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Article

Adaptation to New Climate by an Old Strategy? Modeling Sedentary and Mobile Pastoralism in Semi-Arid Morocco

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Abstract: In a modeling study we examine vulnerability of income from mobile (transhumant) pastoralism and sedentary pastoralism to reduced mean annual precipitation (MAP) and droughts. The study is based on empirical data of a 3410 km^2 research region in southern, semi-arid Morocco. The land use decision model integrates a meta-model of the Environmental Policy Integrated Climate (EPIC) simulator to depict perennial and annual forage plant development. It also includes livestock dynamics and forward-looking decision making under uncertain weather. Mobile livestock in the model moves seasonally, sedentary livestock is restricted to pastures around settlements. For a reduction of MAP by 20%, our model shows for different experimental frequencies of droughts a significant decrease of total income from pastoralism by 8%–19% ($p < 0.05$). Looking separately at the two modes of pastoralism, pronounced income losses of 18%–44% ($p < 0.05$) show that sedentary pastoralism is much more vulnerable to dryer climate than mobile pastoralism, which is merely affected. Dedicating more pasture area and high quality fodder to mobile pastoralism significantly abates impacts from reduced MAP and droughts on total income by 11% ($p < 0.05$). Our results indicate that promotion of mobile pastoralism in semi-arid areas is a valuable option to increase resilience against climate change.

Keywords: adaptation; bioeconomic land use modeling; climate change; EPIC; North Africa; resilience; semi-arid pastoralism; transhumance

1. Introduction

Livestock husbandry worldwide contributes to livelihoods of more than 600 million people, most of them living in semi-arid areas of developing countries in Asia and Africa [1]. Projections for these countries indicate increasing population pressure and reductions in rainfall due to climatic change [2,3]. In order to alleviate poverty and social disruptions in affected regions, the investigation of possibilities to secure or adapt pastoral livelihoods is of great interest.

For Northern Africa in general and more specifically for our research region in Southern Morocco, climate researchers expect until 2100 reductions in rainfall between 10% and 30% compared to the beginning of the century [4,5]. Without other changes occurring simultaneously, this climatic development would inevitably lead to lower income from livestock husbandry. However, the extent of future income losses from livestock husbandry is very difficult to assess for real world systems. In particular, many pastoral systems in Morocco represent a combination of mobile and sedentary modes of pastoralism. The extent of income losses will, therefore, depend on the future combination of these alternative production strategies and their specific vulnerability to a dryer climate.

In Morocco, livestock husbandry is exposed to a variety of changes: Young people are attracted to modern lifestyles, with access to electricity, television, and Internet. Furthermore, the fast growing rural population accelerates urbanization [6]. Income sources are diversified by accepting wage labor in urban centers or by emigration of family members to the EU [7]. Most mobile pastoralists also experience a governmental preference for settlement [8–10]. As a consequence of these drivers, a general trend from mobile pastoralism towards more sedentarization and commercialization of pastoralism has been observed for Morocco during the last decades [11,12]. For Southern Morocco, this trend is expected to continue [13].

Population growth, societal changes and climate change lead to new boundary conditions, for which historical experiences are lacking. Therefore, model based analyses of complex, socio-ecological systems are an important tool for the understanding of their typically non-linear dynamics and the development of adaptation strategies [14]. Many modeling studies address the impact of reduced precipitation and droughts on livestock husbandry in dry-land systems [15–18], which demonstrate the capabilities of socio-ecological models.

In our research region, previous studies have focused on the dynamics of rangeland vegetation as the natural resource base [19], on mobility patterns of herds [20] and adaptive management strategies concerning forage plant species [21], and on the impacts of droughts on sedentary pastoralism [22]. Recent studies show that local institutions play a key role for the adaptive management of natural resources [23] and that commercial pastoralism is a valuable option for current mobile pastoralists [13].

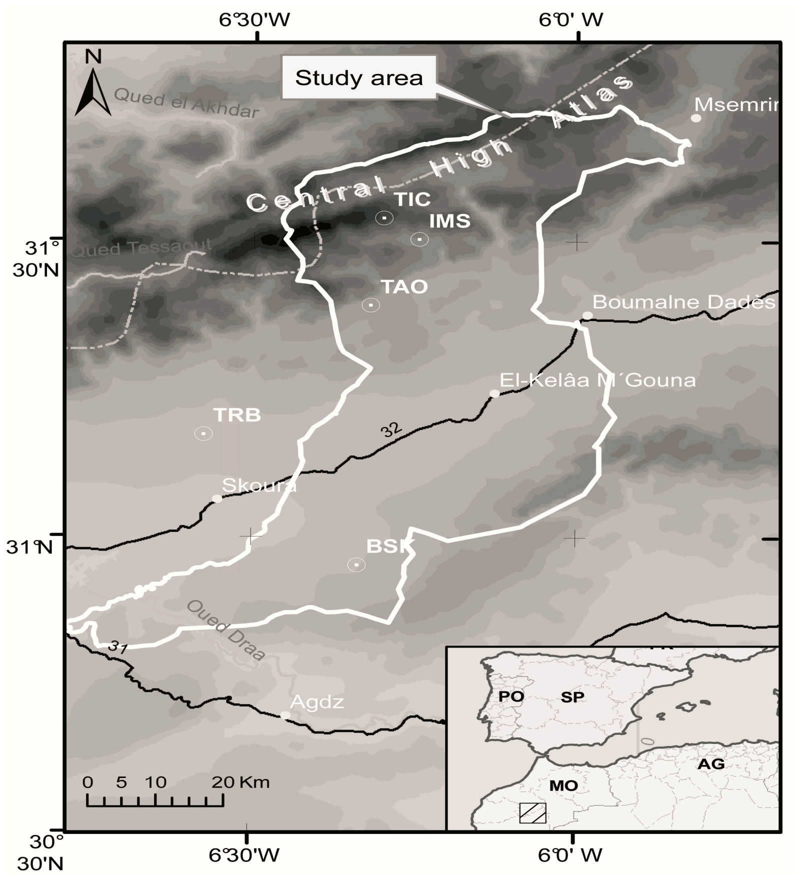
The impacts of a dryer climate on large-scale livestock husbandry systems in southern semi-arid Morocco have so far only been investigated with a stylized model [24], which did not account for real topography, site specific soil, vegetation and slopes, and pasture distribution between sedentary and mobile pastoralists. Hence, the magnitude of impacts of a dryer climate combined with a variation of drought frequencies is still poorly known. Because of this research gap, it is difficult to assess the possibilities of mitigation in a quantitative way.

In this study, we develop an integrated regional land-use decision model based on a broad range of empirical data to investigate impacts of a dryer climate on pastoralism in the upper Drâa Catchement in Southern Morocco. We focus on differences in income generation between two alternative modes of pastoral production: mobile (transhumant) pastoralism and sedentary pastoralism. Particularly, we attempt to assess (a) whether the two modes of pastoralism show a different vulnerability towards dryer climate and droughts and (b) whether resilience against climatic changes can be increased by dedicating more resources to mobile pastoralism, such as the production of high-quality fodder in oases and the use of pasture areas for mobile herds.

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 mobile and sedentary pastoralism. The LDM is based on data for livestock herding at the southern slopes of the Central High Atlas in Morocco. The model simulates vegetation dynamics, livestock growth, herd mobility, and 5-years planning by livestock managers. The spatial resolution of the model is based on homogenous response units. Herd movements are possible between four types of pastures. The temporal resolution of the model is daily for weather input data (for the underlying soil-vegetation meta-model), quarterly for management decisions on livestock movements and yearly for the remaining management decisions. The model is parameterized, calibrated, and validated with empirical data from the semi-arid study area (Figure 1).

Figure 1. Study area located in Southern Morocco. The boundary of our research area is given in bold white. The locations of the measurement sites are indicated with white circles (TIC: Tichki, IMS: Ameskar, TAO: Taoujgalt, TRB: Trab Labied, BSK: Bou Skour).



2.1. Study Region

Our study is based on data from a pastoral land use system in the upper Drâa catchment in the province of Ouarzazate in Southern Morocco. Two research projects have been active in the region for around 10 years [25,26], providing the empirical data basis for our modeling 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 1). The pastures in the High Atlas belong to territories of three kin groups, 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 [27]. The 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* semi-deserts 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 [28].

Before the 1960s–1970s, livestock production in our research region was dominated by transhumant pastoralism (transhumance), a type of mobile pastoralism, which follows seasonal rainfall and vegetation changes [12,29]. 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 [11]. For the future, most livestock owners tend to opt for sedentarity [13]. 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, showing that animals from sedentary livestock keepers are found on pastures which are less than 3 km away from settlements and within less than 400 m difference in altitude [30].

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*) [23] and to members of the kin group, which rules the respective territory [31]. 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 [32]. 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 [33].

2.2. Model Setup

We extend an existing land use decision model (LDM) originally designed to describe grazing of sedentary herds around the village of Taoujgalt (TAO, see Figure 1) [22]. The LDM simulates aggregate human behavior by maximizing equally (a) animal numbers and (b) profit from livestock selling, both over a 5-years planning horizon. Coupled to the model are a stochastic weather generator and a meta-model of the soil-vegetation model EPIC in order to achieve a realistic representation of weather and vegetation dynamics. The details of the LDM and the underlying meta-model are described in [22].

Technically, the LDM is a linear programming optimization model, where the objective of the utility function is equally a high number of living livestock and a high profit from sold livestock within the planning horizon. This objective is subject to several constraints: (1) Livestock growth is limited by fodder availability and fodder quality. Livestock growth would follow a sigmoid growth function if fodder supply is fixed and no human management decisions are constraining growth; (2) Fodder availability is limited by the grazing intensity which is applied to a pasture; (3) Fodder availability is constrained by grazing intensities and weather conditions of previous years, representing a memory of land use and climate, which is able to account for pasture degradation.

The level of the control variables in the utility function, such as (1) selling livestock and (2) adjusting the intensity of grazing, is chosen endogenously by the LDM to control the land use intensity. The selling of livestock by the LDM reduces herd sizes and generates income for the simulated pastoralists. The grazing intensities represent management decisions. The model choses how long animals stay on a pasture and how much biomass they are allowed to remove until they proceed to the next pasture.

To achieve the sensitivity of the model to land use history, pasture degradation and weather conditions, a dynamic representation of vegetation is included into the model, by including a meta-model of EPIC (environmental policy impact calculator by Williams [34]). The meta-model was generated beforehand and uses above ground plant material (AGPM) as a classified state variable. This state variable is mapped to follow-on states using Markov chains, which have been established by repeated runs of EPIC beforehand [22]. 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 [26]. Vegetation data is retrieved from the BIOTA-Maroc database [25].

The meta-model for vegetation dynamics is used to reduce the computational effort for modeling human inter-temporal planning with forward-looking behavior. 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 [22].

Human decision making is simulated in our LDM using dynamic optimization of a utility function over a 5-year planning horizon. The entire run-time of the model in experimental runs for analyzing scenarios 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 [35]. While the LDM uses a prescribed "real" weather for year one of the planning horizon, the average of empirically observed weather from 2002 to 2009 is used as expectation for the remainder years. Only in year four of the planning horizon, the modeled pastoralists expect a drought to include risk-averse behavior.

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 represent own assumptions, which have shown to reproduce characteristic patterns of the land use system such as grazing intensities and flock composition [22].

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 [36]. The amount of available lucerne is parameterized based on data of crop mix in the region and cultivated area in oases per household [37]. The share of supplementary fodder from oases, which is used for transhumant or sedentary herds is an explicit scenario assumption which is clearly indicated as such.

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 behavior is considered in our LDM.

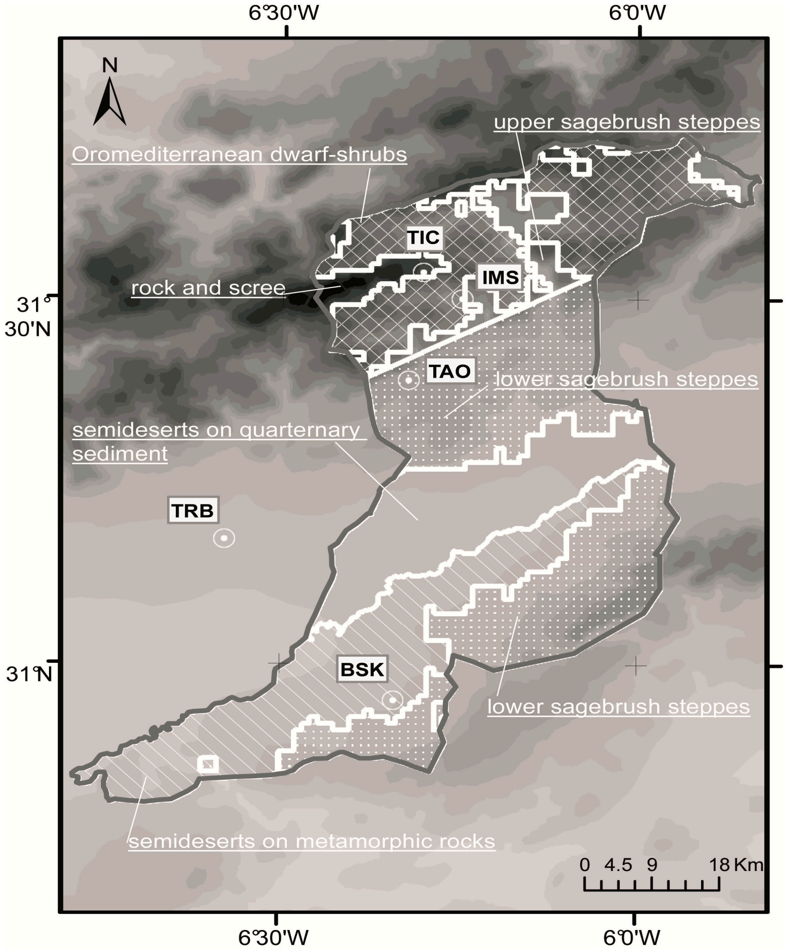
2.3. Spatial Discretization and Herd Movements

Spatial resolution of the model is based on homogeneous response units (HRUs), which are used to reduce the computational effort compared to a raster-based resolution [38]. HRUs aggregate data from raster cells with similar slope and vegetation characteristics (in our case vegetation is closely correlated to soil characteristics). Raster cells, where the slope and vegetation value fall in the same class, are merged into a larger unit, the HRU. Impacts from alternative land management regimes are then only simulated at HRU level but not for every individual raster cell. The aggregation to HRU preserves much of the spatial heterogeneity but reduces the computational effort by orders of magnitude. In this study, HRUs additionally distinguish socio-economic factors, such as territorial ownership by kin group and pastoralism type.

To construct the HRUs (Figure 2), the research area is classified according to five types of vegetation as observed in the field [25], which is again subdivided by three classes of slope in order to include erosive effects into the meta-model (not shown in Figure 2). The considered vegetation types are: (1) Oromediterranean dwarf-shrubs; (2) upper and (3) lower sagebrush steppes; and semideserts on (4) quarternary sediment and on (5) magmatic and metamorphic rocks.

The vegetation classes relate to five measurement sites (Table 1), where meteorological observations, vegetation monitoring, and livestock-exclosure experiments have been conducted from 2002 to 2009. The measurement sites where selected beforehand by the projects BIOTA-Maroc and IMPETUS [25,26] in order to represent all dominating vegetation types. The values of AGPM where assessed yearly for subdivisions of each measurement site (grazed and ungrazed) by harvesting [25].

Figure 2. Homogenous response units (HRUs) are established in order to correspond to one of five vegetation types (and tree classes of slope, not shown). The locations of the measurement sites are indicated with white circles (TIC: Tichki, IMS: Ameskar, TAO: Taoujgalt, TRB: Trab Labied, BSK: Bou Skour).

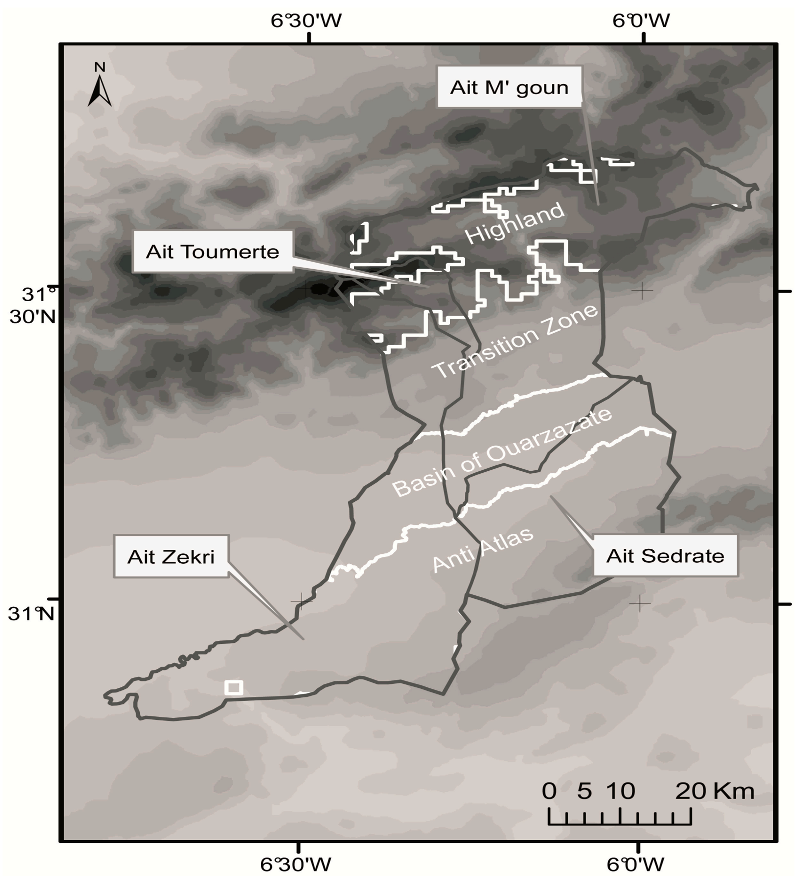


To represent the movement of mobile pastoralists in our LDM, we introduce several additional equations into the model version used in [22]. Mobile (transhumant) herds migrate in reality and in our model between four pastures (see Figure 3): (1) highland; (2) transition zone; (3) basin of Ouarzazate; and (4) Anti Atlas. Highland and transition zone have restricted access for kin groups. Additionally, the pastures in the highland are traditionally closed during winter and spring (*agdal*) by the respective kin group in order to prevent overgrazing. The *agdal* regime starts at the end of the grazing season and ends on agreement of the elders of a kin group, as soon if they judge the regrowth of the vegetation as sufficient. In the model, the *agdal* is applied for half a year (winter and spring). The pastures in the basin of Ouarzazate and in the Anti Atlas are accessible for all kin groups in the research region all year round (Figure 3). In the model, we do not include harmful competition among different kin groups for fodder resources (*i.e.*, there is no "tragedy of the commons" due to profit maximization of individual herders).

Table 1. Characteristics of five measurement sites used for calibration of our model. Figure 2 shows the location of these sites. Above ground plant material (AGPM) is used as state variable in our meta-model of EPIC.

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}

Figure 3. Migration of transhumant herds in our LDM is possible between four pastures (white lines). Territories of four kin groups 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. The position variable is used to enable access to the available fodder of a pasture as shown in Equations (1)–(3).

$$AF_{ipt} \leq mcap \cdot P_{ipt} \quad \forall\ i, p, t \tag{1}$$

$$\sum_{i} AF_{ipt} \leq RB^{*}_{pt} \quad \forall\ p, t \tag{2}$$

$$FC_{it} \leq \sum_{p} AF_{ipt} \quad \forall\ i, t \tag{3}$$

In Equation (1), available fodder (AF_{ipt}) for a herd i from a pasture p at time t is less or equal than a maximum capacity for that vegetation type (*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 removed (Equation (2)). The variable RB^{*}_{pt} is calculated by the meta-model of EPIC using biophysical constraints and management decisions (for details see [22]). In Equation (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.

While the LDM uses annual time-steps, we implicitly consider seasonal movements of the transhumant herds. Reflecting observations, we constrain the position variable P to a maximum of four movements per year between the four types of pastures (one movement for each season). For a given pasture type, mobile herds have access to all land areas (HRUs) of this pasture for the respective season. Sedentary herds, on the other hand, cannot move regionally and are restricted to the area around their stables. However, the sedentary herds have as well access to all HRUs, which belong to their local pasture.

The model-code is available from the corresponding author upon request.

2.4. Calibration and Validation

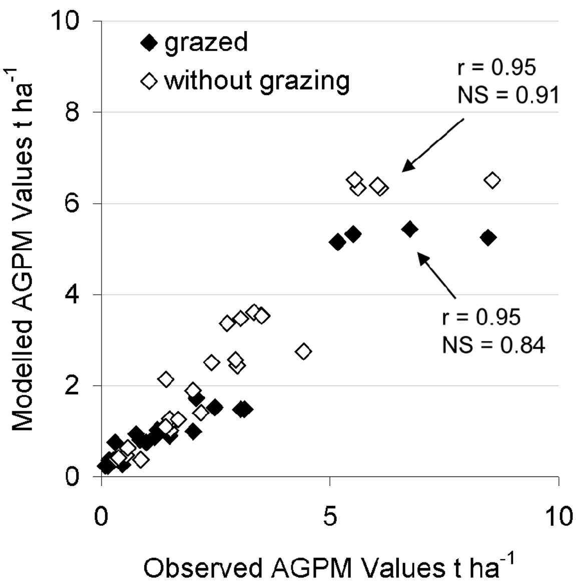
We calibrate our model in two steps: First, the meta-model of EPIC is adjusted to depict observed values of above ground plant material (AGPM); second, we tune the regional LDM to reproduce the current abundance of sedentary livestock as reported by census data. The results of both calibration steps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

For calibrating the meta-model of EPIC, we use the parameter "plant population density", which is exogenously prescribed. First, the parameter is used to fit modeled values of AGPM to observed values at the measurement sites for the period 2002–2009 under exclosure of grazing and average rainfall. Second, by applying continuously the highest grazing intensity in the meta-model, 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 under grazing. The range between highest and lowest AGPM values is then covered by 8 different grazing intensities that are available each year. In experiments with different resolutions of grazing intensity, we found a cluster of 8 intensities to be a good compromise between model accuracy and computational requirements.

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

Figure 4 shows the correlation between modeled and measured values for all test sites. The coefficient of correlation (Pearsons' 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 4, the correlation within the samples from the individual test sites is lower. This lower correlation reflects the fact that we calibrated the meta-model only with the 7 years average of observed values and it shows that there is room for improvement, for instance by including further state variables such as soil moisture. Furthermore, a Nash Sutcliffe coefficient [39] of 0.91 for ungrazed conditions and 0.84 for grazed conditions shows that the LDM has a systematic offset between modeled and observed values, which is bigger for grazed conditions. Hence our LDM slightly underestimates AGPM under grazed conditions.

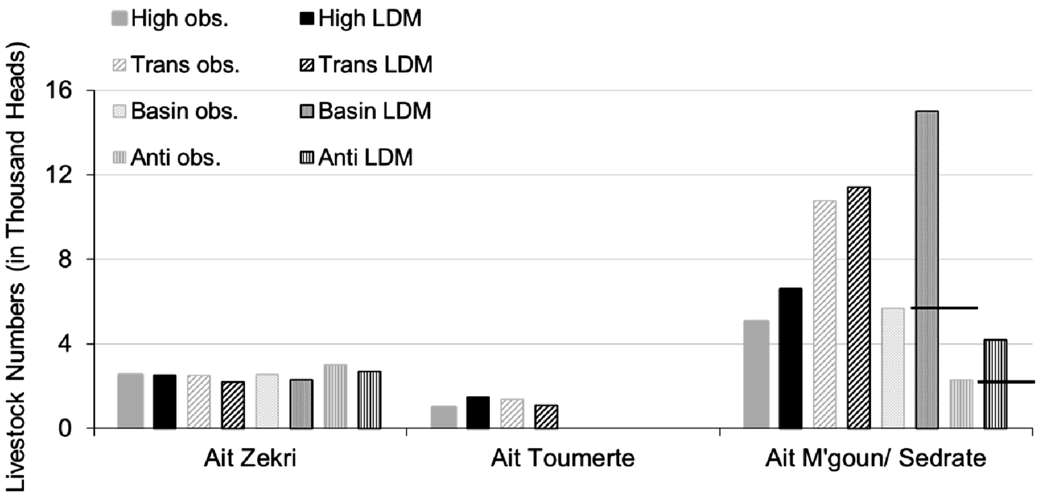
Figure 4. Validation of simulated above ground plant material (AGPM) for all measurement sites through comparison with observed values (between 2002 and 2009) under observed climate; r: coefficient of correlation; NS: Nash Sutcliffe coefficient.



To calibrate the calculation of livestock numbers to the reported abundance of sedentary livestock as given by a census [40], 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 [41] and 2.1 GJ·t^{-1} DM for poorest fraction of AGPM from rangelands [36]. 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 modeled 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). The fit between model and observations is generally good and there are no statistically significant differences between modeled and observed data (p < 0.05), except for the basin of Ouarzazate and the Anti Atlas within the territory of the Ait M'goun/Ait Sedrate (four rightmost bars in Figure 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. For instance, the settlement El-Kelâat M'Gouna (see Figure 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).

Figure 5. Calibration (Ait Zekri) and validation (Ait Toumerte and Ait M'goun/Sedrate) of livestock abundance showing observed and modeled values (land use decision model, LDM) for each region; High: Highland, Trans: Transition Zone, Basin: Basin of Ouarzazate, Anti: Anti Atlas; the horizontal lines indicate the manual reduction of fodder supply in rural areas.



Unfortunately, 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. 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 able to move, and receive a different amount of additional fodder from oases which depends on scenario settings.

2.5. Experimental Setup

By experimenting with our LDM, we want to investigate possible effects from climatic changes on the regional livestock production system. To assess the vulnerability of the modeled system with respect to different modes of pastoral production, we vary in our experiments the allocation of land and high-quality fodder between transhumant pastoralism and sedentary pastoralism. Explicitly stating that our model is an experimental tool for testing hypotheses under restricted assumptions, we do not use a real-world time axis (e.g., 2020–2035) in order to avoid confusion. Instead, we refer to years, which have been elapsed since start of the model experiment.

The extent to which transhumant pastoralism is practiced in our model can be controlled by two parameters: (1) The share of high-quality fodder from oases and (2) the share of pasture area, which is dedicated to transhumant livestock production. Increasing both factors in favor 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 6. Within these FPA scenarios 80%, 50%, and 30% of fodder produced in oases is dedicated to transhumance, while 30% are roughly reflecting the current share of families engaged in transhumance.

The allocation of pasture area in our FPA scenarios is motivated by collar data [30], where it has shown that 69% of pasture area is used presently by transhumant 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 [31]. This expansion of settlements leads to a reduction by about 20% of area used by transhumance. A third set of scenarios simulates a hypothetical alternative of increasing the pasture area, which is used by transhumant herds by one quarter to a total of 86%.

We compare properties of the livestock system under (i) observed climate (2002–2009); (ii) reduced average rainfall; and (iii) five alternatives of drought duration and drought frequencies. For reduced average rainfall we use a reduction by 20%, which is plausible for the region for climatic conditions in 2050 [4]. Since climate projections for that region show considerable uncertainties [6] and spatial resolution of climate models is low compared to diversity in our observed and included climatic parameters, we do not use modeled 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 in order to simulate climatic conditions of 2050, is the amount of precipitation. Our results should therefore be seen as a scenario analysis with 20% less average precipitation 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 [5], we introduce in some experiments an additional decrease of 50% in precipitation which affects all sub-regions. According to [42], years with a distinct drought show a deficit in yearly precipitation between 38% and 62%. Therefore, we assumed reductions of 50% as plausible approximation in our model. 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. As observed during the past decades for Morocco, the average interval between droughts is chosen to be three years [6].

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

For each experiment we use ensemble simulations, as they are used in climate models, in order to compensate the sensitivity of our mode towards initial values and stochastic boundary conditions. The usage of ensemble simulations enables us to identify alterations in variability of outputs. In our case, we use a number of 15 individual model runs to calculate each ensemble mean and standard deviations, where for each run stochastic weather conditions are applied which fit to the observed mean characteristics. Additionally, initial pasture conditions, livestock numbers and the positions of the mobile livestock herders are perturbed for each individual model run within the ensemble. The perturbations are achieved by executing the 15 individual model runs in a sequence while at the end of each individual 15-year run the model experiences three lapse-years of average weather conditions. The number of 15 ensemble members has been chosen in order to achieve a compromise of model runtime and stability of standard deviations.

3. Results and Discussion

3.1. Effects of Reduced Precipitation

Decreasing precipitation by 20% in our LDM, results in considerable income losses for pastoral livestock husbandry. Calculating the unweighted average over all nine FPA scenarios (see Figure 6), we find a 15% decrease of average 15-years income under normal weather variability. Comparing weather scenarios with 5 recurrent droughts within 15 years, the average 15-years income from pastoralism even drops by 37%.

Using the FPA scenario which is most probable for present day conditions (see Figure 6), we find that under these assumptions transhumant (mobile) pastoralism is merely affected by the reductions in precipitation (Figure 7c), while the average 15-years income of sedentary pastoralists is significantly ($p < 0.05$) reduced for all investigated scenarios of drought occurrences (Figure 7b). The overall reductions of the livestock productions system are ranging from 8.4% to 19.4% for the different drought scenarios (Figure 7a, $p < 0.05$). This result is clearly dominated by the reductions for sedentary pastoralists in 15-years income, which are ranging from 17.9% to 44%. At the same time, standard deviations are increasing significantly by 25% to 75%. This clearly shows a high sensitivity of sedentary livestock production in our model towards reductions in precipitation.

Transhumant (mobile) pastoralists on the other hand, are experiencing only 9.4% significant losses ($p < 0.05$) for the scenario of three droughts within a 15 years experiment. Under all other drought scenarios we find no significant reductions in average 15-years income from transhumant pastoralism. Our results agree to the findings of a study by [24] with a stylized model, which shows that under reduced mean annual precipitation, mobile pastoralism can sustain higher animal numbers than sedentary pastoralism.

Figure 6. Fodder and pasture allocation scenarios (FPAs) as used in the LDM. Framed parameterizations are most plausible for present conditions.

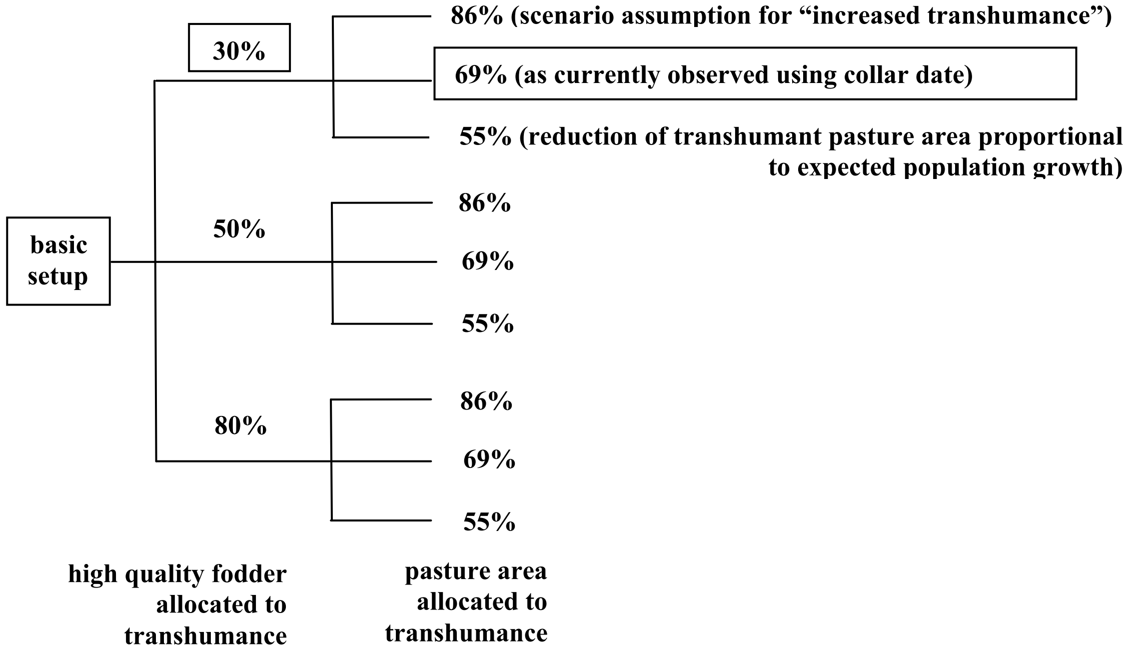
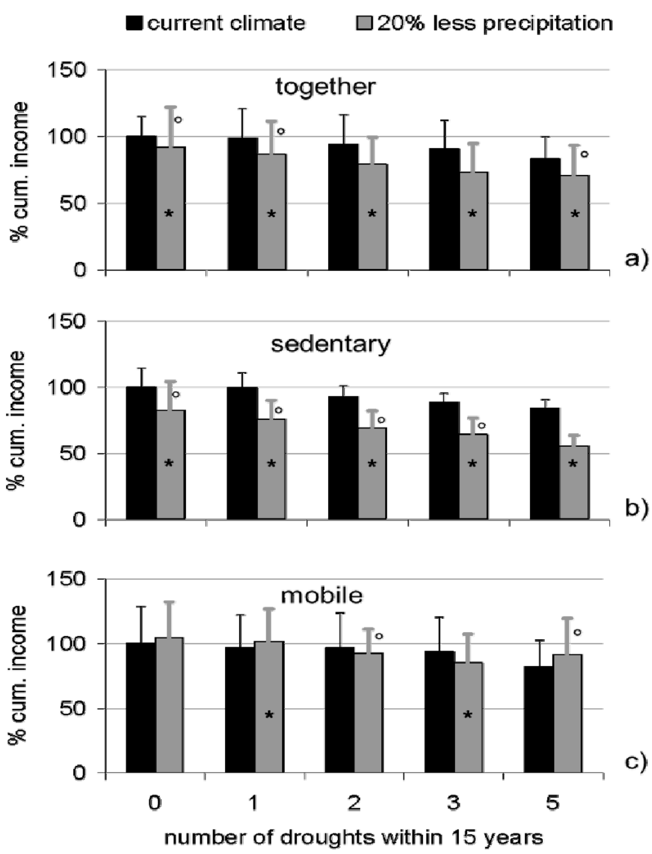


Figure 7. Modeled 15-years cumulative income from pastoralism relative to present-day conditions with different occurrences of droughts. (**a**) the whole pastoral system; (**b**) income from sedentary pastoralism; (**c**) income from mobile pastoralism. * significant differences of means ($p < 0.05$); ° significant differences of standard deviations ($p < 0.05$).

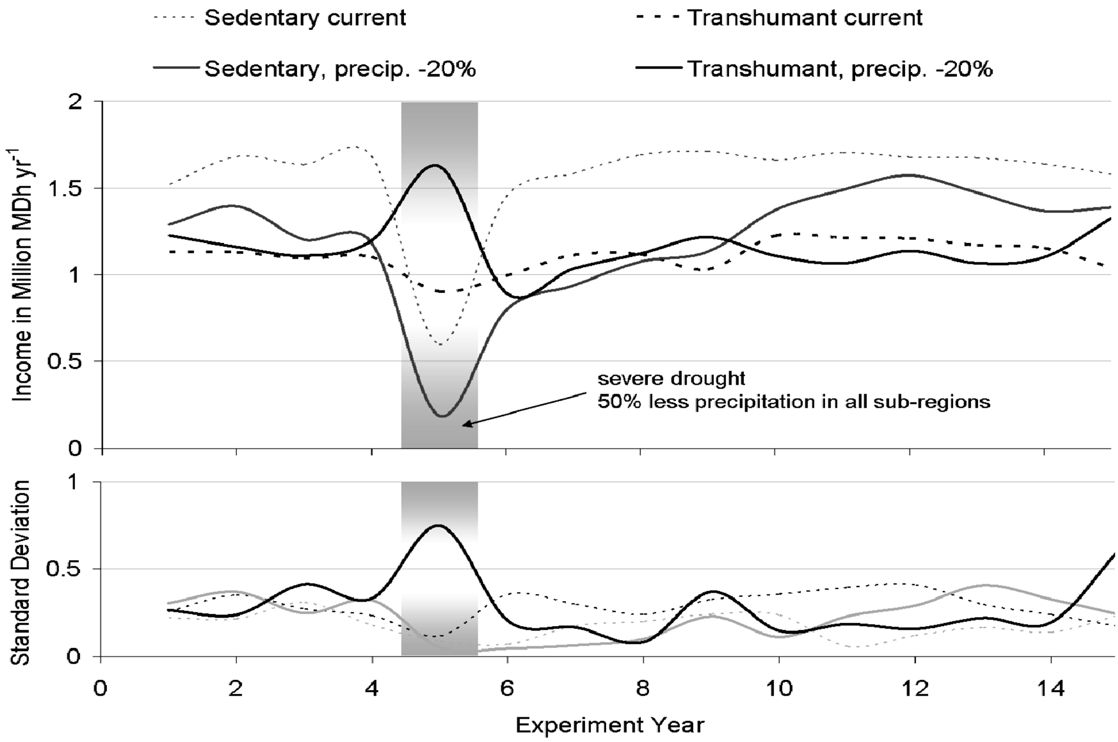


For the scenario of one year of drought within a 15 years experiment, the income is unexpectedly significantly increased ($p < 0.05$) by 4.5% for transhumant pastoralism. This seemingly paradox model result shows that transhumant pastoralism in our model under that specific FPA scenario is mainly constrained by the availability of high-quality fodder from oases, while capacities of transition zone vegetation and highland vegetation are sufficient to buffer a 20% reduction in rainfall. Furthermore, the relatively myopic behavior of our agents with a five years planning horizon leads to a relatively high grazing pressure under average rainfall. The high grazing pressure is relaxed in the individual FPA scenario with a one-year drought, because of destocking in the year of drought by 60%. In contrast, under current climatic conditions herd sizes are only reduced during droughts 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 an increase in 15-years income for transhumant pastoralists is possible in our model under reduced average precipitation.

To better understand the described dynamic, Figure 8 shows a time series of income generation from transhumant and sedentary pastoralism facing a severe drought under two different climatic conditions. The drought occurs in year five of the model experiment. 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 7 (30% of high-quality fodder and 69% of area allocated to transhumance), the influence of a climate with reduced precipitation is clearly visible. The continuing offset between the grey lines in Figure 8 indicate a more pronounced impact on sedentary pastoralists. Income losses during the year of drought are more pronounced for sedentary pastoralism for both climatic scenarios. With less precipitation the LDM is using a more intense destocking during droughts for transhumant pastoralism. This is indicated by the huge income peak of transhumant pastoralists in the year of drought, where a considerable proportion of the livestock is sold in order to prevent starvation. The intense destocking generates more income than in no-drought years even though prices for livestock are reduced by 50% during droughts. However, a more pronounced drop of income follows in the year after the drought. Additionally, as the lower graph in Figure 8 shows, the standard deviation of our ensemble calculation increases for transhumant pastoralists in the year of the drought, indicating an increased variability of annual income under less average precipitation. However, four years after the drought (year 9 in Figure 8) income generation for transhumant pastoralists under a climate with less precipitation is even higher than income under a climate as currently observed, because rangeland vegetation was able to regenerate under a low grazing pressure. The behavior of our model agrees with the so-called "unintended resting" of non-equilibrium rangeland-systems found in other modeling studies [18,24].

This result of our model on the role of destocking supports the criticism of fodder subsidies during droughts in semi-arid areas [43–46]: Fodder subsidies allow livestock keepers to sustain high stocking rates during droughts and long term income generation of the system decreases since rangeland vegetation is not able to reach maximum productivity after the drought. Previous studies have suggested destocking as mitigation strategy against droughts in semi-arid areas [47]. Our model additionally shows that with dryer climatic conditions the importance of destocking is even increasing. Scrutinizing the policies of fodder subsidies is therefore an important element of adaptation to climate change (see also [48]). Furthermore, our model clearly shows that income from sedentary pastoralism is much more vulnerable towards a change in climatic conditions.

Figure 8. Ensemble mean (N = 15) of annual income from sedentary and transhumant pastoralism in the study region (top); standard deviation below; a severe drought occurs in year five of the experiment. Fodder and pasture allocation scenario as most probable for present day conditions (see Figure 6); income in million Moroccan Dirham.



3.2. Options for Adaptation

Can resilience against climatic changes be increased by dedicating more resources to transhumant pastoralism? Considering the generation of total income over a 15-year time frame, we can easily compare the characteristics of the different FPA scenarios, which have been investigated. In Table 2, we compare the results displaying the three best performing FPA scenarios for given climate and drought occurrences. Scenarios marked with three bars are able to generate most 15-years cumulative income, followed by scenarios marked with two bars, and one bar.

Table 2 can be interpreted by observing the "density" of bars: The more bars occur in an area of the table, the better performing are the respective FPA scenarios. The results given in Table 2 clearly show 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 present day conditions, 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).

Table 2. Comparison of investigated scenarios concerning their performance on cumulative 15-years income generation from pastoral livestock husbandry.

Area Partition	**Trh 86%**			**Trh 69%**			**Trh 55%**		
Fodder (Trh)	**80%**	**50%**	**30%**	**80%**	**50%**	**30%**	**80%**	**50%**	**30%**
Current Climate									
ND15	I	II	III						
1D15	I						III	II	
2D15	III				I			II	
3D15	III			II				I	
RD15	III						I	II	
Precipitation −20%									
ND15		III			I	II			
1D15	II			III				I	
2D15		II		III	I				
3D15	II	III			I				
RD15	II	III	I						

The first two lines indicate fodder and pasture allocation (FPA) scenarios (see Figure 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; III: FPA scenario with highest income generation; II: second highest income generation; I: third highest income generation.

Under current climatic conditions, increasing or decreasing the area share of transhumant production is of less importance on its own. Of greater importance is that the share of high-quality fodder production, which is dedicated to transhumance fits to the share of dedicated pasture area. For example, if the area share used by transhumant pastoralists is increased to 86%, scenarios, which dedicate more high-quality fodder to transhumant production (80%) perform better. Similarly, if the area share is decreased to 55%, scenarios that assign less fodder production from oases (50%) to transhumant livestock are performing better.

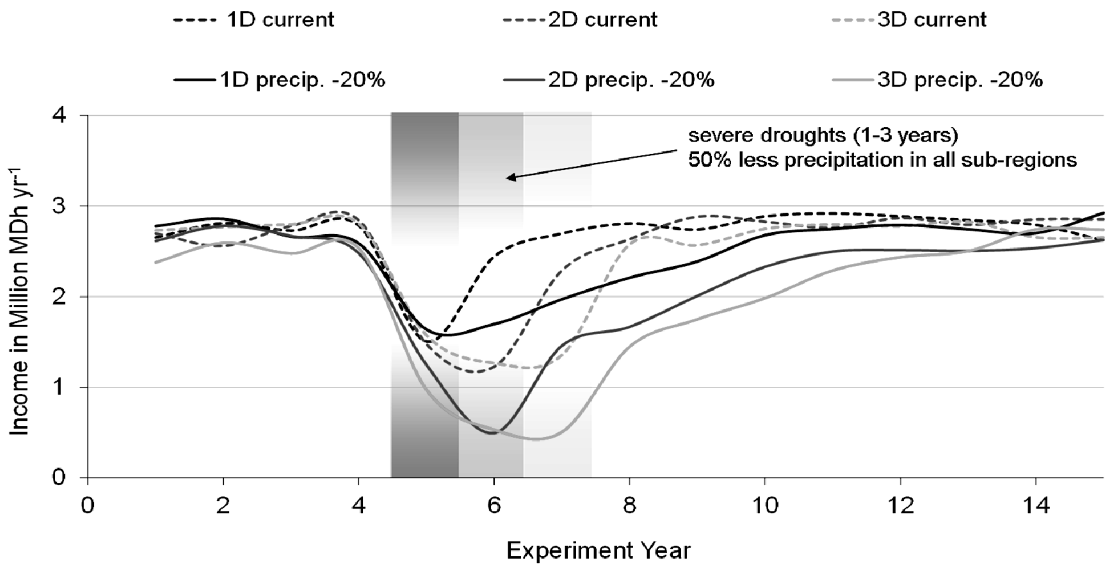
For a climate with 20% less precipitation, the results of our LDM show that scenarios with a higher proportion of area and fodder dedicated to transhumant production perform better. Best strategies are clustered in the left part of Table 2. This clearly indicates that an increase in sedentary pastoralism as currently observed [11] is in our LDM counterproductive for adaptation to climate change.

The temporal resolution of our model allows a closer look into the dynamics of the livestock husbandry system. In Figure 9 we display the dynamic effects of an increased share of sedentary pastoralism under a decreased level of precipitation. 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. To simulate conditions which could prevail around the mid of the 21st century, experiments with 20% less precipitation are calculated with only 55% of pasture area allocated to transhumant production.

The ensemble means in Figure 9 demonstrate that the overall income from pastoralism is not affected by a reduction of precipitation during average years. This is due to the fact that the FPA scenario is sub-optimal under current climatic conditions. However, droughts show significant impacts under current climatic conditions as well as under scenarios with decreased precipitation.

The magnitude and duration of the negative impacts are considerably higher in the −20% rainfall scenarios (significant on a $p < 0.05$ level). While under current climate, one, two, and three years of drought lead to a drop of income generation by 54%, 55%, and 51%, a climate with 20% less average precipitation leads to losses of 40%, 82%, and 85% under these droughts, respectively.

Figure 9. Ensemble means (N = 15) of total annual income from pastoralism in the study region (transhumant + sedentary). In the experiment with minus 20% precipitation (solid lines) the pasture area which is used by transhumant herds is additionally reduced to 55%. 1D, 2D, and 3D are scenarios with droughts of one to three years in length; income in million Moroccan Dirham.



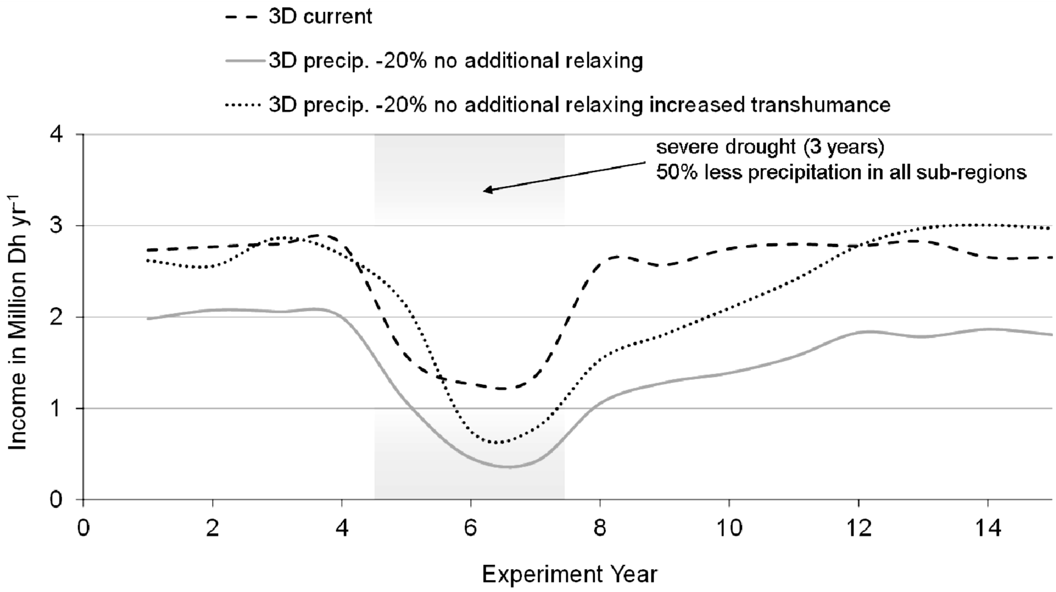
Interestingly, to achieve the results shown in Figure 9, we had to alter the basic model setup for the scenario with a three-year drought under 20% less precipitation: To calculate this scenario, we had to expand the buffer between each ensemble run from 3 to 10 years in order to get independent model runs. Figure 10 shows the effect if we would not have extended this "ensemble-buffer".

The solid grey line in Figure 10, which represents an impact of a three-year drought under reduced average precipitation, reveals that such an event is sufficient to provoke a lock-in effect in our model if we don't allow the system to recover for more than 10 years without any drought: With less than 10 years of recovering (which is a plausible reality), income after the drought is not able to reach again levels of present day conditions. This effect is demonstrated by the offset between the solid grey line and dashed line. However, if we allow the model to increase the share of fodder and pasture area dedicated to transhumance, the lock-in effect does not appear.

This behavior of our model indicates that (1) the investigated land-use system can show long lasting impacts of droughts under future climatic conditions and (2) that an increase in transhumance is able to abate such effects.

Using the insights from Table 2, we investigate whether the negative impacts on income generation, caused by reduced average rainfall and droughts, can be diminished by dedicating more resources to transhumant pastoralism. To answer this question, we run a FPA scenario under reduced average precipitation and a variation of droughts where the pasture area used for transhumant production is increased to 86% and where 50% of the production of high-quality fodder from oases is used to feed transhumant livestock.

Figure 10. Ensemble means (N = 15) of total annual income from pastoralism in the study region (transhumant + sedentary). The solid grey line displays a lock-in effect of the system, if the model is not allowed to recover for more than 10 years under reduced average precipitation.



The experiment results in a significant reduction ($p < 0.05$) of drought impacts by 11% on average, in comparison to FPA scenarios with less pasture area dedicated to transhumant pastoralism. This clearly demonstrates that it is possible to abate the impacts of droughts under a reduced average precipitation by increasing the share of transhumant livestock production. This finding confirms on a more empirically based attempt the results by [24] with a stylized model. Our result clearly demonstrates positive characteristics of transhumant pastoralism in order to abate impacts of droughts under a dryer climate.

3.3. Model Limitations

A major limitation of our model arises from missing plant population dynamics in the meta-model of EPIC, 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 [22].

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 [49,50]. 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 [51]. 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 favorable properties: Stocking rates on transhumant pastures in our LDM are only one tenth the rates around settlements. Therefore, it can be said that transhumant pastoralism in our model favors lower rates of erosion [48], 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 [52] a more secure livelihood from pastoralism is possible even under climate change.

4. Conclusions

In our model, the vulnerability of sedentary pastoralism towards reduced mean annual precipitation and a variation of droughts are striking in contrast to the vulnerability of transhumant pastoralism. Increasing the share of transhumant livestock production in the model is a favorable option to adapt to reduced rainfall and different frequencies of droughts.

Since our model emphasizes the increased importance of destocking during droughts under a dryer climate, newly available land-use strategies such as pastoralism which uses far-distance transport by trucks need to be monitored or embedded in traditional management systems to prevent deterioration of rangeland vegetation and social disruptions [53].

Our results indicate that the current social and political trend towards more sedentary pastoralism in semi-arid areas is likely to increase vulnerability of income from pastoral production towards climate change. In our model, the seemingly old strategy of transhumance is clearly a good option for abating impacts of climate change.

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Author Contributions

Korbinian P. Freier developed the approach and study design for this paper. Manfred Finckh and Uwe A. Schneider supported the development of the approach. Manfred Finckh provided data and assisted with expertise from the field campaign. Uwe A. Schneider supported with modeling expertise. Korbinian P. Freier build the model, performed the analysis and drafted the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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