morocco. Given the governmental objectives of increasing the area share of olives and citric fruits (Maroc, 2008b), it is plausible that erosion rates might be decreasing in the future, since perennial crops show good properties concerning erosivity if at least a minimum of understory is allowed (Kosmas *et al.*, 1997).

Shifting rainfall patterns and a reduction in average values of precipitation will lead to a decrease in average agricultural productivity in Morocco by around 30% till 2080 (see Table 4.2). Especially legumes and cereals will be affected by less favourable growing conditions and might experience a decrease in productivity of 40% and 15%, respectively, given climate projections for 2030 to 2060 (Giannakopoulos *et al.*, 2009). Prospects of further yield increases for cereals are generally limited (Latiri *et al.*, 2010).

Higher rates of evapotranspiration will increase salinization of irrigated farmlands if no adequate measures are taken to prevent a deterioration of the current situation. In the case of salinization, as in the case of soil erosion, human management is decisive for making projections. It has been shown for Morocco that within less than 20 years, irrigated soils can suffer a loss of more than 50% of their productivity through salinization (Badraoui *et al.*, 1998). Hence, since a big part of the Moroccan agricultural income is generated by irrigated agriculture (Badraoui *et al.*, 2000), the problem of salinization is critical: It is a problem on its own and it will considerably aggravate negative impacts from climate change.

Both, climatic changes as well as salinization of soils will hit hardest the poorer parts of the Moroccan population, since 57% of poor people are considering agriculture as their major income source, and even up to 75% in rural areas (Maroc, 2011). Additionally, 48% of irrigated farmland is managed by small to medium-scale farms where quality of irrigation techniques is widely varying (Debbarh & Badraoui, 2002). However, even more severe can be the impacts of an increased frequency and intensity of droughts, which already have led to visible social unrest in the past. Therefore, we will now turn our focus to past and future impacts of droughts.

Droughts

As mentioned, droughts are a common phenomenon in Morocco. Analyzing the period of 1456 to 2002, Touchan *et al.* (2008) find on average 16 single drought years per century. The 20th century lies above this average with 19 single drought years (ibid.). For the time period 1912 to 1992, Swearingen (1992) gives an average interval between droughts of only three years. So far, no chronological pattern has been identified (Skees *et al.*, 2001; Swearingen, 1992). As shown in 4.2, the trend of increasing temperature and mainly decreasing precipitation will increase the drought risk for Morocco in the future (see also Karrouk, 2007; WBGU, 2007). To assess what impacts these droughts could have on Morocco's agriculture, economy and food security, it is of interest to investigate effects of past droughts.

Morocco's most important agricultural product over the past decades has been wheat (FAO, 2010b; Kamal, 2008). Its production is highly sensitive to climatic conditions. During the drought period of 1971 to 1975 the wheat production fell by 27% from the first to the last year of the drought. The drought also decreased the number of sheep by 22% and goats by 17% during the same period (FAO, 2010b). The reduction of livestock was similar in further drought periods (1979 to 1983, 1994 to 1995) but decreased after 1995 due to fodder subsidies (see Figure 4.7). The wheat losses during the last decades became less dramatic from the beginning to the end of each drought period, but each drought invariably included one year of drastic reduction, and variability of yields and harvested areas is very high (see Figure 4.6). Compared to the last year before a drought, wheat production declined by 51% in 1981, by 80% in 1994, by 36% in 1999, and by 50% in 2005 (Figure 4.6). The most recent drought of 2007 in North Africa hit Morocco hardest, causing the wheat production to drop by 76% (compared to 2006). To compensate for the losses, the government significantly increased the import of cereals over the past decades and especially during drought years (FAO, 2010b). Consequently, the wheat supply per capita was not as strongly affected as the production. In general, undernourishment was not a widespread problem in Morocco as only 5% (1990 through 2002) or less (2004 through 2006) of the population have suffered from it (FAO, 2010b). Still, Morocco's vulnerability to climate change may have a certain conflict potential and/or can lead to social inequality.

There are some indications for a link between drought, food security and social instability in Morocco. In 1981 and 1984, drought "played a pivotal role" in "food-related insurrection" and "greatly exacerbated existent social and economic problems" (Swearingen, 1992:408ff)[16]. Seddon (1984) further points to Marrakesh, where drought "had seriously affected the availability of food and the cost of living" (Seddon, 1984:11), especially for the poorest of the society (Glantz, 1994). More recently, riots broke out in Morocco in early 2008 after a year of severe losses in food production (see Fig. 4.6 and Guardian, 2008). However, the drought related production losses were only one factor leading to social disruptions. High global food

[16] see also Brauch (2007)

prices as well as national (food price) policies also played a significant role in the outbreak of violence (Swearingen, 1992). Further, the violence did not destabilize Morocco nationwide but rather occurred on a more localized level. Nonetheless, regarding an increasing urbanization and strong growth in population, it is essential to improve options for adaptation to drought in order to avoid price shocks and food insecurity.

Social inequality

Contribution to social inequality can be another effect of more frequent and intense droughts. Pastoral livestock husbandry, using climate sensitive rangelands, is here a key element. In rural areas of semi-arid Morocco, pastoralism offers jobs for up to 38% of the working population, while 60% of herders own less than 60 sheep and goats (Maroc, 2008a). Small scale livestock keeping additionally serves in many cases as a saving asset (Lybbert *et al.*, 2009b). However, as Quaas *et al.* (2007) show theoretically, a diversification of income sources, as presently observed for Morocco, might shift the objective of larger-scale pastoral production away from risk minimization towards profit maximization. This promotes unsustainable ways of rangeland management. For Morocco, it has been shown that wealthier families rely less on natural resources, because they can afford buying fodder during droughts (Hazell *et al.*, 2001; Kuhn *et al.*, 2010). As an effect of that behaviour, herd sizes are increased artificially during times of fodder scarcity (see Figure 4.7). For the poorer livestock owners, the impacts of droughts will therefore very likely become more severe in the future, because the high grazing pressure on natural vegetation leaves little reserves for buffering water scarcity without subsidized or purchased fodder supply. After droughts, the herds of poorer farmers will then be more reduced in size than the herds of wealthier ones; and the latter ones are then in a position of using the resources of a recovering vegetation more efficiently (Zimmerman & Carter, 2003). Therefore, poorer families might get poorer and wealthier ones wealthier (Werner, 2004). If no social adjustment mechanisms are in place, this development is likely to aggravate income disparities and can turn into a vicious cycle (Lybbert *et al.*, 2009b).

4.4.3 Future options of adaptation

As shown, shifting precipitation patterns, more frequent and intense droughts as well as a general reduction in precipitation in Morocco have certainly the potential to contribute to income inequality, limited food security and shocks in food prices. Those are ingredients for societal instability. It is therefore important to consider pre-emptive agricultural and socio-economic policies which seriously take into account climate change and its societal implications.

Set of options: preconditions for adaptation

In general, adaptation to climate change arises by interaction of two major (groups of) agents: firstly, private actors, including associations on communal level and commercial enterprises; secondly, governmental initiatives. Figure 4.8 summarizes possible adaptation strategies and shows the potential influence of governmental initiatives on farming and pastoral activities.

At a first glance on Figure 4.8, one precondition for successful adaptation to climate change can easily be seen: It is the ability, in principle, to activate the full spectrum of alternatives, which means that private entities as well as governmental initiatives are active. The new Moroccan agricultural includes this notion as "aggregation" of governmental and private initiatives (Maroc, 2008b). In contrast to the more centralized policies of the past, a decentralized agricultural policy is therefore legitimately considered as a key factor for a vital agriculture, in which governmental agencies recognize the small-scale farmers as most important agents (Toumi, 2008). However, since the majority of small scale farmers can also be considered poor, it remains questionable why the Plan Maroc Vert (PMV) dedicates only 12% of the intended financial resources to the fight against poverty (Maroc, 2008b).

Another feature which becomes visible in Figure 4.8 is that farmers and pastoralists can either adapt to climate change or switch to alternative livelihoods. However, alternative livelihoods often affect agriculture in an indirect way. For example, nomads who decide to get sedentary increase demand in firewood in the surroundings of settlements. This in turn decreases fodder availability for livestock and increases dependency on supplementary fodder. Hence, each policy needs to be sensitive to the described complexity of the actor-actor and human-environment interlinkages.

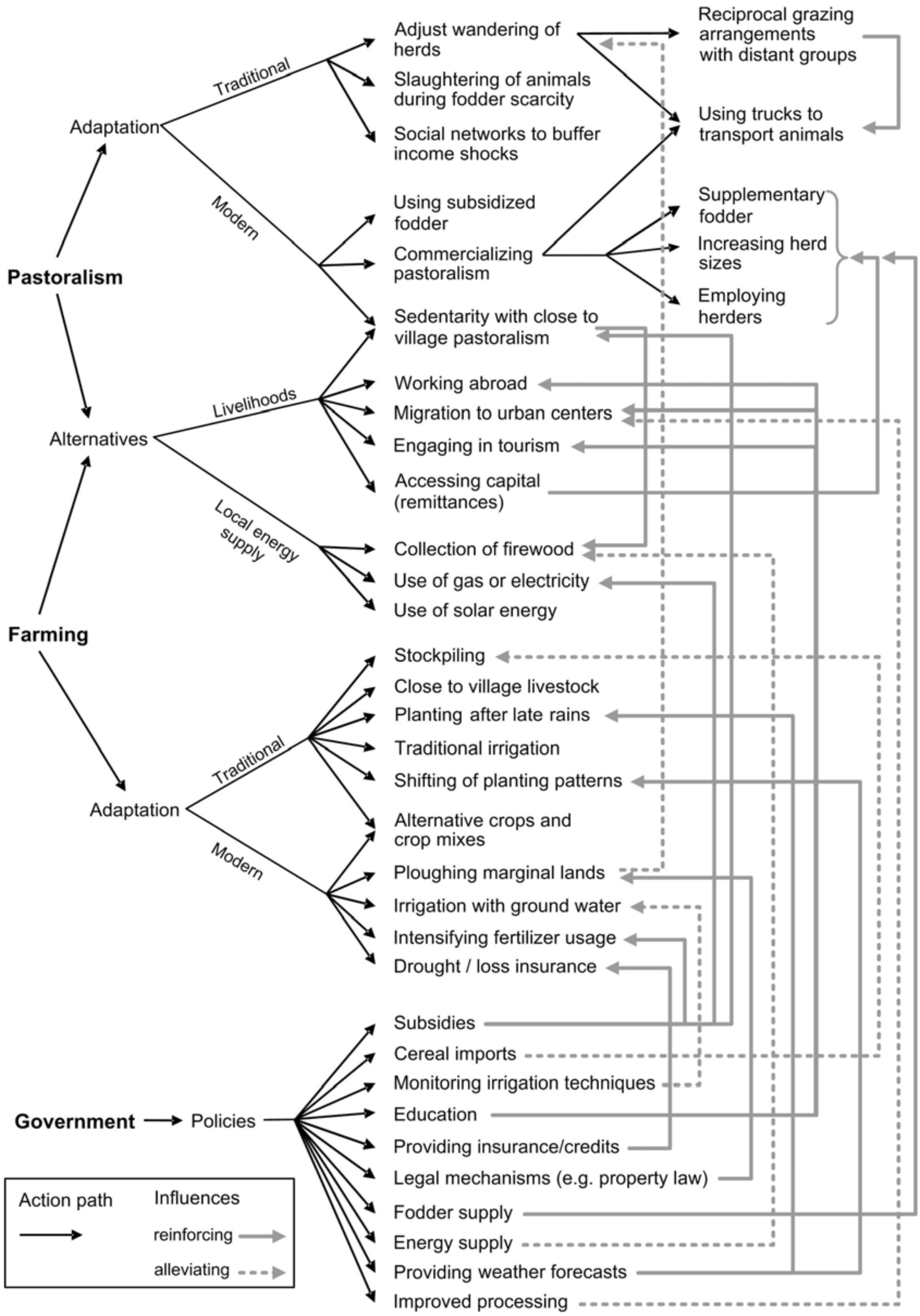

Figure 4.8: Adaptation options and action paths of pastoralists, farmers and the government in Morocco (own representation)

In general, adaptation strategies which are indicated with "traditional" in Figure 4.8 can be expected to be of less environmental impact, because these strategies evolved over hundreds of years (see section 4.4.1). Therefore, policies promoting traditional adaptation strategies can be regarded as "safer" concerning negative side effects. However, increasing population pressure as well as the necessities of the Moroccan economy make it inevitable to include modern adaptation strategies to sustain the functioning of the country's socio-economic system. Since these modern adaptation strategies in some cases are accompanied by critical side effects, a careful monitoring and assessment of their results is essential.

Farming

Since options for expanding irrigated areas are limited (Badraoui *et al.*, 2000), adaptation to projected precipitation patterns in rain fed agriculture has to arise from altered land use practices. As we showed in section 4.2, average yearly precipitation is decreasing, but monthly precipitation is likely to increase from December to February. Thus, during the phase of highest water demand, the supply of water by precipitation and soil storage will be sufficient. For most parts of rain fed Morocco, the negative effects for cereal farming could therefore be compensated by shifted planting patterns, since early growth stages are most important for cereal yields (Latiri *et al.*, 2010). However, due to the decreasing trend in precipitation for April and May, an emphasis on the traditionally used barley as dominant cereal can be recommended, since barley ripens faster than wheat.

As shown, the expansion of cropland, the increasing usage of nitrogen fertilizer, and a mechanization of agriculture were able to increase harvests in Morocco during the past. However, shocks from droughts were amplified by these new techniques (Figure 4.6). Ploughing of marginal lands additionally degraded rangelands and decreased buffering capacities and the ability of mobile pastoralists to adjust their wandering in dryer years. Concerning future prospects, the focus of agricultural production should therefore be shifted from maximization of outputs towards stabilization of outputs. This would have three effects: First, the year to year variation in agricultural outputs would decrease, which in turn increases efficiency of processing of agricultural goods because of the possibility to utilize capacities more continuously. Second, traditional adaptation strategies of the livestock sector would be strengthened. Third, even though prices of agricultural goods would be higher in good years due to lower domestic supply (which might even stimulate other adaptation mechanisms), production losses in years of drought would be reduced by producing on qualitative good soils with low salinity, and by using groundwater capacities primarily to buffer years of drought. In this way, price shocks and dependency from international markets during droughts would be reduced. The latter point is especially interesting, because, as shown in the previous section, food riots are decisively influenced by international food prices. Independency from international food markets in years with limited rain is therefore a measure of reducing conflict potential caused by climate change.

Within a shift from maximization to stabilization, much more emphasis should be given to the problem of salinization: A higher present-day output of soils under irrigation might come at a high price of severe losses of production in the future if inadequate techniques are used (Badraoui *et al.*, 1998). Salinization has the potential of strongly amplifying impacts of climate change. Therefore, as already suggested for Morocco (Debbarh & Badraoui, 2002) and as partly done by countries like Egypt or Pakistan (Smedema & Shiati, 2002), every irrigation project should be accompanied by measures to ensure leaching and drainage of the soils, as well as a monitoring of mobilized salts and their effects on other components of the hydrological system. Such a monitoring system could in turn also improve management of groundwater resources (see Figure 4.8).

At the producers' side of agricultural products, area-based rainfall insurances offer the option to buffer income shocks during droughts. In contrast to subsidies, which can show many negative side effects, rainfall insurances could improve the resilience against droughts through financial means without interfering significantly with the actual land use strategies (Hazell *et al.*, 2001; Skees *et al.*, 2001). In Morocco, a rainfall insurance programme of the World Bank failed in the 1990s because of a continuing non-stationary downward trend in precipitation (Lybbert *et al.*, 2009a). However, governmental support of the private sector in order to establish innovative insurance schemes could be a promising complement to technical options of adaptation.

For Morocco there is a certain potential in seasonal weather forecasting (see section 4.2). Substantial losses of investments due to crop failure in rain fed areas could therefore be prevented in the future. Furthermore, even yield increases in good years could be achieved by using seasonal weather forecasts: In more drought prone areas farmers often hesitate to apply adequate amounts of fertilizers in order to minimize losses from low returns of investments in dry years (Latiri *et al.*, 2010). Given sufficient precise weather information in the future, it might be of interest for those farmers to apply adequate amounts of fertilizers in order to achieve higher returns.

For oases in southern Morocco, agricultural income is likely to be 17% to 30% less in 2020 than the average of 1972-2000, even though groundwater consumption is likely to double (Kuhn *et al.*, 2010). A different pattern of water usage or groundwater pricing has been identified as a measure to abate these losses. However, both options face several problems concerning administrative, social and equity issues (Kuhn *et al.*, 2010). One focus of the new Moroccan agricultural strategy lies therefore on improving the processing of agricultural primary products (Maroc, 2008b). It has been shown that the net monetary return from irrigated agriculture is comparably low with about 0.2 Euro per cubic meter water in Morocco, which indicates potential for improvements (Badraoui *et al.*, 2000; Maroc, 2008a). For instance, since presently products from olives show a considerable range of net returns, there can be expected an increment just by improving the processing (Maroc, 2008a). Since processing facilities for agricultural products offer additionally the option to create labour opportunities in rural areas, it might as well reduce the incentive for educated people to migrate to urban areas and slow down the rate of urbanization (see Figure 4.8).

Pastoralism

Given the dependence on socio-economic boundary conditions such as firewood collection, the development of the pastoral livestock sector in Morocco is hardly predictable. If precipitation will become too scarce in order to pursue pastoralism, 38% to 50% of transhumant pastoralists in the south indicate to give up transhumance and opt for sedentarity as the main alternative option (Freier *et al.*, 2011a, chapter 3). However, sedentarity with irrigated agriculture as alternative will put further pressure on groundwater resources and arable lands (Kirscht, 2008). In order to activate other livelihood alternatives instead of sedentarity, such as working abroad or engaging in tourism, it can be shown that a better access to capital as well as education are prerequisites in this highly unpredictable setting (Freier *et al.*, 2011a, see also Fig. 4.8 and chapter 3). Investments in education can therefore be regarded as an option to adapt to climate change without considering agricultural techniques as a major controlling element.

In the past, many governmental options which have been used in the pastoral sector with respect to drought mitigation risk "achieving little more than postponing disaster and [...] interfering with indigenous recovery systems" (Blench & Marriage, 1999). In contrast, traditional property rights have managed rangeland ecosystems mostly in a sustainable way by incorporating local ecological knowledge over long periods of time. This fact rarely has been appreciated by governmental institutions (Davis, 2006; Linstädter *et al.*, 2010; Smith, 2005) and is certainly worth more emphasizing. Re-arranging traditional management systems whilst preserving their traditional core is therefore an option to increase resilience of pastoral livelihoods.

A more recent innovation in the pastoral sector, which offers a further option for adaptation, is commercial pastoralism. Increased herd sizes, trading of animals for supplementary fodder, employing additional herders, and using trucks to move herds to adequate pastures is typical for this new mode of pastoralism ("truck transhumance", Breuer, 2007b). It allows livestock owners getting less dependent of price fluctuations and variability of weather. For many pastoralists, commercial pastoralism is seen as an attractive alternative. However, having sufficient capital (livestock or financial) is again a pre-condition for this alternative (Freier *et al.*, 2011a). Hence, this points to a further problem of social inequality, because it shows that wealthier pastoralists have more options to adapt to climate change than poorer ones (Werner, 2004).

Truck transhumance, additionally can cause social conflicts, for example over the access and property rights of distant pastures (Breuer, 2007b). Further, commercial pastoralism promotes insufficient destocking during droughts and high stocking rates if local and non-local herds coincide. This in turn can easily lead to degradation of rangelands and impoverishment of traditional pastoralists. It is therefore important that innovations emerging from the private sector which have the potential to abate impacts from climate change, such as commercial pastoralism, are scrutinized on possible negative side effects. Regulation of these side effects can then be addressed from communal or governmental institutions.

Rural energy supply

An interesting option for adaptation to climate change arises from the plan of the Moroccan government to install solar power plants with a capacity of 2000 megawatt till 2020 (Maroc, 2010). The envisioned project thereby offers the option to combine a stimulus for economic development in semi-arid rural areas with the possibility of replacing firewood demand by solar powered electricity.

In Morocco, the majority of energy demand in rural areas is currently satisfied through firewood (El Moudden, 2004). This is putting significant pressure on vegetation and reduces buffering capacities towards droughts and climate change.

Using a bio-economic model of pastoral livestock husbandry, we investigated the potential of replacing firewood collection from rangelands in order to increase buffering capacities of the vegetation. The model was parameterized for a village located in the Ouarzazate province south of the High Atlas Mountains using sedentary livestock. The pastures of the village are situated at an altitude of 1900 meters and have an average precipitation of 270 mm per year (see Figure 4.1 for exact location). A detailed description of the model can be found in Freier *et al.* (2011b, see chapter 2). We simulated reductions in precipitation as projected for the 21st century, and left it to the model to arrange grazing intensities. The model used the objective of optimizing revenues with planning horizons of two and five years, and with perfect foresight (indicated as "optimal" in Figure 4.9). Additionally, we investigated a scenario, where we assumed an alternative energy supply and thus disabled collection of firewood from rangelands.

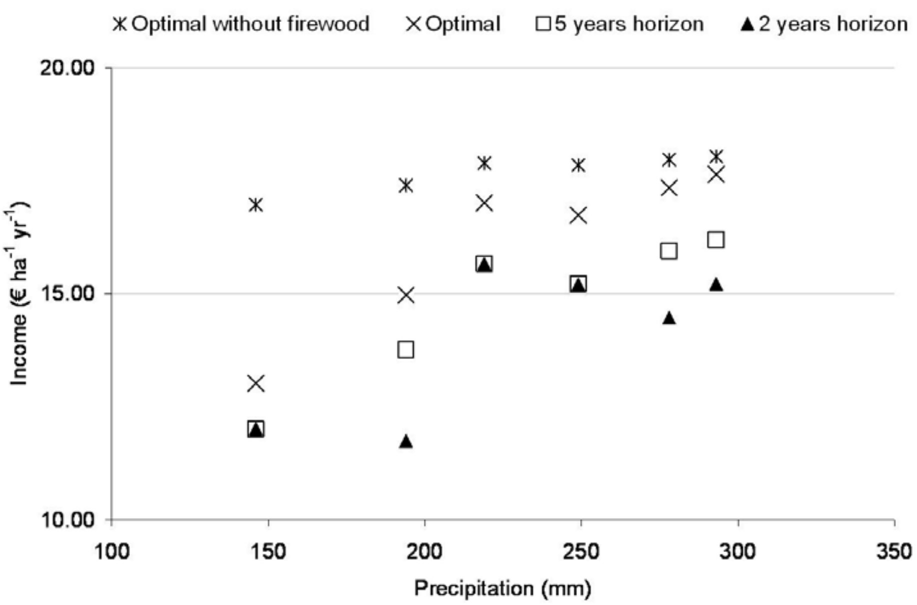

Figure 4.9: Income from livestock husbandry without transhumance (own calculations). Different optimization horizons were used. Optimal: land users have perfect foresight and maximize their profits over 20-years; Five and two years horizons: land users optimize only with respect to the given time horizon (myopic behavior); without firewood: energy demand for cooking and heating is covered by other sources than firewood from rangelands

The results of the simulations (Figure 4.9) clearly show the significant potential of compensating impacts of climate change on rangelands by replacing firewood as traditional energy source. Even under a scenario with a reduction of precipitation by 45% (less than 150 mm in Figure 4.9), revenues from pastoral livestock husbandry without firewood collection are still higher than present-day values with firewood collection. Thus, replacing rural energy supply is legitimately considered since long as a promising remedy to increase resilience and agricultural productivity of semi-arid to arid rangelands (Le Houerou, 1996).

In the Ouarzazate province, rural households represent around 300 000 people with an energy consumption of about 140 MW (El Moudden, 2004; Maroc, 2008a). A 500 megawatt solar power plant, as presently under construction in the Ouarzazate province (Bakkoury, 2010), could easily satisfy the energy demand for cooking and heating of these households, if sufficient network capacities are provided. The initiative of creating the Moroccan Agency for Solar Energy (MASEN) in 2010 (Maroc, 2010) is therefore not only promising from an economic perspective, but it has as well the potential to contribute to adaptation to climate change by reducing human pressure on natural rangelands.

4.5 Synthesis

After having addressed climatic changes and vulnerability in North Africa, as well as impacts and adaptation options for agriculture in Morocco, we are now able to summarize our findings and to conclude our assessment.

4.5.1 Summary

The trend of increasing annual mean temperatures that has been observed for the second half of the 20th century in North Africa is likely to continue and to cause warmer and drier conditions. Temperatures are likely to rise between 2 and 3°C while precipitation is likely to decrease between 10% and 20% until the year 2050 under the SRES A1B scenario. North-western Africa could experience a very strong warming of up to 6°C in the 21st century. Although, projections of future climate change for Africa exhibit considerable uncertainties (including the possibility of the greening of the Sahara), both the risk and the duration of droughts are likely to increase in Northern Africa.

Water scarcity (highest in Libya and Algeria) and the dependency on rain fed agriculture (highest in Morocco) contribute to the sensitivity of the region. The sensitivity is increased by population growth which is strongest in Egypt. The adaptive capacities of the North African states are lower than in Europe but higher compared to the average of the African continent. Low per capita income and its unequal distribution (most unequal in Morocco and Tunisia) limit the generic adaptive capacity while the high level of corruption is a general weakness of the impact specific adaptive capacity. In summary, climate change exposure, pronounced sensitivity and limited adaptation capacities make the region and Morocco in particular, vulnerable to climate change. Concerns that the vulnerability to climate change could contribute to social instability are reasonable. Despite the political and social changes of 2011, our analysis of conflict implications find Algeria, Egypt and Morocco to be most prone to climate change related instability.

In Morocco, the social stability has already been affected by past droughts. Climate change is likely to cause a decrease in primary agricultural production in the 21st century in Morocco of 15% to 40%. Future droughts additionally have the potential to increase social inequality, and threaten social stability by severe shocks in food prices. Both, reduction in productivity and impact of drought will be strongly aggravated by soil degradation, mainly due to salinization if the current development is projected into the future.

The incentives used in the past to increase the agricultural production in Morocco are inadequate to buffer effects of droughts, especially for the poorer part of the population which still depends largely on income from agriculture. On the contrary, some recent developments like cropping of marginal lands, depletion of groundwater resources, and the growing of wheat instead of the traditionally used barley are likely to increase the vulnerability of the agricultural sector to climate change.

The new agricultural strategy of Morocco "Plan Maroc Vert" addresses some of these issues as it builds on two pillars: output maximization for industrial agriculture and the fight against poverty for small-scale agriculture. The emphasis on increasing the added value of agricultural products, such as from olives, indicates a shift in policy which has additionally the potential to reduce the rate of urbanization by creating job opportunities in rural areas. However, agriculture is still seen as a major motor of the future Moroccan economy which bears the risk of increasing present-day output while sacrificing future durability.

Analyzing policy options for adaptation we find a great variety. In general, it can be recommended to switch the focus of agricultural production from output maximization to output stabilization. For rain fed agriculture, the shifting of planting patterns and adjusting of planted crops is able to reduce impacts of climate change substantially, but a monitoring of irrigation practices and soil conditions will be crucial to secure future productivity. Area based rainfall insurances as well as future improvements of seasonal weather predictions are further options to reduce vulnerability.

Since poorer parts of the population have less options of adaptation and will be affected more heavily, agricultural interventions should be accompanied by measures which balance social inequalities. This will contribute to social stability.

A commercialization of pastoral livestock husbandry can be recommended if it is closely linked to an empowering of traditional management institutions. Additionally, our bio-economic model shows that a replacement of firewood by electric energy supply is able to over-compensate the impacts of climate change on semi-arid rangelands in vicinity to settlements. Pushing forward the development of solar power plants in arid areas, as envisioned by the Moroccan government, is therefore promising because it combines a stimulus for the domestic economy with the adaptation to climate change.

4.5.2 Conclusions

The significant challenges posed by climate change increase the importance of adaptation in North Africa. Adaptation measures have to address the specific elements of exposure and sensitivity to efficiently reduce vulnerability. Further, adaptation to climate change can not be achieved by one sector alone.

For the agricultural sector, strategies are most promising which focus on conservation of productive assets instead of depleting them to maximize present day output. A mismanagement of soil quality, rangeland vegetation, and groundwater extraction will have severe consequences in the future since it amplifies the impacts of climate change.

There are many options for adaptation to climate change available in agriculture. In the past, traditional options have been considerably altered and partly devaluated in the course of a restructuring of institutional regulation. In order to take advantage of the full spectrum of technological innovations such as localized irrigation and commercial pastoralism, it is necessary to have strong monitoring mechanisms to ensure a sustainable application. The efficiency of the monitoring mechanisms depends on the degree to which they include local and specific knowledge. This suggests a decentralization of structures.

Failure to implement policies which address both, agriculture specific needs and socio-economic developments, considerably increases the risk that climate change contributes to social inequality and instability in North Africa.

Acknowledgments

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Chapter 5

Adaptation to new climate by an old strategy? Modelling transhumant and sedentary pastoralism [17]

In our study, we examine whether the current trend towards more sedentary pastoralism increases vulnerability towards climate change in the 21st century. A mathematical land use model based on empirical data is used to address this research question for a case study region in southern Morocco. The model includes vegetation dynamics, stochastic weather, and far sighted human decision making. Mobile livestock in the model is enabled to move seasonally, sedentary livestock is restricted to pastures around settlements. The share of pasture and the amount of high-quality fodder which is dedicated to mobile pastoralism is subject to scenario analyses. For a reduction of average precipitation by 20%, which is likely for the middle of the 21st century, our model shows for different drought scenarios a decrease of total income from pastoralism by 15-37%. Sedentary pastoralism is affected by 23-39% while mobile pastoralism is only affected by 8-31%. Increasing the share of pasture area and fodder used for mobile pastoralism under future climatic conditions is able to abate impacts from droughts in total income by 11%. We show by our land use model that policies which are aiming on sedentarization of former mobile pastoralists in semi-arid areas enhance their vulnerability towards climate change.

5.1 Introduction

Livestock husbandry worldwide secures presently livelihoods of more than 600 million people, most of them living in semi-arid areas of developing countries in Asia and Africa (Thornton *et al.*, 2009). Projections of future developments in these

[17] This chapter has been submitted to *Global Environmental Change* as: Freier KP, Finckh M, Schneider UA: Adaptation to new climate by an old strategy? Modelling sedentary and mobile pastoralism in semi-arid Morocco; more than 90% of the work of this chapter has been done by Korbinian P Freier.

countries show an increasing population pressure (Millennium Ecosystem Assessment, 2005) and reductions in rainfall due to climate change (IPCC, 2007b). Possibilities to secure livelihoods of people in the affected regions are therefore of great interest.

For centuries, livestock husbandry in most semi-arid regions was dominated by mobile pastoralism (e.g. Smith, 2005). During the last decades, lifestyles of pastoralists have changed because of social, ecological, economic, and political developments (Niamir-Fuller, 2008). Many formerly mobile households have settled, and their members engage in agriculture and wage labour. Large-scale herd mobility has been replaced by a more localized pattern of livestock husbandry (e.g. Turner & Hiernaux, 2007). We want to investigate for a case study in southern Morocco, how this shift from mobile to sedentary pastoralism affects resilience to climate change.

Though the movement of pastoralists in semi-arid areas is motivated considerably by social reasons such as political liberty (Kaufmann, 2009; Marx, 2006), nomadic livestock husbandry allows pastoralists to access grazing resources in areas which are inadequate for permanent usage because of poor soils, vulnerable vegetation, temporally restricted fodder availability, or scarce precipitation. Mobile pastoralism may therefore be described as an evolved adaptation of livestock husbandry to scarce feed biomass and variable rainfall patterns (Chatty, 2006).

However, while mobile pastoralism is an adaptation to variable climate, it is still hit by droughts which can lead to huge losses of animals and deprive many people from their means of subsistence (Hazell *et al.*, 2001). Furthermore, since rainfall is the principal factor that limits vegetation growth in subtropical semi-arid areas, a large scale downward trend in precipitation over decades and centuries cannot be mitigated by any kind of mobility. For North Africa, climate researchers expect until 2100 reductions in rainfall by 10% to 30% compared to the beginning of this century (e.g. Paeth *et al.*, 2009; Sillmann & Roeckner, 2008). This climatic development will almost inevitably lead to a lower production of livestock, both from mobile and sedentary pastoralists. On the other side, income losses of the pastoralists might be compensated by higher prices for livestock in the future due to scarcity in supply and a higher income level of consumers (Thornton *et al.*, 2009). Additionally, global meat demand is growing at a factor of two compared to population growth (Niamir-Fuller, 2008).

Beside climatic changes, livestock husbandry in semi-arid areas is exposed to a larger set of changing boundary conditions: Young people are attracted by the "modern" way of life, with access to electricity, television, and internet. Furthermore, rural population is growing and wage labour in urban centres is often necessary as additional source of income (Breuer, 2007b); urbanisation is accelerating (Schilling *et al.*, 2011); and the introduction of technological innovations such as trucks in the 1970s and mobile phones in the late 1990s enable new modes of pastoral production, where larger distances can be covered and information about pasture conditions is rapidly spread. Politically, most mobile pastoralists additionally find themselves in a situation where governments predominantly promote settlement (Davis, 2006; Niamir-Fuller, 1999; Werner, 2007). As consequence of all of these drivers, a general trend from mobile pastoralism towards more sedentarization and commercialization of pastoralism has been observed for Morocco and other semi-arid areas of the subtropics during the last decades (Breuer, 2007a; Casciarri, 2006; Niamir-Fuller, 1999). For southern Morocco, this trend is expected to continue (Freier *et al.*, 2011a, see chapter 3). Additionally, the changes within the last decades have lead in some cases to a social disruption of pastoral livestock producers into "wealthy entrepreneurs", which are less vulnerable to weather conditions and socio-economic changes, and "marginalized pastoralists", which are highly vulnerable and threatened by impoverishment (Werner, 2004).

It is still unclear, to which degree pastoralism will be affected by global and climate change during the 21st century. Investigating future development possibilities of pastoralism in subtropical semi-arid regions is challenging due to a variety of influencing factors and complex relations between vegetation dynamics, soil dynamics, climate variability, livestock dynamics, and human management. Most current studies which examine different modes of pastoralism therefore focus on descriptive statistics and analysis of empirical data (e.g. Baker & Hoffman, 2006; Jones & Thornton, 2009; Seo & Mendelsohn, 2008; Turner & Hiernaux, 2007). Mathematical models that depict the underlying dynamics are rare, mainly because of a lack of empirical data to calibrate and validate such models, and difficulties of integrating biophysical models into models of human decision making.

In this study, we address this research gap and investigate options of future livestock management in the central High Atlas in southern Morocco by means of an exploratory land use model. Focus of our study is the question, how the pastoral system in this area will respond to expected precipitation changes during the 21st century, and how different modes of pastoral production are affected by these changes. Concentrating on the shift from mobile transhumant pastoralism to sedentary pastoralism, we investigate the effects of certain shares of mobile pastoralism on the output of a regional livestock system. With the results of our model at hand, we will discuss whether the traditional strategy of mobile transhumant pastoralism is a valuable adaptation for facing climate change.

5.2 Methods

To address our research questions, we solve a mathematical land use decision model (LDM) of pastoral livestock management for different scenarios of future climate, droughts, and different modes of sedentary and mobile pastoralism. The LDM depicts livestock herding at the southern slopes of the central High Atlas in Morocco. The model simulates vegetation dynamics, livestock growth, herd mobility, and farsighted decision making by livestock managers. Herd mobility is included into the LDM at a sub-regional scale. The model is parameterized and calibrated with empirical data from the semi-arid study area (Figure 5.1).

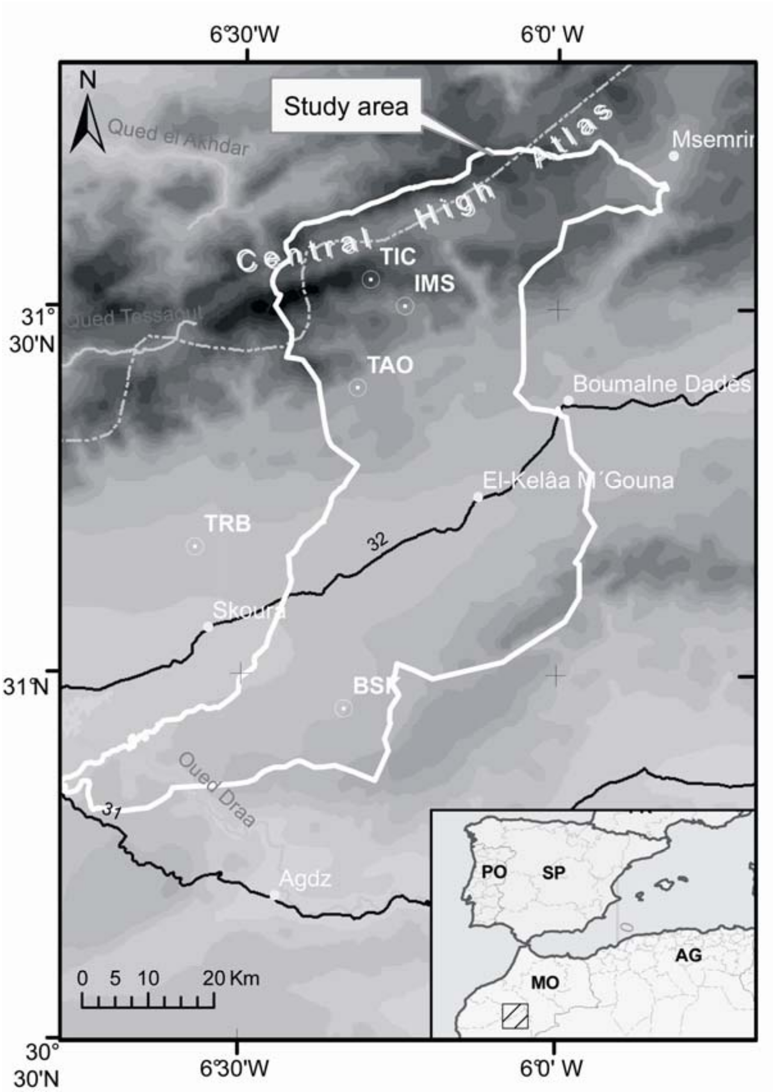

Figure 5.1: Study area located in southern Morocco. The boundary of our research area is given in bold white.

5.2.1 Study Region

The object of our study is a pastoral land use system in the upper Drâa catchment. It is located in the province of Ouarzazate in southern Morocco. Two research projects have been active in the region during the past 10 years (BIOTA Maroc, 2011; IMPETUS, 2011), which provide the empirical data basis for our modelling attempt. The research area of 3410 km^2 extends between the High Atlas Mountains in the north and the Anti Atlas in the south (Figure 5.1). The pastures in the High Atlas belong to territories of three tribal fractions, the Ait Zekri, Ait M'goun, and Ait Toumert. Pastures in the Anti Atlas are located within the territory of the Ait Zekri and the Ait Sedrate.

The upper Drâa catchment is characterized by a semi-arid climate. Annual precipitation ranges from about 100 mm in the basin of Ouarzazate to more than 600 mm in the High Atlas Mountains (Schulz *et al.*, 2010). This diversity in precipitation is due to an altitudinal gradient ranging from 1400 m above sea level in the basin to more than 4000 m in the High Atlas. Vegetation types follow site specific precipitation values, with *Hammada scoparia - Convolvulus trabutianus* semideserts in the basin of Ouarzazate and the lower parts of the Anti Atlas, and *Artemisia herba-alba* dominated sagebrush steppes in the higher parts of the Anti Atlas and towards the High Atlas Mountains. Vegetation above roughly 2500 m altitude can be characterized as oromediterranean scree and dwarf-shrub vegetation (Finckh & Goldbach, 2010).

Before the 1960s -1970s, livestock production in our research region was dominated by transhumant pastoralism, a type of mobile pastoralism which follows seasonal rainfall and vegetation changes (Casciarri, 2006; Rachik, 2007). Dominant livestock are goats and sheep. The transhumant mode of production was always combined with oasis-agriculture done by some family members. Presently, an estimated 22% of households still engage in pastoral activities where transhumance plays a role to a varying degree (Breuer, 2007a). For the future, most livestock owners tend to opt for sedentarity (Freier *et al.*, 2011a). Currently, 69% of our research area can be regarded as pastures used by transhumant livestock. The calculation of this area is based on collar data which show that sedentary animals are mainly found on nearby pastures which are less than 3 km away from settlements and within less than 400 m difference in altitude (Akasbi *et al.*, 2011).

In search of fertile pastures, transhumant herders move with their animals between the Anti Atlas in the south, the basin of Ouarzazate and the High Atlas Mountains in the north. The access to the pastures in the High Atlas is restricted to summer and autumn months (*agdal*) and to members of the tribal fraction which rules the respective territory (Rössler *et al.*, 2010a). Access to the pastures in the basin of

Ouarzazate and in the Anti Atlas with less average precipitation is shared among all kin groups which are considered in our study.

Characteristic for the region is that most families have at least one member which has emigrated to Europe and which considerably contributes to household income by remittances (Rössler *et al.*, 2010b). This opens up new alternatives in pastoral land use, such as buying additional fodder for livestock or investing in livestock as saving asset. This might be responsible for an increase in livestock density in the High Atlas Mountains as observed during the last decades (Chiche, 2007).

5.2.2 Land use decision model

We extend an existing LDM originally designed to describe grazing of sedentary herds around the village of Taoujgalt in the northern Ouarzazate province (Freier *et al.*, 2011b, chapter 2). The LDM is an optimization model which maximizes the number of goats and sheep over a planning horizon using a utility function. Control variables, which are chosen endogenously by the LDM to influence herd sizes, are selling of livestock and grazing intensities. The selling of livestock reduces herd sizes and generates income. The grazing intensities represent management decisions by herders such as how long animals stay on a pasture and how much biomass they are allowed to remove until they proceed to the next pasture.

Objective of the utility function of the LDM is a high number of living livestock and a high profit from sold livestock within the planning horizon. Both variables are weighted equally. This objective is subject to several constraints: (1) Livestock growth is limited by fodder availability and fodder quality, and follows a sigmoid growth function if fodder supply is fixed and no human management decisions are constraining growth such as selling of livestock. (2) Fodder availability is limited by the grazing intensity which is applied to a pasture. (3) Since the LDM represents vegetation dynamics, the grazing intensities and weather conditions of previous years also constrain fodder availability.

To achieve the dynamic representation of vegetation, the LDM includes a meta-model of EPIC (environmental policy impact calculator, Williams *et al.*, 1989). The meta-model uses above ground plant material (AGPM) as state variable and maps this variable to follow-on states using Markov chains. For every grazing intensity and weather scenario, the applied Markov chain uses specific state transition probabilities and thus, states of AGPM for each site depend on applied grazing intensities and weather conditions in the present and in the past. The individual state transition probabilities are computed from a sequence of EPIC simulations as described in Freier *et al.* (2011b, see chapter 2). Input data for the EPIC runs include soil depth, soil texture, soil pH, field capacity, wilting point, organic and inorganic carbon, nitrogen, slope, rooting depth, maximum plant growth height, and a parameter describing plant phenology (heat units). Daily weather data and soil parameters for calibrating the EPIC model are retrieved from the IMPETUS database (IMPETUS, 2011). Vegetation data is retrieved from the BIOTA-Maroc database (BIOTA Maroc, 2011).

The Markov chain based representation of vegetation dynamics is used to reduce the computational effort for modelling inter-temporal planning with forward looking behaviour. Daily time-steps used in EPIC are additionally reduced by our Markov chain representation to yearly time-steps as used in our LDM. However, since we use daily weather data as input for EPIC and individual Markov chains for each weather scenario, it is possible to represent different rainfall distributions over a year. A detailed description of the meta-model of EPIC and how it is included into the LDM can be found in Freier *et al.* (2011b, see chapter 2).

Human decision making is simulated in our LDM using dynamic optimization of a utility function over a five-year planning horizon. The entire run-time of the model spans 15 years. To simulate divergence of real weather from expected weather we incorporate the dynamic optimization into a recursive framework with yearly time-steps (Barbier & Bergeron, 2001). While the LDM uses a prescribed "real" weather for year one of the planning horizon, the average of observed weather from 2002-2009 is used as expectation for the remainder years. Only in year four of the planning horizon, the modelled pastoralists expect a drought to include risk-averse behaviour. The results of the first year of the optimization are then used as input for the next recursive step together with updated weather information. Hence, for every year in the recursive run, the LDM adapts its plans to prevailing weather conditions. The specification of a five year planning horizon together with a zero discounting of future utility as used in our LDM represents two assumptions. However, as shown in Freier *et al.* (2011b), the associated results seem to fit well to observed patterns of the land use system such as grazing intensities and flock composition.

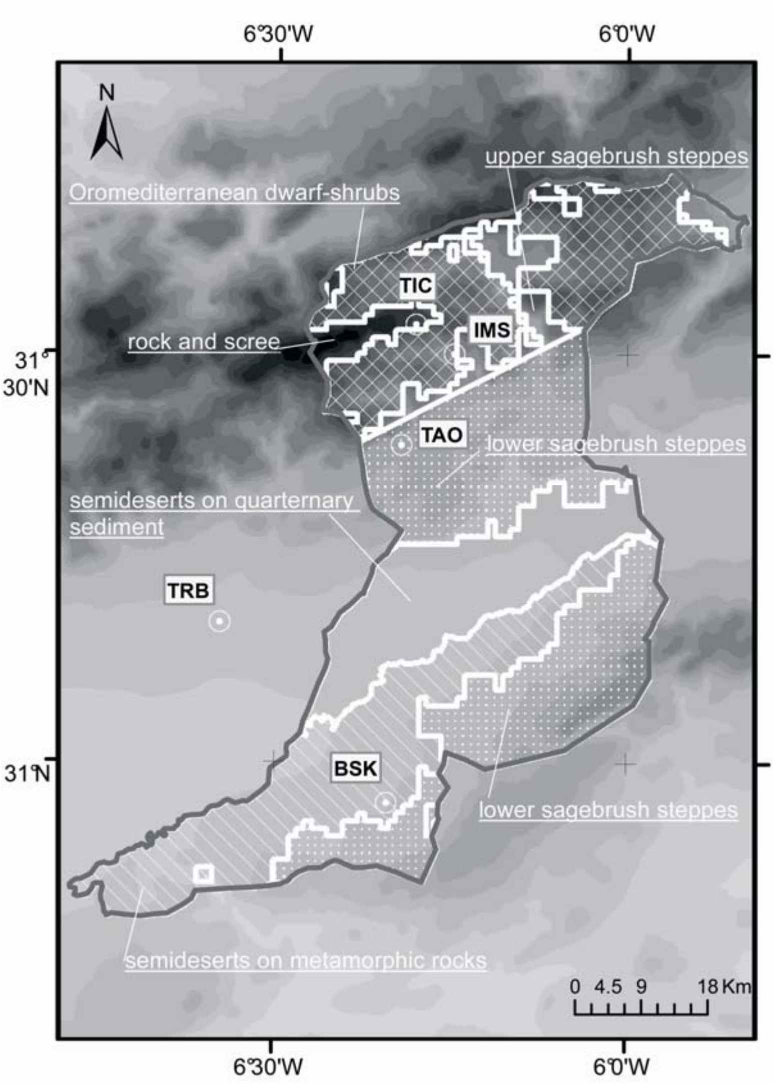

Figure 5.2: HRUs are established in order to correspond to one of five vegetation types. The location of the measurement sites are indicated with white circles.

Spatial resolution of the model is based on homogeneous response units (HRUs), which are used to further reduce the computational effort compared to a raster based resolution (Skalsky *et al.*, 2008). To construct the HRUs, the research area is classified according to five types of vegetation as observed in the field (Figure 5.2), which is again subdivided by three classes of slope (not shown in Figure 5.2). The considered vegetation types are: (1) Oromediterranean dwarf-shrubs; (2) upper and (3) lower sagebrush steppes; and semideserts on (4) quaternary sediment and on (5) magmatic and metamorphic rocks. The vegetation classes relate to five measurement sites (Table 5.1), where meteorological observations, vegetation monitoring, and livestock-exclosure experiments have been conducted from 2002 to 2009.

Table 5.1: Characteristics of five measurement sites used for calibration of our model. Figure 5.2 shows the location of these sites.

Test site (abbreviation)	Coordinates (lon/lat)	Altitude	Mean annual temperature	Mean annual precipitation	Mean AGPM (grazed/ungrazed)
Tichki (TIC)	-6.30289 31.53746	3174 m	4.6 °C	580 mm	6.5 t ha^{-1} 6.4 t ha^{-1}
Ameskar (IMS)	-6.24755 31.50144	2241 m	13.3 °C	307 mm	2.6 t ha^{-1} 2.8 t ha^{-1}
Taoujgalt (TAO)	-6.32203 31.38994	1960 m	14.1 °C	340 mm	0.9 t ha^{-1} 2.7 t ha^{-1}
Trab Labied (TRB)	-6.57849 31.17099	1400 m	19.1 °C	144 mm	0.2 t ha^{-1} 0.5 t ha^{-1}
Bou Skour (BSK)	-6.33982 30.95166	1476 m	19.3 °C	139 mm	1.5 t ha^{-1} 1.6 t ha^{-1}

To represent transhumant pastoralism in our LDM, we introduce several additional equations, which make this version different from that one used in Freier *et al.* (2011b). Transhumant herds can migrate in our model between four types of pastures (Figure 5.3): (1) Highland, (2) transition zones, (3) basin of Ouarzazate, and (4) Anti Atlas. Highland and transition zones have restricted access for kin groups, additionally the pastures in the Highland are closed during winter and spring (*agdal*). The pastures in the basin of Ouarzazate and in the Anti Atlas are accessible for all kin groups in the research region (Figure 5.3).

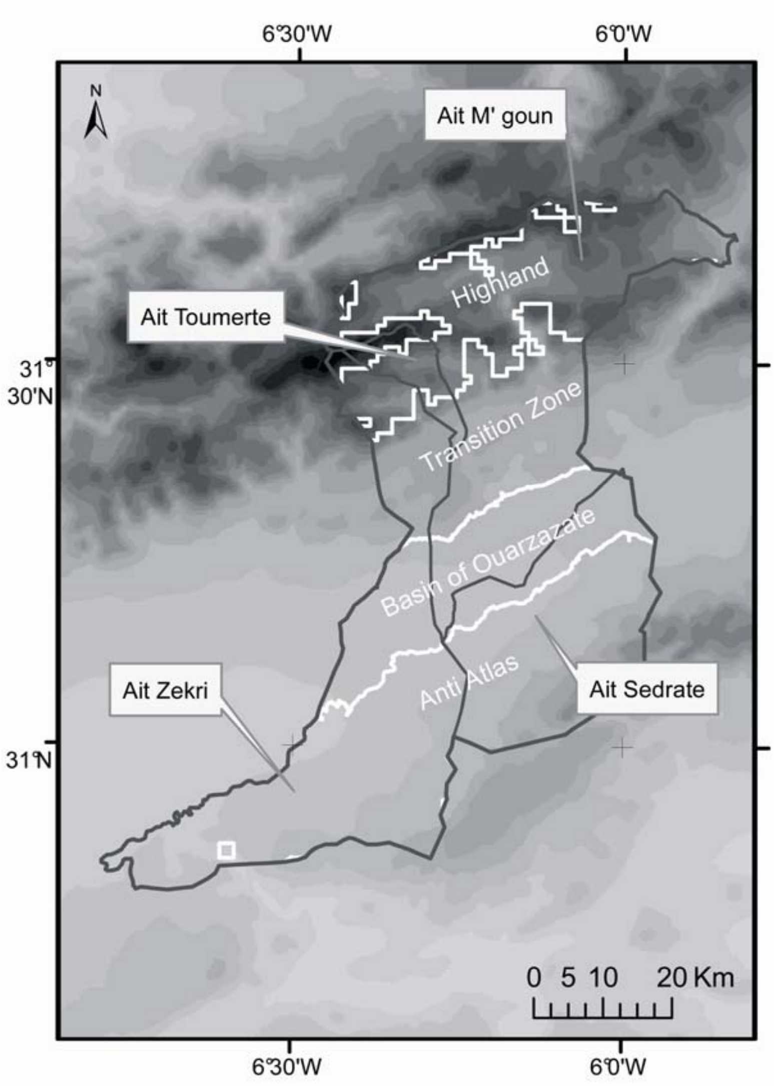

Figure 5.3: Migration of transhumant herds in our LDM is possible between four types of pastures (white lines). Four tribal areas are considered (grey lines).

Movement of transhumant herds is simulated by using a binary position variable *P* for every transhumant herd, where each entry corresponds to a pasture visited in an individual year. The entries of the position variable can either be 0 or 1. It is used to enable access to the available fodder of a pasture as shown in Eqs. 5.1-5.3.

$$AF_{ipt} \leq mcap \cdot P_{ipt} \quad \forall\, i, p, t \tag{5.1}$$

$$\sum_i AF_{ipt} \leq RB^*_{pt} \quad \forall\, p, t \tag{5.2}$$

$$FC_{it} \leq \sum_{p} AF_{ipt} \quad \forall \ i,t \tag{5.3}$$

In Eq. 5.1, available fodder (AF_{ipt}) for a herd i from a pasture p at time t is less or equal than a maximum capacity ($mcap$) times the position variable P_{ipt}. If the pasture is not visited by a herd, the position variable for that pasture is zero and no fodder is available from there. Available fodder for all herds is additionally constrained by the amount of biomass RB^{*}_{pt} that is grazed (Eq. 5.2). The variable RB^{*}_{pt} is calculated by the meta-model of EPIC using biophysical constraints and human management (see chapter 2, Eq. 2.5, p.21). In Eq. 5.3, the fodder consumed by herd i at time t (FC_{it}) is then constrained to not exceed the sum of fodder, which is available to the herd from all visited pastures.

Considering seasonal movements of the transhumant herds, we constrain the position variable P to a maximum of four movements per year (one for each season). Movements are possible between each pasture. In order to prevent artificial movements with no use for the pastoralists, we introduce a small cost of movement into the utility function. Within a pasture, herds have access to all HRUs of this pasture. Sedentary herds cannot move and are restricted to the area around their stables. However, they have as well access to all HRUs which belong to the local pasture.

To allow growth of sheep which is constrained by a low energy content of the fodder from the steppes, we allow the model to supplement livestock feed with lucerne produced in the oases. This is supported by observations in our research area and literature (Le Houerou, 1980). The amount of available lucerne is parameterized based on data of crop mix in the region and cultivated area in oases per household (Kirscht, 2008).The share of supplementary fodder from oases, which is used for transhumant or sedentary herds, is an explicit scenario assumption (see "experimental setup" below).

The generation of income is calculated in the LDM from sold livestock and observed livestock prices. Price data has been gathered from informal interviews performed in May 2009 at the livestock market in Ait'Toumert. Prices of one-year-old sheep and goats have been 600 and 400 Moroccan Dirham per head, respectively. During years of severe drought, prices have been reported to drop on average by 50%. This behaviour is considered in our LDM.

5.2.3 Calibration and validation

We calibrate our model in two steps: First, EPIC is adjusted to depict observed values of above ground plant material (AGPM); second, we tune the regional LDM to reproduce the abundance of sedentary livestock as reported by census data. The results of both calibration steps are then validated with data that was not used for calibration.

For calibrating EPIC, we use the parameter "plant population density", which is exogenously prescribed. The parameter is used to fit modelled values of AGPM to observed average values for the period 2002–2009 with zero grazing management and average rainfall. By applying continuously the highest grazing intensity, we additionally adjust the lower AGPM limit (below which no further grazing is allowed in EPIC) to values that are lower than the lowest observed ones for the period 2002–2009. The range between highest and lowest AGPM values is then covered by 8 different grazing intensities that are available each year.

After including the calibrated meta-model of EPIC into our LDM, we validate the calibration by comparing the time series of the measurement sites with the model results. In contrast to the model calibration, we use the observed rainfall for each year for validation. Validation is performed for zero grazing management and for applied grazing. The grazing intensity under applied grazing is endogenously chosen by the LDM.

Figure 5.4 shows the correlation between modelled and measured values for all test sites. The coefficient of correlation (Pearsons's r) is relatively high with 0.95 for both grazed and ungrazed conditions. However, as indicated by the horizontal spread of the values in Figure 5.4, the correlation within the samples from the individual test sites is lower. This lower correlation reflects the fact that we calibrated the EPIC model only with the 7 years average of observed values and it shows that there is room for improvement of the EPIC meta-model, for instance by including further state variables such as soil moisture. Furthermore, a Nash Sutcliffe coefficient (Nash & Sutcliffe, 1970) of 0.91 for ungrazed conditions and 0.84 for grazed conditions shows that the LDM has a systematic offset between modelled and observed values which is bigger for grazed conditions. Hence our LDM slightly underestimates AGPM under grazed conditions.

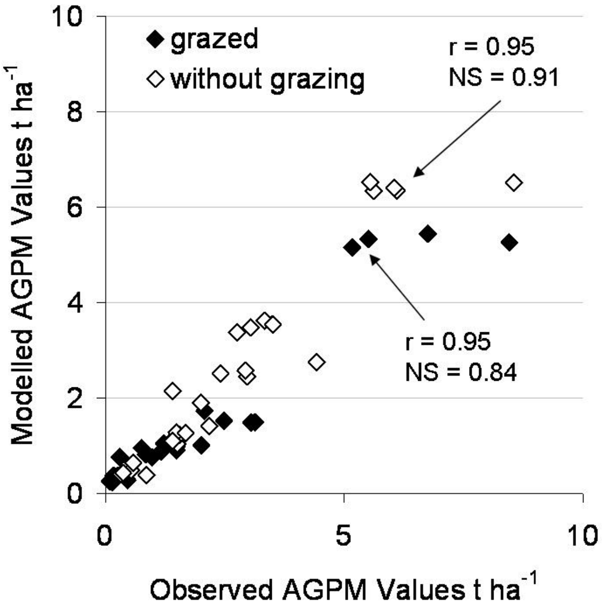

Figure 5.4: Validation of modelled AGPM values with observed values under observed climate; r: coefficient of correlation; NS: Nash Sutcliffe coefficient

To calibrate the calculation of livestock numbers to the reported abundance of sedentary livestock as given by a census (Maroc, 2002), we adjust boundaries of fodder quality classes. We have three classes of fodder quality (high, medium, low) in our model, which range between 9.8 GJ t^{-1} dry matter (DM) for lucerne and 2.1 GJ t^{-1} DM for poorest fraction of AGPM from rangelands. The partition of that range into three classes is used for calibration of livestock numbers. To calibrate our LDM, we use data from the territory of the Ait Zekri.

To assess the performance of the model, we compare modelled livestock numbers with census data from territories of the Ait Toumerte and Ait M'goun/Ait Sedrate which were not used for calibration (Figure 5.5). The fit between modelled and observed data is generally good, except for the basin of Ouarzazate and the Anti Atlas within the tribal area of the Ait M'goun/Ait Sedrate (four rightmost bars in Figure 5.5). This overestimation by the model is due to the fact that we calculated the fodder production in the oases based on number of households and average acreage data per rural household. The high population density in these two regions which drop out of the general pattern indicates that many households can be considered as exclusively agricultural or urban. This is confirmed by own observations where for instance the settlement El-Kelâat M'Gouna (see Figure 5.1) and the settlements along the Dades Valley show urbane characteristics. To compensate the offset we reduced the fodder supply from oases in these regions manually in order to fit livestock numbers to observed values (solid lines in Figure 5.5).

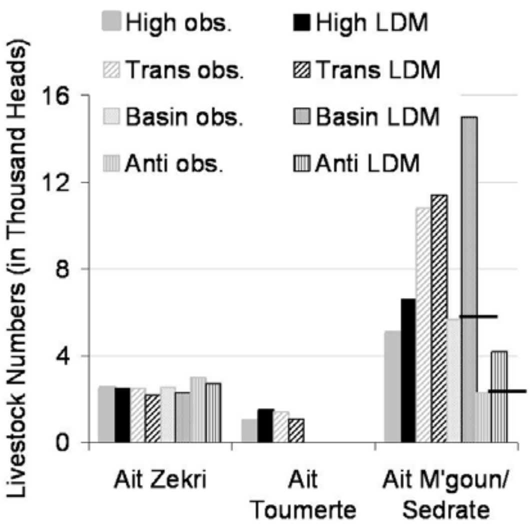

Figure 5.5: Calibration (Ait Zekri) and validation (Ait Toumerte and Ait M'goun/Sedrate) of livestock abundance for each region; High: Highland, Trans: Transition Zone, Basin: Basin of Ouarzazate, Anti: Anti Atlas.

We are not able to calibrate and validate our model for transhumant herds which is due to scarcity of observational data and the high effort which would be required to gather such data. For the representation of transhumant herds we therefore rely on the same parameterization as sedentary herds. The only difference between sedentary and transhumant herds is that transhumant herds are using other pastures, are able to move, and receive a different amount of additional fodder from oases which depends on scenario settings.

5.2.4 Experimental Setup

By experimenting with our LDM, we want to investigate the effects from likely climatic changes on a regional livestock production system. To assess vulnerability of the system with respect to different modes of pastoral production, we vary in our experiments the share to which transhumant pastoralism is used in comparison to sedentary pastoralism.

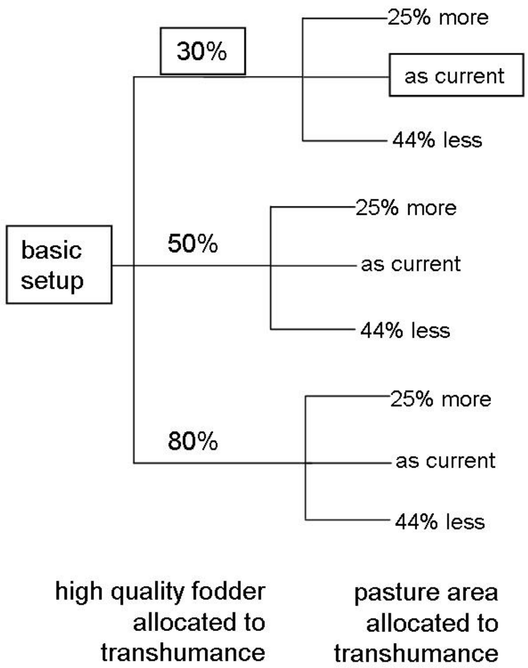

Figure 5.6: Fodder and pasture allocation scenarios (FPAs) as used in the LDM. Framed parameterizations are most plausible for present conditions

To influence the extent to which transhumant pastoralism is practised in our model, we have two major controlling parameters: The share of pasture area and the share of high-quality fodder production from oases which is dedicated to transhumant livestock production. Increasing both shares in favour of transhumance increases fodder supply for transhumant livestock.

To investigate a range of combinations of these two parameters, we use nine fodder and pasture allocation (FPA) scenarios, see Figure 5.6. Within these FPA scenarios 80%, 50%, and 30% of fodder produced in oases is dedicated to transhumance. Since currently only 22% of pastoral households are still engaged in transhumance (Breuer, 2007a), a current share of 30% of fodder allocation to transhumant livestock is assumed to be plausible. FPA scenarios with less than 30% of fodder allocation to transhumance resulted as very unfortunate for livestock production in our LDM and are therefore excluded from further discussion in this study.

The allocation of pasture area in our FPA scenarios is motivated by collar data, where it has shown that 31% of pasture area is used presently by sedentary herds. A second set of FPA scenarios uses a partitioning where the area used for sedentary livestock is increased by a factor of 1.44, which corresponds to expected population growth by 2050 (Rössler *et al.*, 2010a). A third set of scenarios simulates a hypothetical alternative of increasing the pasture area which is used by transhumant herds by 25%.

To compare properties of the livestock system under current climatic conditions and under conditions which are likely for the mid of the 21st century, we concentrate on a reduction of rainfall by 20% which is plausible for the region for around 2050 (Paeth *et al.*, 2009). Since climate projections for that region show considerable uncertainties (Schilling *et al.*, 2011) and spatial resolution of climate models is low compared to diversity in our observed climatic parameters, we do not use modelled climate data for 2050 for our LDM directly. Instead, based on our observed meteorological parameters we simulate climatic changes by reducing the amount of precipitation of each rainfall event by 20%. The statistical temporal variability of rainfall from day to day and from year to year as well as the spatial variance within our sub-regions is kept as observed. Hence, the only characteristic which is changed in the input data of our meta-model of EPIC in order to simulate likely climate conditions of 2050 is the amount of precipitation. Our model results should therefore be seen as a scenario analysis and not as a projection.

In general, we use simulation runs of 15 years for our experiments. The weather scenarios are created by a random weather generator which uses the observed statistical rainfall distribution of 2002-2009 for every sub-region to prescribe meteorological boundary conditions. As observed for 2002-2009, the probability of a certain amount of rainfall in a sub-region is not dependent on rainfall in other sub-regions.

To model severe large-scale droughts, which are likely to occur more often in the near future (Sillmann & Roeckner, 2008), we introduce in some experiments a decrease of 50% in precipitation which affects all sub-regions. To investigate the effect of different lengths of droughts, we use experiments with up to three consecutive drought years within 15 years. Additionally we investigate five disconnected drought events within 15 years runtime, where each drought has a length of one year. The average interval between droughts is chosen to be three years (Schilling *et al.*, 2011).

For each experiment we use ensemble simulations with 15 members to eliminate the sensitivity of our results to specific meteorological boundary conditions and to input parameters. The number of 15 members has been chosen in order to achieve a compromise of model runtime and accuracy. The usage of ensemble simulations additionally enables us to identify alterations in variability of outputs.

For each tribal fraction, the LDM can assign five different movement patterns for each year, representing five groups of transhumant pastoralists per tribal fraction. The number of three times five transhumant groups per year (represented as integer variables in our LDM) was again chosen in order to achieve a compromise between model runtime and accuracy.

5.3 Results and Discussion

5.3.1 Effects of reduced precipitation

Decreasing precipitation by 20% in our model results in considerable income losses for pastoral livestock husbandry. Calculating the unweighted average over all FPA scenarios, we find a decrease in average annual income under normal weather variability of 15% (ND15 in Figure 5.7). Comparing weather scenarios with 5 recurrent droughts within 15 years (RD15 in Figure 5.7), the annual income from pastoralism even drops by 37%.

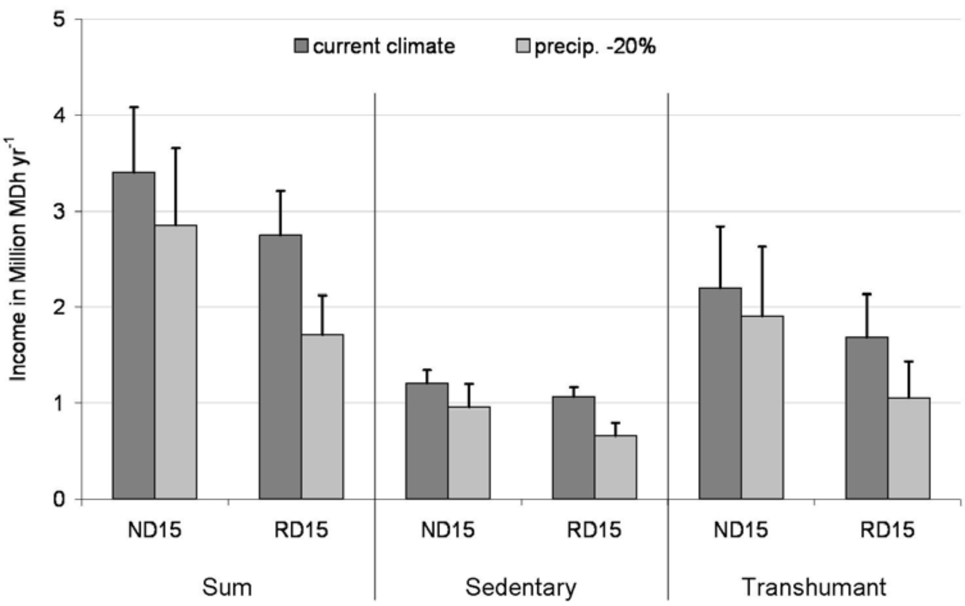

Figure 5.7: Annual income from pastoralism in the study region and standard deviation of fodder and pasture allocation (FPA) scenario ensembles under current climate, and under a 20% reduction in precipitation. Unweighted averages over all investigated FPA scenarios with 15 random repetitions each (ensembles). ND15: 15-year average without drought, RD15: 15-year average with 5 recurrent droughts; income in Million Moroccan Dirham.

Considering sedentary and transhumant pastoralism separately, the relative income reduction is more pronounced for sedentary livestock husbandry. For sedentary pastoralists, our FPA scenarios show an average income loss of 23% for normal weather variability and 39% for scenarios with five recurrent droughts (Figure 5.7, middle). Variability of annual income from sedentary pastoralism indicated by standard deviations of our ensembles' output increases by 33% to 87% (error bars in

Figure 5.7). In contrast, transhumant livestock producers are less affected and suffer smaller income reductions of 8% and 31% respectively (Figure 5.7, right). Variability of annual income from transhumance increases under normal weather variability by 13% while it even decreases by 16% under recurrent droughts.

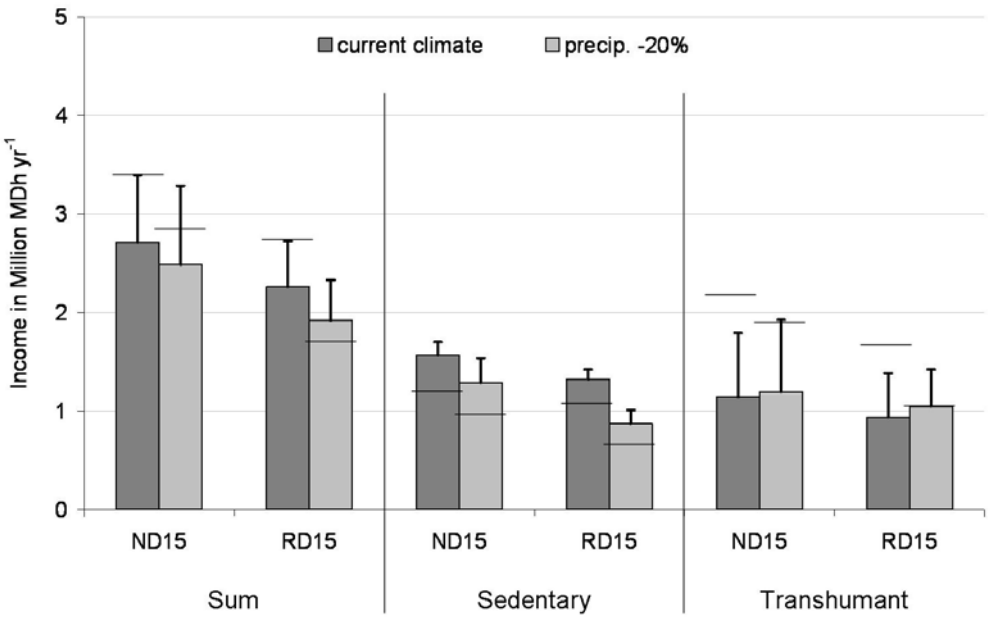

Figure 5.8: Ensemble mean (N=15) and standard deviation of annual income from pastoralism in the study region under current climate, and under a 20% reduction in precipitation. Fodder and pasture allocation scenario as assumed for present day conditions (see Figure 5.6). ND15: 15-year average without drought, RD15: 15-year average with 5 recurrent droughts; solid black lines indicate values of Figure 5.7 for comparison; income in Million Moroccan Dirham

Using conditions which are plausible for current fodder and pasture allocations (69% of pasture area and 30% of high-quality fodder from oases dedicated to transhumance), annual income from sedentary livestock production in our LDM is increased in general at the expense of income from transhumance. Differences to the FPA scenarios average are indicated with black horizontal lines in Figure 5.8. Under such a scenario, the income losses due to a reduction in precipitation are less pronounced in comparison to the FPA scenarios' average, with 8% for normal rainfall variability and 15% for recurrent droughts. This reduction in impact is mainly due to a sub-optimal allocation of high-quality fodder and pasture area to the two pastoral production regimes. As in the FPA scenarios' average, relative income losses in this individual FPA scenario are pronounced for sedentary pastoralism. Surprisingly, this individual experiment results in a 5%-12% income gain from transhumant pastoralism under reduced precipitation.

This seemingly paradox model result shows that transhumant pastoralism under that specific FPA scenario is mainly constrained by the availability of high-quality fodder from oases, and capacities of transition zone vegetation and highland vegetation are sufficient to buffer a 20% reduction in rainfall. Furthermore, the relatively myopic behaviour of our agents with a five years planning horizon leads to high grazing pressure under average rainfall. The high grazing pressure is relaxed in the individual FPA scenario, because under 20% less average precipitation transhumant herders are reducing herd sizes by 60% during dry years, while under current climatic conditions herd sizes are only reduced by 10%. Since enlargement of herds after dry years is lagging behind vegetation growth, the reduction of herd sizes leads to a lower grazing pressure afterward. This allows rangeland vegetation to regenerate to high levels of biomass and leads to higher average levels of fodder availability from rangelands in the long run. This effect explains, why the increase in annual income for transhumant pastoralists is more pronounced in our LDM under the weather scenario with recurrent severe droughts, were reductions in herd sizes occur repeatedly (Figure 5.8, right).

To better understand the described dynamic, Figure 5.9 shows a modelled time series of income generation from transhumant and sedentary pastoralism facing a severe drought under two different climatic conditions. The drought occurs in year 5. Dashed lines represent current climatic conditions. The differences between dashed and solid lines represent the impact of a climate with 20% lower precipitation. Using the same FPA scenario assumptions as in Figure 5.8 (30% of high-quality fodder and 69% of area allocated to transhumance), the influence of a climate with reduced precipitation is more pronounced for sedentary pastoralism. This is indicated by a continuing offset between the grey lines in Figure 5.9. Income losses during the year of drought are as well more pronounced for sedentary pastoralism for both climatic scenarios.

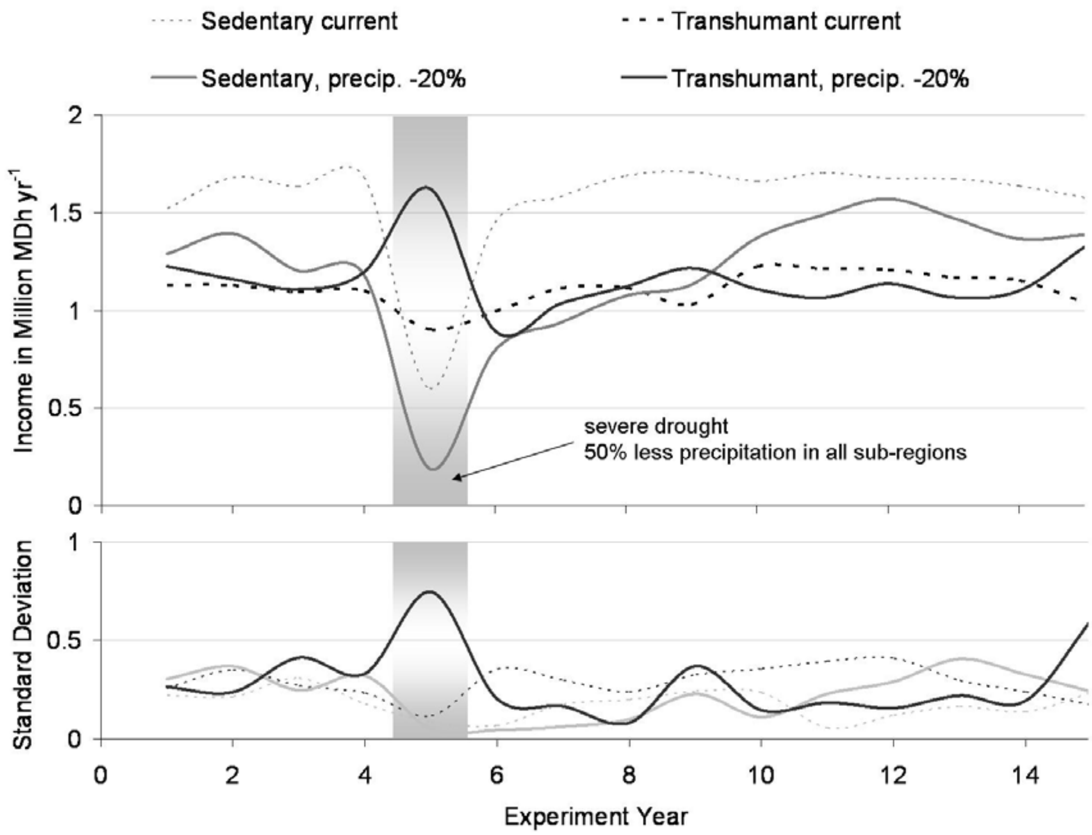

Figure 5.9: Ensemble mean (N=15) of annual income from sedentary and transhumant pastoralism in the study region (top); standard deviation below; severe drought in year 5. Fodder and pasture allocation scenario as assumed for present day conditions (see Figure 5.6); income in million Moroccan Dirham

Our LDM shows that under a climate with less precipitation, transhumant pastoralism is mainly affected by more intense destocking during droughts. This impact is indicated by the huge income peak of transhumant pastoralists in the year where drought occurs. The intense destocking generates more income than in no-drought years even though prices for livestock are reduced by 50% during drought. However, a more pronounced drop of income follows in the year after the drought. Additionally, as the lower graph in Figure 5.9 shows, the standard deviation of our ensemble calculation increases for transhumant pastoralists in the year of drought, indicating an increased variability of annual income under less average precipitation. However, four years after the drought (year 9 in Figure 5.9) income generation for transhumant pastoralists under a climate with less precipitation is even higher than income under a climate as currently observed, since rangeland vegetation was able to regenerate under a low grazing pressure. Introducing recurrent droughts into a model is therefore able to create a higher income even though average precipitation decreases.

This result of our model supports the criticism of fodder subsidies during droughts (Blench & Marriage, 1999; Hazell *et al.*, 2001): since fodder subsidies allow livestock keepers to sustain high stocking rates during droughts, long term income generation of the system decreases because rangeland vegetation is not able to reach maximum productivity. Our model shows that with dryer climatic conditions the importance of destocking increases. Scrutinizing policies of fodder subsidies is therefore an important element of adaptation to climate change (see also Linstädter *et al.*, 2010).

Table 5.2: Comparison of investigated scenarios concerning their performance on total 15-years income generation from pastoral livestock husbandry.

Area partition	Trh plus 25%			Trh as currently			Trh minus 44%			
Fodder (Trh)	80%	50%	30%	80%	50%	30%	80%	50%	30%	
Current climate										Max-Min
ND15	-	+	*							41 %
1D15	-						*	+		39 %
2D15	*				-			+		95 %
3D15	*			+				-		34 %
RD15	*						-	+		35 %
Precipitation -20%										
ND15		*			-	+				39 %
1D15	+			*				-		33 %
2D15		+		*	-					41 %
3D15	+	*			-					33 %
RD15	+	*	-							45 %

The first two lines indicate fodder and pasture allocation (FPA) scenarios (see Figure 5.6). ND15: Experiment without droughts during 15 years; 1D15: Experiment with one severe drought within 15 years; 2D15: Experiment with a severe two-year drought within 15 years; 3D15: Experiment with a severe three-year drought within 15 years; RD15: 15 years experiment with 5 recurrent droughts with one year length;

*: FPA scenario with highest average income generation; +: second highest income generation; -: third highest income generation; Min-Max: Difference of income generation between best and least performing FPA scenario

5.3.2 Options for adaptation

Comparison of fodder and pasture allocation scenarios

Investigating a set of different pastoral strategies and weather/climate scenarios in our LDM, we are able to compare livestock husbandry systems with different shares of transhumant and sedentary production. Considering the generation of total income over a 15-year time frame, production strategies are compared in Table 5.2 by displaying best performing FPA scenarios. Different weather scenarios of drought length and drought occurrence are investigated (left-most column), as well as current climatic conditions and a 20% reduction of precipitation. Scenarios marked with an asterisk are able to generate most income in comparison to other scenarios, followed by scenarios marked with a plus, and a minus. The right-most column indicates the difference in income generation as given in our model results between best and worst performing scenarios.

The analysis of pastoral production modes clearly shows that there is no single best performing strategy for different frequencies of droughts and altered climatic conditions. However, better and worse performing strategies are clustered around certain FPA scenarios. For instance, a distribution of high-quality fodder as assumed for 2006, where only 30% of the high-quality fodder goes to transhumant production, seems in almost all cases not to be most effective. Based on that result, one could suspect that in reality a higher share of fodder production from oases is dedicated to transhumant livestock or transhumant livestock is able to access high-quality fodder in the rangelands (see "model limitations" below).

Under current climatic conditions, increasing or decreasing the area share of transhumant production is of less importance on its own. Important is that the share of fodder production which is dedicated to transhumance fits to the pasture area share. For example, if the area share used by transhumant pastoralists is increased by 25%, scenarios which dedicate more high-quality fodder to transhumant production (80%) perform better. Similarly, if the area share is decreased by 44%, scenarios which assign less fodder production from oases (50%) to transhumant livestock are performing better.

For a climate with 20% less precipitation, the results of our LDM show that scenarios with a higher proportion of area and fodder dedicated to transhumant production perform better. This is indicated by a clustering of best strategies in the left part of Table 5.2. An increase in sedentary pastoralism as currently observed (Breuer, 2007a) is therefore in our LDM counterproductive to adapt to climate change.

Modelling future scenarios

Since the trend to urbanisation and sedentarity is expected to continue in Morocco (Freier *et al.*, 2011a, see chapter 3), we use a scenario analysis to display the effects of an increased share of sedentary pastoralism under a decreased level of precipitation. Figure 5.10 displays the impacts of droughts of different lengths in our LDM. For current climatic conditions, 30% of high-quality fodder production from oases is dedicated to transhumant production and the pasture area share is as currently observed (69% are used by transhumant herds). To simulate conditions which could prevail around the mid of the 21st century, experiments with 20% less precipitation are calculated with 44% less pasture area which is allocated to transhumant production.

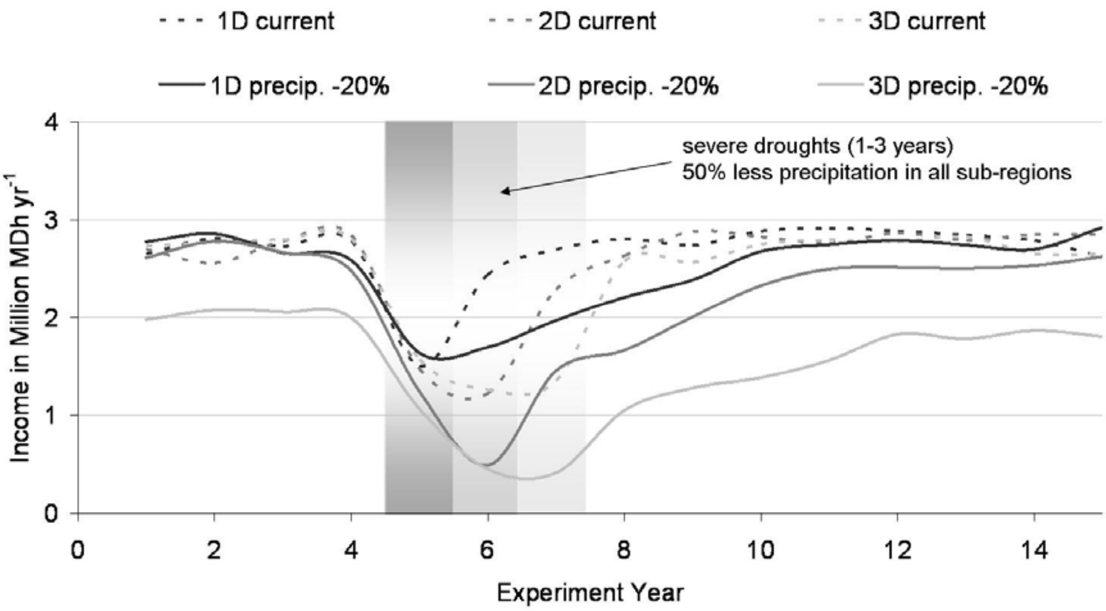

Figure 5.10: Ensemble means (N=15) of annual income from pastoralism in the study region (sum of sedentary and transhumant production). In the experiment with minus 20% precipitation (solid lines) the pasture area which is used by sedentary herds is increased by 44% in comparison to the experiment with current climatic conditions (dashed lines). 1D, 2D, and 3D are scenarios with droughts of 1 to 3 years length; income in million Moroccan Dirham

The ensemble means in Figure 5.10 demonstrate that the overall production during average years is not affected by a reduction of precipitation. This is due to the fact that the FPA scenario is sub-optimal under current climatic conditions and in the future more area is available for sedentary livestock while fodder production in oases is not decreasing in the LDM, assuming technological innovations under a currently relatively low performance of irrigated agriculture in Morocco (Badraoui *et al.*, 2000). However, especially droughts which last longer than one year show significant impacts (grey lines in Figure 5.10). Even 6 years after the end of a two-year drought event, income losses are notable. The magnitude and duration of the negative impacts are considerably higher in the -20% rainfall scenarios. While under current climate 1, 2, and 3 years of drought lead to a drop of income generation by 54%, 55%, and 51%, a climate with 20% less precipitation leads to losses of 40%, 82%, and 85% under these droughts, respectively.

The solid grey line in Figure 5.10, which represents an impact of a three-year drought under reduced average precipitation, reveals an even more interesting behaviour of our LDM: Since we calculate our 15 ensemble members consecutively with three years in between each member to allow the vegetation in the model to recover, the three-year drought experiment shows that such a drought is sufficient to provoke a lock-in effect in our model: The income after the drought is not able to reach again levels of the 1-year and 2-year drought scenarios. This effect is demonstrated by the offset between the solid grey line and the remainder lines in Figure 5.10. Only if we introduce a 10-year buffer with favourable weather conditions between each ensemble run, the lock-in effect disappears. Our model therefore shows the possibility of long lasting impacts of droughts on livestock production systems in semi-arid areas.

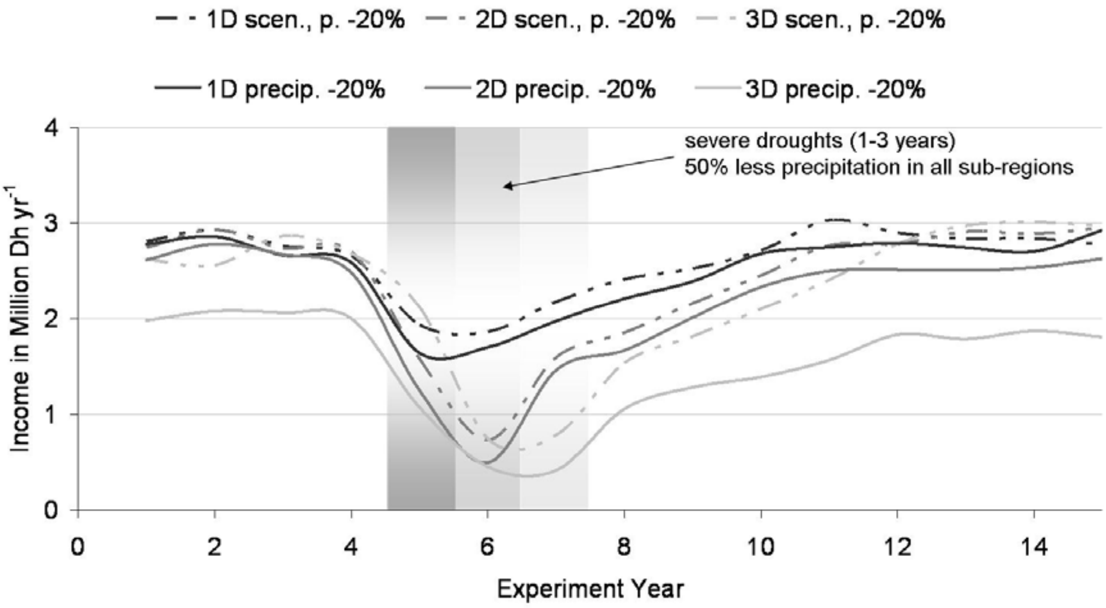

Figure 5.11: Ensemble means (N=15) of total annual income from pastoralism in the study region (transhumant + sedentary). A scenario is tested with increased fodder supply and increased area for transhumant herds (dashed lines). Solid lines are the same as in Figure 5.10; income in million Moroccan Dirham

Using the insights from Table 5.2, we investigate if the negative impacts on income generation caused by reduced average rainfall and droughts can be diminished by encouraging transhumant pastoralism (Figure 5.11). Solid lines in Figure 5.11 are the same as in Figure 5.10; the dashed lines represent a FPA scenario where pasture area used for transhumant production is increased by 25%, and 50% of the production of high-quality fodder from oases is used to feed transhumant livestock.

The experiment shows that it is possible to abate the impacts of a reduced average rainfall by increasing the share of transhumant livestock production. Impacts of droughts are reduced by 11% on average. Additionally, the lock-in effect in our

LDM (as described for Fig. 10) is avoided by a strategy of enhanced transhumance. This indicates an increased resilience of the system.

5.3.3 Model limitations and co-benefits of transhumance

A major limitation of our model arises from missing plant population dynamics in the EPIC model, and even further, missing alterations of plant species composition in EPIC. Therefore, secondary effects of grazing pressure such as diminishing palatability of forage over yearly and decadal timescales are not considered in our model. However, the potentially negative effect on plant species composition will be more pronounced with higher stocking rates. Since our LDM applies stocking rates which vary for sedentary pastoralism from 1.1 to 3.3 heads/ha, and 0.1 to 0.3 heads/ha for transhumant pastoralism, negative effects of plant species dynamics should be more pronounced for sedentary pastoralism because around settlements grazing pressure is roughly 10 times higher. The high grazing pressure is supported by empirical data, where in vicinity to settlements rangeland vegetation is more degraded and the abundance of plants with high palatability is reduced (Finckh & Goldbach, 2010).

Another limitation of our model is the fact that forage values of AGPM are only roughly depicted. There is no seasonal variability of nutritive quality of plants included, while it might be of some importance for transhumant livestock. In our model, sheep are only able to produce offspring if they are supported with high-quality fodder from oases. However, it is possible that the energy content of vegetation from rangelands seasonally fluctuates and suffices sometimes to provide sufficient energy supply for pregnancy and lactation of sheep (Golley, 1961; Mattson, 1980). Being able to follow rainfall patterns, transhumant pastoralists might therefore be able to compensate the missing support from fodder production in oases by accessing pastures with seasonally high forage value (Roth, 2009). Therefore, without the option of seasonally fluctuating forage quality, our model likely underestimates the capacity of transhumant livestock production.

Both mentioned limitations, plant species composition and seasonal forage quality, work in the same direction. This overestimates income generation from sedentary pastoralism and underestimates capacities of transhumant livestock production. The results of our model, which support increased transhumance as an adequate option for adaptation to climate change, are therefore not reduced in validity. Instead, considering the mentioned differences in stocking rates, transhumant pastoralism shows even more favourable properties: Stocking rates on transhumant pastures are only one tenth the rates around settlements. Therefore, it can be said that transhumant pastoralism favours lower rates of erosion (Linstädter *et al.*, 2010), and decreases the probability of degradation of vegetation. Turning the argument around, it is likely that initiatives which aim on biodiversity conservation through encouraging transhumance achieve a social co-benefit as well: By re-activating traditional transhumant rangeland management systems in southern Morocco (UNDP, 2010) a more secure livelihood from pastoralism is possible even under climate change.

5.4 Conclusions

Our model shows that the current trend of increased sedentary pastoral production increases the vulnerability in semi-arid areas to climate change. On the contrary, increasing the share of transhumant livestock production is a favourable option to adapt to reduced rainfall and higher frequencies of droughts. Two factors can be used in our model for enhancing transhumant livestock production: a) dedicating a larger share of pasture area to transhumance, and b) assigning more high-quality fodder produced in oases to transhumant livestock.

In contrast to our suggestions, social reasons might still favour sedentarity as preferred way of life in the society of southern Morocco in the 21st century. New developments like mobile telecommunication for spread of information on pasture quality (Casciarri, 2006), usage of trucks to displace herds, and commercialization of pastoralism (Rachik, 2007) might be measures which encourage an increased share of transhumant pastoralism in the future. However, since our model emphasizes the importance of destocking during droughts, newly available strategies such as commercial pastoralism need to be monitored or embedded in traditional management systems to prevent deterioration of rangeland vegetation and social disruptions (Werner, 2004).

To respect the dynamical properties of the investigated pastoral system, the insights from our model shows that fixed high stocking rates as caused by fodder subsidies during droughts are able to lead to long-term losses of annual income especially under low average precipitation. Variable stocking rates which allow for pronounced destocking during droughts are better suited to enable a sustainable livestock production. The mitigation of social impacts from droughts and climate change should therefore concentrate on attenuating effects of income losses rather than on flooding drought prone areas with subsidised fodder.

Our results disagree with the dominant policy of governments in semi-arid areas which encourage sedentarization of former mobile pastoralists. Such policies are counterproductive in order to buffer impacts from climate change on pastoral livestock husbandry. In our model, the seemingly old strategy of transhumance is a better option than sedentary pastoralism for facing the challenges of climate change.

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Chapter 6

Summary and conclusions

As complex and interrelated socio-ecological systems are, as difficult it is to recommend simple strategies for building up resilience towards global and climate change. However, the studies presented in this thesis create a robust basis of knowledge about development pathways of semi-arid pastoral land use systems by using transdisciplinary modelling and research.

For a case study in southern Morocco, this thesis shows that for the 21st century considerable negative impacts from climate change are likely, namely lower productivity, more pronounced impacts from droughts, and contribution to social inequality. The magnitude of negative impacts depends very much on socio-economic and political boundary conditions, which range from local to global scales. This thesis clarifies that the dependency on these boundary conditions risks amplifying impacts, but it also offers the opportunity for mitigation.

As shown in chapters 3 and 4, the current trend towards sedentarization, which in the past was mainly driven by political and social reasons, will be aggravated by climatic changes. This in turn will further weaken resilience of the collective income generation from pastoral livestock production, since sedentary pastoralism is less resilient against shocks from droughts than mobile pastoralism (see chapter 5).

Sedentarity, if mainly associated with agriculture, will additionally increase pressures on scarce resources such as irrigation water and arable land. Since irrigated soils in Morocco already have high levels of salinity which negatively influence soil fertility, irrigation water and arable land are critical resources. If not addressed, increasing salinity levels will additionally increase severity of climate change impacts on agricultural production and livelihood security. The conversion of marginal lands to farmland will furthermore contribute to a weakening of adaptive capacities of mobile pastoralists (see chapter 5). Hence, the trend from mobile to sedentary pastoralism directly and indirectly affects the resilience of livelihoods with respect to climate change in many negative ways.

Social equality is a major issue concerning climate change impacts in semi-arid areas, because options of adaptation as well as sensitivity of pastoralists depend on their wealth. For instance, richer livestock keepers are able to adopt new management strategies more easily such as “truck transhumance”, which allow them to abate impacts from lower levels of precipitation. Additionally, the dynamic properties of pastoral livestock systems allow richer livestock keepers to increase their relative wealth during and after droughts (chapters 2 and 4). Climate change is therefore very likely to contribute to an increasing social gap between rich and poor in rural areas. As shown in chapter 4, high social inequality and stronger impacts on pastoral production increase the risk of social instability.

In many subtropical semi-arid areas, existing policies increase the risk of negative impacts from climate change. Especially the provisioning of fodder subsidies during droughts and the promotion of sedentarization of former mobile pastoralists by governmental institutions can be considered counterproductive for securing livelihoods (see chapter 5). Instead, more indirect means such as enhancing the level of education and enabling the access to financial resources can be recommended to increase stability of the socio-ecological system (see chapter 3).

Despite all critical points, the studies which have been developed for this thesis show considerable potential for mastering the challenges which many semi-arid areas are facing at the beginning of the 21st century. However, some of this potential can only be exploited if old paradigms are questioned, for instance, the idea of considering semi-arid areas to be economically marginal. If solar energy projects like the 500 MW power plant in the Ouarzazate region is successful, many impacts from climate change could be mitigated (chapter 4). For instance, job opportunities could be created aside from pastoralism, farming, and tourism, offering alternative livelihood options. Additionally, a replacement of firewood as energy source for cooking and heating could enable rural societies to reduce the pressure on rangeland vegetation considerably, which will compensate impacts from climate change on sedentary pastoralists.

Even more outdated is the stereotypical attitude adopted by the majority of governments in semi-arid regions to regard mobile pastoralism as a nuisance rather than as a capacity for facing climatic challenges. It has been shown in this thesis, even under very restrictive assumptions, that seasonally mobile pastoralism (transhumance) is characterized by many advantages in comparison to sedentary pastoralism: lower stocking densities, higher resilience to droughts, and a higher level of total long-term income generation (chapter 5). These advantages are increasing if precipitation decreases. Hence, a successful adaptation to climate change in semi-arid regions calls for support of mobile pastoralism instead of fighting it.

To sum up our insights gained from the studies in this thesis, we can recommend six key elements for semi-arid pastoral land use systems which are important for facing the challenges created by projected climate change and socio-economic developments:

1) Adaptation of pastoral land use systems to climate change is not only a technical problem of different modes of pastoralism but it is dependent on a set of socio-economic boundary conditions. Climate change will increase the pressure on people which are dependent on pastoralism in subtropical semi-arid areas. Social discrepancies are aggravated and poorer livestock keepers will have fewer options for facing the challenges.
2) Fodder subsidies during droughts threaten long-term sustainability of the system since an effective destocking becomes more important under a climate with less precipitation. Additionally, subsidies contribute to social inequality if the wealth of livestock owners is not taken into account for allocation. Policy interventions should therefore be much more aiming at alleviating effects of severe income losses, for instance through social insurance mechanisms, instead of supporting big herd sizes during times of fodder scarcity.
3) An enhanced availability of education and financial resources will reduce adoption of the currently dominating livelihood options: transhumance, sedentary pastoralism, and farming. This will reduce pressure upon natural resources such as arable land, rangeland, and water, and will enable modes of production with a lower variability in income generation and a reduced magnitude of income shocks during droughts.
4) Replacing rural energy supply for cooking and heating by electricity will be able to compensate impacts of climate change on sedentary pastoralism in many semi-arid areas. If the electricity is generated by solar power plants within the same regions, it additionally is able to contribute to alternative sources of income which are not coupled to climate change impacts such as droughts.
5) Commercializing pastoralism has the potential to sustain high levels of livestock production in semi-arid areas if mobility of herds is included into the concept and a strong community-based monitoring is set in place. Such a monitoring needs to focus on sustaining rangeland conditions and can also include the necessity of pronounced destocking during droughts. Additionally, monitoring needs to assure that competition between livestock keepers is not systematically favoring wealthy ones.
6) Mobile pastoralism (in our case transhumance) is better suited for facing projected climate change than sedentary pastoralism. From an environmental, social, and economic perspective it therefore makes no sense to encourage sedentarization of mobile pastoralists in semi-arid areas.

APPENDICES

Appendices

Appendix 1

The originally used questionnaire (chapter 3) was written down in French. The abbreviations of the strategies as used in the text (see Table 3.1, p. 46) are from top to bottom: TRAD, SED, TOUR, CITIES, ABROAD, and COMM. The resource attributes are from right to left: capital, precipitation, education, and experience. The expectations attributes are from right to left: status, income, happiness.

Questionnaire sur les stratégies futures possibles des éleveurs qui pratiquent la transhumance

LES RESSOURCES

	ressources financières	precipitation	education	experience
Transhumance traditionelle	1			
Sédentarité et élevage proche du village	2			
Tourisme p.e. "Gîte"	1			
Travailler dans les grandes villes	0			
Travailler à l'étranger	1			
Élevage commercial	3			

LES ESPÉRANCES

	prestige	revenu	le bonheur
Transhumance traditionelle			
Sédentarité et élevage proche du village			
Tourisme p.e. "Gîte"			
travailler dans les grandes villes			
Travailler à l'étranger			
Élevage commercial			

This questionnaire was filled out by the interviewers (interpreter and scientist) based on the answers of the nomads to establish a ranking in between all strategies for each attribute. An example for resources is given in grey for capital ("ressources financières"): "Pastoralisme comerciale" needs the most followed by "Sedentarité…" followed by "Transhumance…", "Travailler dans l'etranger" and "Tourisme…" which have the same rank. Capital is the less necessary for "Travailler dans les grandes villes".

Appendix 2

Table of meta-information of the 25 performed interviews.

#	Date	Site	Kin Group	Interview quality	Comment
1	04 June 2009	pastures Taoujgalt	Ait Zekri	low	questions too complicated
2	04 June 2009	pastures Taoujgalt	Ait Zekri	low	questions too complicated
3	04 June 2009	pastures Taoujgalt	Ait Zekri	low	unwilling
4	05 June 2009	livestock market Ait Toumert	Ait Toumert	medium	questions differently treated
5	05 June 2009	livestock market Ait Toumert	Ait Toumert	medium	questions differently treated
6	05 June 2009	livestock market Ait Toumert	Ait Toumert	good	feeling save how to ask questions
7	05 June 2009	livestock market Ait Toumert	Ait Toumert	good	
8	06 June 2009	general market Ait Toumert	Ait Toumert	good	
9	06 June 2009	general market Ait Toumert	Ait Toumert	best	
10	06 June 2009	general market Ait Toumert	Ait Toumert	best	
11	06 June 2009	general market Ait Toumert	Ait M'rauwn	best	
12	06 June 2009	general market Ait Toumert	Ait M'rauwn	best	
13	06 June 2009	general market Ait Toumert	Ait Toumert	best	
14	07 June 2009	village Ameskar	Ait M'goun	best	
15	07 June 2009	village Ameskar	Ait M'goun	best	
16	07 June 2009	village Ameskar	Ait M'goun	medium	not clearly transhumant pastoralist
17	08 June 2009	Mountains Ameskar	Ait M'goun	best	
18	08 June 2009	Mountains Ameskar	Ait M'goun	best	
19	08 June 2009	Mountains Ameskar	Ait M'goun	best	
20	12 June 2009	livestock market Ait Toumert	Ait Zekri	medium	new interpreter
21	12 June 2009	livestock market Ait Toumert	Ait M'goun	low	unwilling
22	13 June 2009	general market Ait Toumert	Ait M'goun	medium	new interpreter
23	13 June 2009	general market Ait Toumert	Ait M'goun	good	
24	13 June 2009	general market Ait Toumert	Ait M'goun	best	
25	13 June 2009	general market Ait Toumert	Ait M'goun	best	

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