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How much climate change can pastoral livelihoods tolerate? Modelling rangeland use and evaluating risk

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Abstract

Livestock is the most important source of income for pastoral livelihoods in drylands. Pastoralists have developed flexible resource utilization strategies that enable them to cope with the high spatio-temporal resource variability typical to these areas. However, climate change in the form of decreasing mean annual precipitation accompanied by increasing variability has important consequences for rangeland productivity and thus pastoral livelihood security. Here, we use a spatial simulation model to assess impacts of changing precipitation regimes, and to identify limits of tolerance for these changes beyond which pastoral livelihoods cannot be secured. We also examine strategies to control these limits.

Our results indicate that: (i) While reduced mean annual precipitation always had negative effects, increased precipitation variability can have negative, none or even positive effects, depending on the vegetation's recovery potential. (ii) Depending on income requirements there are limits of tolerance to decreases in mean annual precipitation beyond which precipitation regimes overcharge the coping capacity of the pastoral household and threaten its livelihood. (iii) There are certain strategies, in particular "Increasing mobility" and "Diversifying income for coping with income risks from pastoralism", that allow the limits of tolerance to be shifted to a certain extent. We conclude that it is important to consider climate change and human requirements together to create appropriate climate change mitigation strategies in pastoral systems. Our results also shed new light on the discussion on disequilibrium rangeland systems by identifying mechanisms that can support fluctuating but non-degrading herbivore-vegetation dynamics. The paper finishes with remarks on the broader potential of the presented modelling approach beyond rangelands.

Keywords: social-ecological model, grazing management, drylands, livelihood security, precipitation change

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***Highlights ((without author details, acknowledgements or affiliations)**

- Evaluation of pastoral livelihood security facing climate change in drylands.
- Increasing precipitation variability had negative or positive effects on herd size.
- Identification of critical regimes beyond which livelihoods are endangered.
- Mobility compensates for climate change but not for increasing income needs.
- Appropriate mitigation strategies need to include sufficient resting of pastures.

1. Introduction

In drylands, which cover more than 40% of the surface of the earth (Neely et al., 2009), livestock is the most important source of income (Walker and Janssen, 2002). Facing scarce and variable rainfall, adaptive strategies such as mobility are required to buffer highly variable natural resources and to secure pastoralists' livelihoods (Niamir-Fuller and Turner, 1999; McAllister et al., 2009). Transhumance, the traditional use of rangelands comprising steep environmental gradients with regular herd and household movements (Reid et al., 2008), is a good practice example for locally adapted and sustainable livelihood strategies. However, externally driven changes in the environment and the socio-economy may severely affect ecosystem services such as forage supply (Verstraete et al., 2009). Particularly climatic factors, like mean annual precipitation and precipitation variability, have a huge impact on rangeland condition and fodder production (Williams and Albertson, 2006). Substantial climate change is expected in the form of decreasing mean annual precipitation accompanied by increasing precipitation variability, which is recognized as an important driver for degradation of dryland productivity. However, the direction of precipitation change is discording due to uncertainties in climate models (IPCC, 2007). In several regions in north-west Africa, mean annual precipitation is projected to decrease by 10 to 20% (Paeth et al., 2009). Therefore, climate change is expected to threaten pastoralist livelihoods. Under which local circumstances changing rainfall characteristics may limit the ability of pastoralists to secure their livelihood sustainably if they only rely on local forage resources is an open question.

In the past, research on the effects of changes in climate and land use focused mainly on the ecological subsystem, such as the supply of forage resources and their degradation. During the last two decades, changes in the human subsystem have become more important. The main aim of these studies was to identify causal factors of sustainable pastoralism (Niamir-Fuller and Turner, 1999; Oba, 2011). In this context, political and socio-economic constraints have been identified as major factors in the marginalization of pastoralists (Oxfam, 2008). Studies from economical perspectives elaborated strategies of risk management on stochastic pastoral income (Lybbert et al., 2004) and incentives for reciprocal agistment networks (McAllister et al., 2006; Dixit et al., 2012). Furthermore, decreasing mobility options, as a consequence of multiple drivers leading to fragmentation (Hobbs et al., 2008; Galvin, 2009), may greatly affect pastoral livelihood systems and therefore human well-being (Verstraete et al., 2009). However, it is still difficult to evaluate the relative importance and feedbacks between these external drivers. Now, it is crucial to analyze the vulnerability of pastoral livelihoods to combined threats within a risk-prone environment (Reed et al., 2008; Fraser et al., 2011) and to determine to what extent adaptive strategies can compensate for critical changes.

In this paper, we aim to identify changes in rainfall regimes that can be coped with by pastoral households, and changes which pose a threat to pastoral livelihood security. We focus on dryland systems with a high proportion of woody forage plants, such as sagebrush steppes and Mediterranean ecoystems dominated by shrubs and/or dwarf shrubs. These ecosystems are often found in rangelands comprising steep altitudinal gradients (e.g. in Northern Africa, in the Himalaya) and are typically used via transhumant pastoralism. We hypothesize that decreasing mean annual precipitation accompanied by increasing variability leads to smaller herd sizes and therewith increased risks for pastoral livelihoods. Having identified limits of tolerable precipitation regimes, we examine how robust limits are to changes in income needs, the type of vegetation and mobility.

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

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

We developed a stylized model that aims to fill this gap. It simulates perennial vegetation and compares livestock dynamics under different rainfall regimes, vegetation conditions, and mobility strategies with a quarter-annual, half-annual or no movement frequency. For calibration, vegetation data and empirical patterns of pastoral mobility were used from a case study in mountainous Southern Morocco. In our analysis, we focus on increasing precipitation variability and decreasing mean annual precipitation because these are main components of projected climate change in arid rangelands besides temperature and CO2

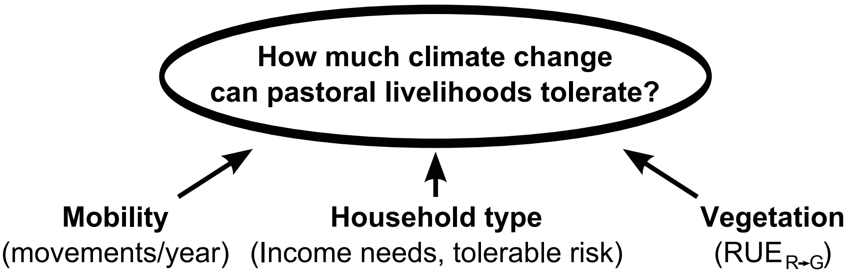

Figure 1: The concept of our analysis with the main research question at the center and three influencing aspects considered for analysis and discussion.

increases (Williams and Albertson, 2006; Scheiter and Higgins, 2009; Linstädter et al., 2010). In order to evaluate changes in terms of sustained pastoral livelihoods, we operationalized livelihood security for a household-based risk assessment. It can be interpreted as the household's specific risk attitude applying a strategy which ensures a certain level of income needs over time while tolerating a certain income variability. By analyzing livestock dynamics with respect to this risk attitude, we assess the household's vulnerability to climate change.

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

2. Methods

The concept of our analysis was to investigate effects of projected climate change in drylands (Williams and Albertson, 2006; Linstädter et al., 2010), in terms of decreasing mean annual precipitation and increasing precipitation variability, on pastoral income and thereby livelihood security (Fig. 1). Three major factors were considered to influence herd dynamics and thus income for pastoral livelihoods. First, the household type is characterized by levels of income needs and tolerable income risk. Further, the vegetation growth, specified by its rain use efficiency, determines the ability of plants to turn available water and nutritional reserves into green biomass (Le Houérou, 1984). This rate regulates the availability of forage for livestock while forage consumption feeds back on the recovery of vegetation. And third, the management of herd movements interacts with the vegetation state and may compensate for heterogeneous forage availability.

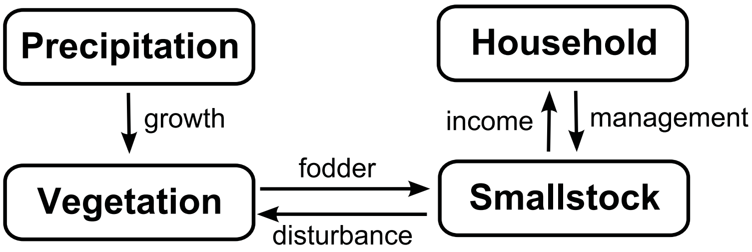

Figure 2: Causal diagram of a rangeland system showing components (boxes) and processes (arrows) that are simulated by our model. We investigate the impacts of precipitation regimes on vegetation and pasture utilization by smallstock. Smallstock population dynamics generate income for pastoral households. We compare household strategies with different levels of income needs, tolerable income risks, and different frequencies of smallstock mobility.

2.1. Model description

Perennial vegetation dynamics were simulated on a set of even-sized and homogeneous pastures utilized by a herd of smallstock (Fig. 2). Annual precipitation is the main driver of vegetation growth here and it is equal for all pastures. But the timing and amount of forage use within a simulation year causes heterogeneous spatial feedbacks. The temporal resolution depends on the herd's movement frequency between pastures (quarter-annual, half-annual or none). The order of intraannual processes is scheduled as follows: First, we calculate the growth of forage based on annual precipitation and its equal distribution over seasons. Second, we simulate herd movement, grazing and herd recruitment. Third, we calculate the effects of grazing on the recovery of vegetation.

2.1.1. Forage production and recovery

The purpose of our vegetation model is to simulate annual forage production in a semi-arid rangeland under the impact of grazing and variable precipitation (similar to Müller et al., 2007b). We focus on perennial plants and their ability to provide forage resources since the vegetation from our case study in Morocco is dominated by shrubs and dwarf shrubs (Baumann, 2009; Linstädter and Baumann, 2013). There, four different vegetation types are found along an altitudinal and climatic gradient, ranging from the *Hammada* semidesert, *Artemisia* steppe, *Juniperus* woodsteppe, to an Oromediterranean shrubland. Functionally comparable utilization forms of transhumant pastoralism can be found in Spain (Olea and Mateo-Tomás, 2009), Pakistan (Omer et al., 2006), Kazakhstan (Milner-Gulland et al., 2006), and Mongolia (Zemmrich et al., 2010). For the simulation of annual precipitation we used a log-normal distribution to capture interannual variability with years of below-average precipitation being typically more frequent than years with above-average precipitation. Due to its skew to the right, the log-normal distribution has been frequently used in dryland ecosystem models before (e.g. Sandford, 1982; Williams and Albertson, 2006).

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

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

2.1.2. Herd movement and growth

We simulated seasonal adaptation and mobility of a smallstock herd consisting of sheep and goats. We acknowledge, that in pastoral systems (including our case study in Southern Morocco) also other risk coping strategies such as feed supplementation play a role (Kuhn et al., 2010; Linstädter et al., 2013). However, we did not include supplementation in this model version, to understand model behavior firstly if no supplementation is available. The impact of supplementation will be part of a future study (see discussion section). Thus, smallstock population dynamics were assumed to be solely dependent on available forage from local pastures. In each season animals move to the pasture with the highest abundance of green biomass (see Fig. 3). Seasonal forage availability on each pasture was updated as consequence of usage in the previous season and growth for the following season (see supplementary material for details). This utilization pattern is comparable to traditional transhumance which is practiced for extensive livestock production. In Southern Morocco, areas are under exclusive or communal tenure regimes that cause varying labor efforts through the seasons (Rössler et al., 2010; Akasbi et al., 2012). We focus on environmental effects as a first step and therefore simplify the analysis based on single households without migration costs that are subject of extensions beyond this study. Here, we compare three resource utilization strategies. First, the pasture area is divided into four pastures where vegetation processes are calculated separately. Second, the pasture area is divided into two equal parts where each pasture is used during half of the year. Third, animals use the complete pasture throughout the year without mobility. Consequently, the part of implicitly rested areas is largest in the quarter-annual case while the total area of pastures remains constant. Before each movement

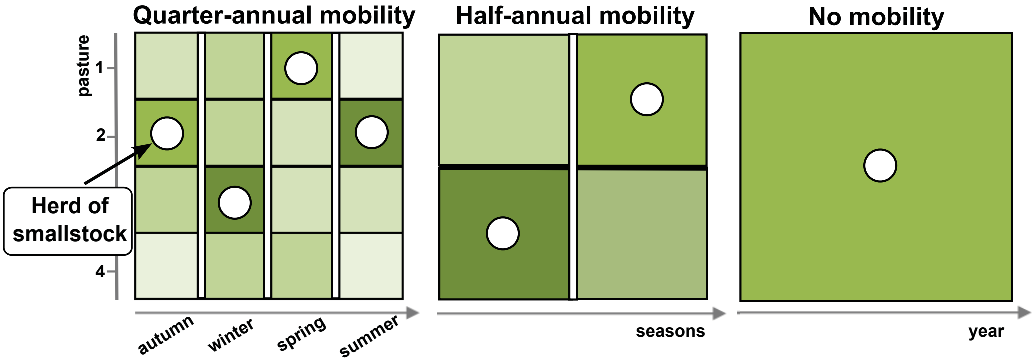

Figure 3: Herd movement over seasons, indicated by dots. Animals are moved to the pasture with the highest abundance of green forage each season. Scenarios compare movement frequencies while the total area remains constant.

between pastures (or in the no-mobility scenario at the end of the year), herds are destocked if the amount of available forage is not sufficient. For the following evaluation only annual herd size dynamics were captured.

2.2. Evaluation scheme for livelihood security

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

Therefore, we developed a risk assessment scheme to evaluate herd size dynamics taking into account two dimensions of risk attitude (Tab. 1). The first dimension is the level of income needed by one household (τ), while the second dimension is the tolerable income risk over time (α). Income needs (τ) are specified by a minimum viable herd size (see supplementary material for details). Tolerable income risk (α) is defined as the fraction of years where the herd size drops below τ. Accounting for the effect of stochastic precipitation, we used an additional threshold ($\Gamma = 95\%$) to ensure that the results were representative.

Table 1: Thresholds for maintaining a pastoral livelihood that were used for risk assessment

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

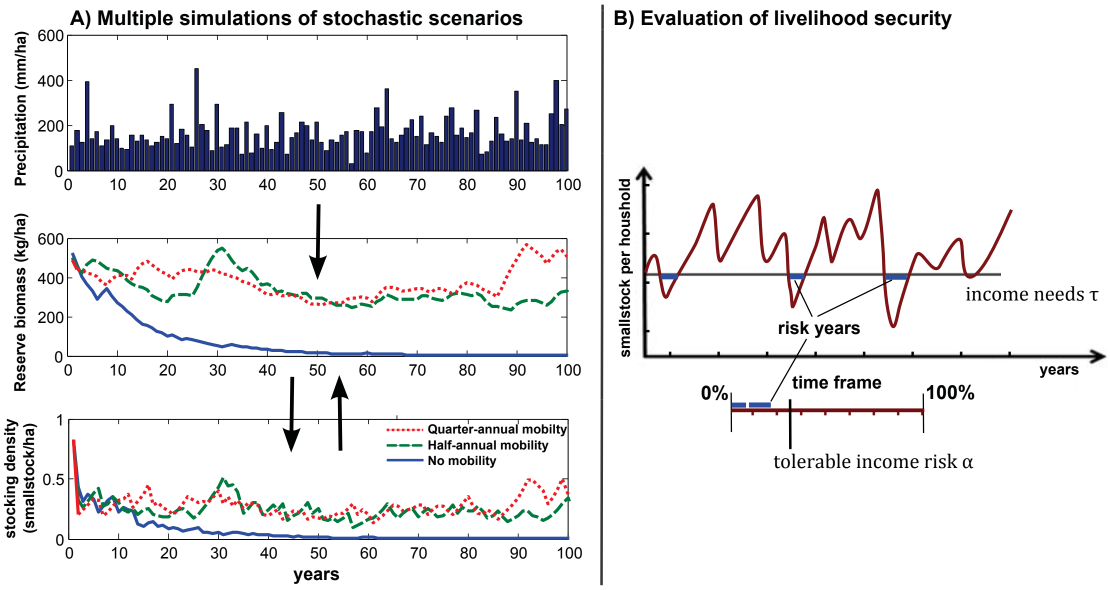

Figure 4: Our methodology including two steps (A - multiple simulations over time, B - livelihood evaluation per run). Below A) is a showcase simulation with stochastic precipitation as the driving force and the interacting vegetation and livestock population over time. The arrows denote causal relations. B) describes the evaluation of livelihood security based on herd sizes from each run to evaluate which levels of income needs can be fulfilled (Tab. 1). If more than 5% of runs cannot exceed τ while staying below α, this scenario is classified as unsafe.

2.3. *Model and evaluation scenarios*

Our study was based on two important steps (Fig. 4). At first, the model was executed for all scenarios providing smallstock time series. Second, time series of smallstock were evaluated using the thresholds for livelihood security (Tab. 1).

Simulations of herd sizes were iterated a hundred times to account for the variability caused by stochastic precipitation. Each simulation comprised 150 time steps (years). To exclude initialization effects, only the last 100 time steps were used for the evaluation of income. Implemented in the computing environment Matlab, it took ca. three minutes to simulate three mobility scenarios. (Source code of implementation can be requested from the first author). Parameter sets were used to analyze changes in precipitation regimes (mean annual precipitation, coefficient of variation), vegetation state ($RUE_{R\rightarrow G}$), or mobility (no, half-annual, quarter-annual) (A summary of scenarios and parameter ranges can be found in Table 3 in the supplementary material).

Changes in the socio-economic background of pastoral households were evaluated based on the risk assessment of model results. For example, human population growth was expressed by rising income needs or additional income from non-pastoral activities interpreted as increased risk tolerance.

3. Results

3.1. Livestock production related to precipitation regimes

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

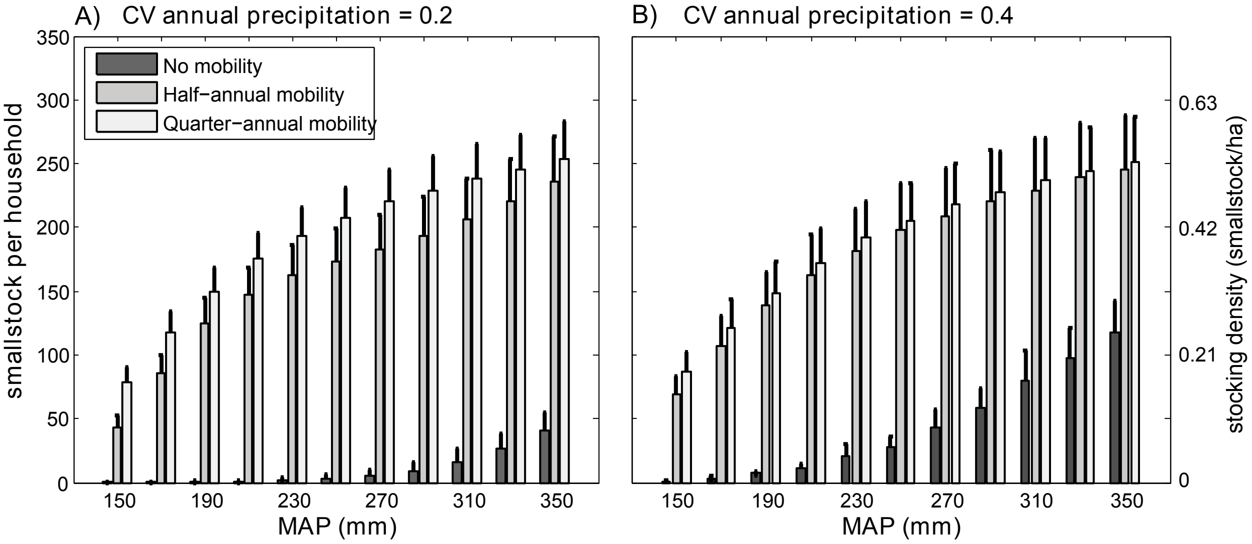

Figure 5: Mean and standard deviation of herd size of smallstock averaged over the set of runs (n=100). Scenarios were parameterized with increasing values for mean annual precipitation (MAP). A) displays results from simulations with a precipitation variability (CV) of 20%, B) with a variability of 40%. The value for $RUE_{R\rightarrow G}$ was constant: 0.001 $kg\ G \cdot (kg\ R \cdot mm \cdot a)^{-1}$. While household-related herd sizes (left y-axis) are linked to our evaluation of livelihood security, area-related herd sizes (right y-axis) are given for a comparison to empirical data.

Increasing mean annual precipitation and mobility supported higher herd sizes of smallstock (Fig. 5). However, the increased coefficients of variation in precipitation had only a small effect on average herd size and on its variation. Compared to the scenario of no mobility, the two mobility scenarios with quarter-annual and half-annual movements both performed similarly well with respect to average herd sizes. Under conditions of low precipitation variability (coefficient of variation = 0.2), mobile herds were six times larger than immobile herds under semi-arid conditions (mean annual precipitation=350 $mm \cdot yr^{-1}$). The difference between mobile and immobile herds decreased with increased precipitation variability (Fig. 5, B); mobile herds were only two times larger than immobile herds then. Notably, the immobile system sustained higher average herd sizes under higher precipitation variability.

We observed different effects of precipitation variability on the mean herd size along a mean annual precipitation gradient (Fig. 6, immobile scenario was excluded since it was qualitatively similar to half-annual scenario) when we evaluated different specific growth rates ($RUE_{R\rightarrow G}$). While we observed a negative effect of precipitation variability on smallstock herd size at high specific growth rate, there was a positive effect

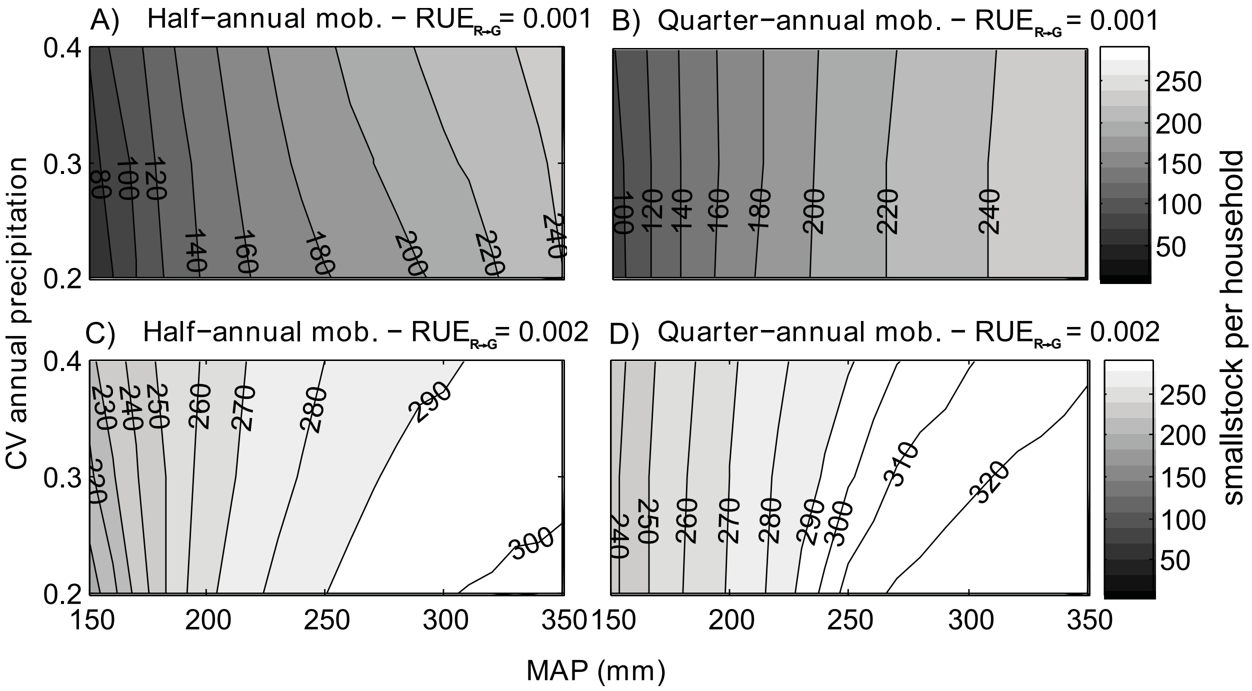

Figure 6: Mean herd size of smallstock for the last 100 simulation years (Lighter shades denote greater herd size). A) and C) show results for the system with half-annual mobility, A) with the value of $RUE_{R\rightarrow G} = 0.001\ kg\ G \cdot (kg\ R \cdot mm \cdot a)^{-1}$ and C) with the value $RUE_{R\rightarrow G} = 0.002\ kg\ G \cdot (kg\ R \cdot mm \cdot a)^{-1}$. B) and D) show results for the same $RUE_{R\rightarrow G}$ values but under quarter-annual mobility. The contour lines are based on a linear interpolation of 105 datapoints. Lines parallel to the y-axes denote that there is no effect of the coefficient of variation (CV). If lines are diagonal from the lower left to the upper right corner, the coefficient of variation has a negative effect on smallstock numbers. In contrast, lines running diagonally from the lower right to upper left corner denote that the coefficient of variation has a positive effect.

at a low growth rate and half-annual mobility (Fig. 6, A and C). However, under conditions of the lower growth rate, no positive effect of precipitation variability was detected when executed in a quarter-annual scenario. Similar to Fig.5, there is only a small difference in the average herd size of smallstock between the half-annual and the quarter-annual system.

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

3.2. Livelihood security evaluation

Given an environment with a specific precipitation regime, a pastoral household aims to secure its livelihood by applying an adequate management strategy. In the following, we first identified the limits of precipitation regimes beyond which no sufficient herd size can be supported (Fig. 7). Second, we evaluated parameters of risk attitude (Tab. 1) and scenarios of mobility to assess how far the limits of tolerable precipitation regimes can be shifted (Changes in income needs are compared between different plots from left to right in Fig. 7, changes in risk tolerance are denoted by line types). Comparisons of limits between safe and

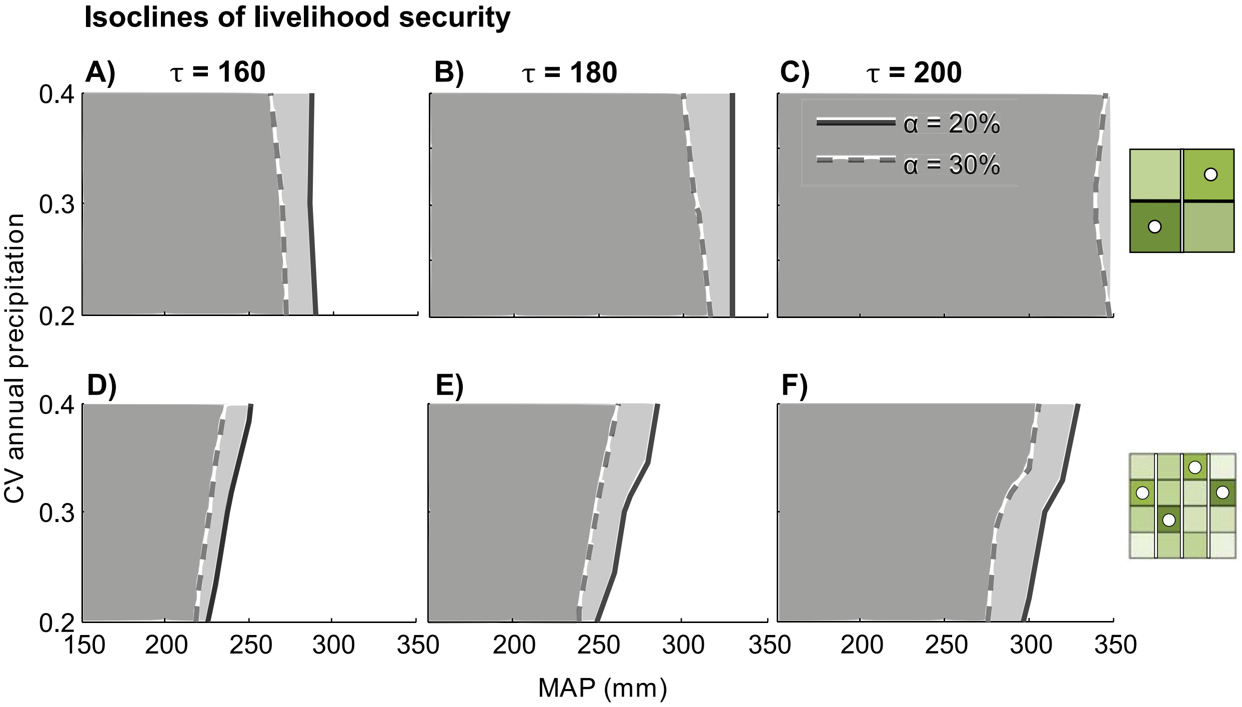

Figure 7: Isoclines in each plot denote limits of precipitation regimes beyond which livelihood conditions are unsafe (shaded side), with a gradation in tolerable income risk (α, based on evaluation scheme of Tab. 1). A to C show isoclines under the half-annual mobility and D to F for quarter-annual mobility. From left to right we varied the level of income needs ($\tau(head\ of\ smallstock)$). The value for vegetation productivity is $RUE_{R \to G} = 0.001\ kg\ G \cdot (kg\ R \cdot mm \cdot a)^{-1}$.

unsafe conditions show that bigger herds require environments with higher mean annual precipitation. Higher mobility ensures pastoral livelihoods under more arid conditions (in terms of mean annual precipitation). We observe a small positive effect of precipitation variability under the half-annual cycle and a small negative effect under the quarter-annual cycle. Increasing the tolerable income risk suits to shift the limits towards smaller mean annual precipitation, which is a more pronounced effect when income needs are high. The comparison of limits has important management implications. That is why we used the the map of isoclines of livelihood security to highlight effects of different adaptation strategies (Fig. 8). From the household's point of view, within an environment of fixed precipitation characteristics, pastoralists can switch from unsafe to safe livelihood evaluation by applying suitable strategies. This is exemplified in Fig. 8 by a household who may increase its alternative income and thereby risk tolerance or who may apply a higher mobility. Only the latter would allow for a safe livelihood evaluation in this case. Alternatively, an even higher risk tolerance than in the plotted example could also ensure a safe livelihood. Thus, this kind of analysis leads to

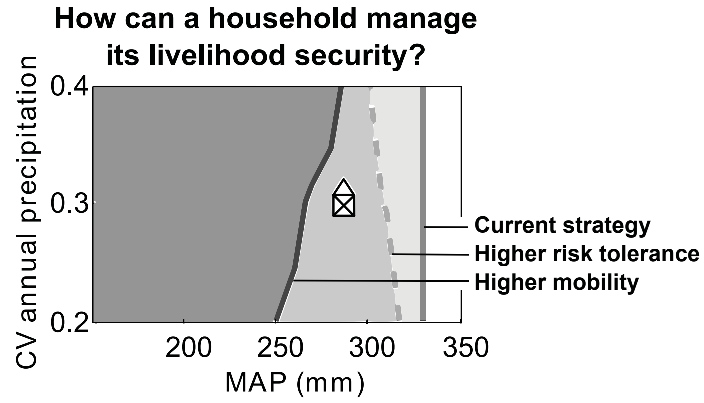

Figure 8: This example shows a household in a specific climate regime which is unsafe under half-annual mobility strategies. The household remains unsafe while increasing its risk tolerance by 10%, but it may become safe by applying quarter-annual mobility.

the identification of factors that most likely pose a threat to vulnerable households when the precipitation regime and its projected changes are known.

The following analysis synthesizes to which extent mobility and pasture states modulate the critical amount of mean annual precipitation that is required to secure livelihoods. We identified the critical amount of mean annual precipitation at the isocline from Fig. 7 at $\alpha = 20\%$ for a fixed coefficient of variation for precipitation of 30%. Fig. 9 shows critical mean annual precipitation related to different levels of income needs. We observed an approximate linear and positive relationship between income needs and critical mean annual precipitation. A higher frequency of herd movements can result in increased income at a fixed mean annual precipitation, thus mobility can compensate for decreases in mean annual precipitation in this case. However, using a pasture area with a higher vegetation growth rate (increased $RUE_{R \to G}$), the benefit of high mobility was less obvious. Both lines were shifted far more towards higher levels of income needs. Surprisingly, for a limited parameter range of 230 to 270 mm mean annual precipitation (Fig. 9b), the quarter-annual system was inferior to the half-annual system, in terms of critical mean annual precipitation and smallstock preservation. This was caused by pasture degradation events which happened in ca. 5-10% of the runs under quarter-annual mobility. Notably, this exception was not detected by observing average smallstock numbers and their variability (as in Fig. 5), but only by evaluating livelihood security with our risk assessment. This example revealed the impact of feedback in the ecological system, since it may influence critical thresholds for pastoral livelihoods.

4. Discussion

The aim of this study was to identify tolerable limits of climate change, specifically precipitation change, where livelihood security of pastoral households can be locally sustained. Therefore, we used a novel approach

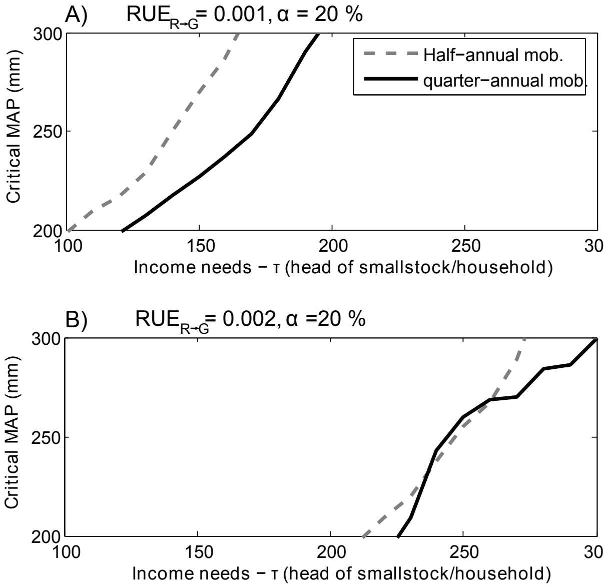

Figure 9: Each line denotes the critical amount of mean annual precipitation required to secure livelihoods along different levels of income needs. A) shows this result for two mobility strategies in a system with a low vegetation growth rate ($RUE_{R\rightarrow G} = 0.001\ kg\ G\cdot(kg\ R\cdot ha\cdot mm\cdot a)^{-1}$), while B) shows the result for a high growth rate ($RUE_{R\rightarrow G} = 0.002\ kg\ G\cdot(kg\ R\cdot ha\cdot mm\cdot a)^{-1}$). Coefficient of variation of precipitation was 30%.

that combines risk assessment with an ecological-economic model. This allowed us to jointly analyze the effects of climate, social and vegetation change on pastoral livelihoods as it was identified to be a research gap (Asner et al., 2004). Our analyses revealed how precipitation change and maladapted management may threaten pastoral livelihoods.

4.1. Different influences of precipitation change on livestock production

In a previous study simulating annual vegetation, increasing precipitation variability in drylands was considered as one of the main determinants of degradation in terms of losses in fodder and livestock production (Williams and Albertson, 2006). In our model, which simulates perennial vegetation and a naturally recovering but eventually destocked smallstock population, precipitation variability had little or no effect on the number of livestock. This is in concordance with a recent study on savannas where also effects of temperature and CO_2 were investigated (Lohmann et al., 2012). We focused on spatially homogeneous precipitation scenarios to exclude positive effects from mobile utilization based on heterogeneous precipitation and interferences of different sources of variability. Perennial plants use reserve biomass as a buffer which allows them to adapt to dry and variable climates (Owen-Smith, 2008). Thus, their forage provision is less vulnerable compared to short-lived plant species that depend on seedbanks in an increasingly variable environment (Morris et al., 2008). Low productive sites dominated by perennial herbs and shrubs may still be in a good state in spite of low ground cover (Linstädter and Baumann, 2013). Thus, a differentiation between vegetation types with respect to the dominant life form (annuals or perennials, see for example Lohmann et al. (2012)) is highly relevant for deducing changes in productivity related to precipitation variability.

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

4.2. Tolerable precipitation conditions to secure pastoral livelihoods on a local scale

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

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

4.3. What controls the limits of tolerable precipitation change while sustaining pastoral livelihoods?

Multiple changes are projected and were partly observed in socio-economic systems of pastoralism, such as population growth and therewith rising income needs, or restricted pasture access regimes due to changed land use directives (ECA, 2004). Social changes that limit the adaptive capacity of pastoralists are considered to threaten their livelihoods (Niamir-Fuller and Turner, 1999; Oba, 2011). Pastoralists adopt different strategies to meet these challenges, for instance becoming partly sedentary and increasing their risk tolerance with income from non-pastoral activities (Breuer, 2007; Linstädter et al., 2013). We compared how effective these strategies would be for increasing pastoral livelihood security. Our simulations have shown that households might manage their livelihoods more effectively by adopting a suitable mobility strategy than by the relatively small benefits from increased risk tolerance. In general, higher frequency of herd movements resulted in higher average herd sizes and enabled households to utilize less productive rangelands. Thus, mobility can to a certain degree compensate for decreased mean annual precipitation or increased income needs even in spatially homogeneous landscapes as it was assumed for simplicity in our model. The reason for heterogeneity of pasture states during the simulation was the time of usage during the year and the subsequent heterogeneous recovery. Thus, the reason for the success of mobile utilization strategies lies indirectly in the resting time which is essential for perennial vegetation. Consequentially, the scenario without mobility has shown degradation of vegetation and smallstock under low productivity conditions.

However, maintaining mobile utilization becomes challenging since more often fragmentation of rangelands leads to decreased migration options and larger costs to maintain livestock (Hobbs et al., 2008; Galvin, 2009). Further, rising income needs are often accompanied by a decreasing ability to be mobile. In this way, the option of an adaptive compensation strategy may be rapidly lost, especially due to losses of labor force (Breuer, 2007). In the face of precipitation change it becomes even more important to protect mobility because indirectly it facilitates the management of vegetation recovery and thereby long-term pastoral utilization.

4.4. Importance of the ecosystem – commenting on the nonequilibrium theory

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

We explored the effect of an increasing variability in a spatio-temporal structured rangeland system (c.t. Illius and O'Connor, 1999). In such systems, working with concepts like density dependence, dynamic equilibrium or strength of resource-consumer interactions (Vetter, 2005; Retzer, 2006; von Wehrden et al., 2012) as usually used in the equilibrium vs. disequilibrium/nonequilibrium debate is problematic. In our context, such functional relationships can be hardly determined as one would be forced to average out the responses over the different pastures, which is not straightforward. Our study presents an alternative approach to explain the effect of variability on pastoral systems. The approach is based on mechanisms (vegetation recovery, benefits from upward fluctuations, mobility mediating sufficient resting) that are fully compatible with spatio-temporal heterogeneous resource utilization rather than with averaged functional relationships.

4.5. Remarks on stylized rangeland models for social-ecological systems

We recognize the shortcomings of our stylized model based on homogeneous pastures, which can be resolved by future extensions. Using a stylized model and excluding multiple sources of heterogeneity (such as seasonality, spatially heterogeneous precipitation) enabled us to identify the mechanisms of why and under which circumstances mobility remains beneficial. The reason for heterogeneity of pasture states during our simulation is the time of grazing during the year and the subsequent heterogeneous recovery.

So far, we did not consider transaction costs for mobility because we assumed them to be negligible in our case due to its focus on a small regional scale. This makes our results comparable to models of rotational grazing systems (e.g. Jakoby, 2011) or experimental studies where circumstances were identified where rotational grazing is not superior to continuous grazing (Briske et al., 2008). Integrating costs for mobile activities and herd size adaptations (costs for transport, but also social and reciprocity costs in practicing livestock mobility if pastoralists do not have exclusive property rights, see for example McAllister et al. (2006)) are important future extensions. They would probably show a trade-off between increasing mobility beyond the local scale and labor force or monetary investments to implement the strategy (Dressler et al., 2012). Since cases of pastoral households whose income is solely based on livestock raising are rare (Lybbert and McPeak, 2012), strategies to obtain additional income or to buy supplementary fodder should be considered for further analysis. Interviews with pastoralists in general (Lybbert and McPeak, 2012) and in our case study in particular (Breuer, 2007; Linstädter et al., 2013) have shown that their choice of adaptation strategies can be very different depending on their labor force, monetary resources and social relations.

Although our model addresses nomadic livestock systems that were simplified to few essentials, it reflects consequences of major land use change in global drylands. We have developed a risk assessment tool which includes an operationalization of the concept livelihood security in stochastic environments. Our approach may be transfered to studies beyond rangelands whenever dynamics of ecosystem services are closely linked with livelihood security. This analysis proved to be useful to evaluate multiple changes and managements options and to weight them against each other.

5. Conclusion

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

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