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Risk management in an uncertain environment - A study from semi-arid grazing systems

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Abstract: Since livestock grazing is the most important type of land-use in arid and semi-arid rangelands with uncertain and highly variable climatic conditions, well adapted grazing strategies are crucial for effective risk management. However, local environmental characteristics and individual needs and perception lead to a broad range of different management forms used in practice. In this paper we (i) analyse how uncertain climate conditions and the individual farmer's characteristics like risk aversion, economic constraints and effort cost affect the choice of management, (ii) evaluate the viability of different management options, and in particular (iii) their robustness under climate variability. We use a generic stochastic simulation model that consists of a physiologically well-founded vegetation model combined with a rule-based management model. Thereby, we implement a feedback of grazing management and rangeland state. Changes in the rangeland state are driven by stochastic precipitation and livestock grazing. In turn all management actions taken by a farmer adapt to changes in the rangeland condition. Management is temporally resolved on a weekly scale and spatially on the local scale of an individual farm. With our approach we can characterise strategies that are robust over a wide range of climatic condition and those that are vulnerable to unexpected changes. Hence, we can identify appropriate strategies for an adaptation to climatic risk and therefore support sustainable land-use.

Keywords: semi-arid rangelands, generic simulation model, risk management, environmental uncertainty, climate change

1 INTRODUCTION

Arid and semi-arid rangelands are characterised by highly uncertain and variable climatic conditions. In this uncertain environment, the primary production is low and erratic. This pose the major challenge to extensive livestock farming that is the predominant form of utilisation in these areas and provides livelihood for a large part of the local population. Hence, the need for flexible and viable land-use strategies is especially high. Particularly, on commercial rangelands, where farm borders prevent the formerly widespread large scale moving of early pastoral systems, arises the need for new, well adapted grazing strategies for a risk management on a local scale.
What are the important characteristics of viable grazing strategies in semi-arid rangelands? The four principles of grazing management (i.e. timing, distribution, kind of livestock, and stocking rate) are widely accepted [Heitschmidt and Taylor, 1991]. Based on these principles emerged various kinds of (rotational) grazing systems that are used in practice [e.g. Heady and Child, 1994]. However, the strength of the impact of the different factors is heavily discussed. Whereas, the high importance of an appropriate stocking rate is widely agreed [Holechek, 1988], there are ongoing discussions on the importance of timing, distribution, and in particular on the suitability of rotational grazing systems in general [Briske et al., 2008; Barnes et al., 2008]. Furthermore, the specific strategy and the overall result of rangeland management must always serve the individual goal of the land manager. This goal varies, however, as a function of many social factors of which the economic is usually dominant [Connor, 1991]. Farmers can for instance aim to maximise their income, or might be risk averse and try to minimise the fluctuation in the income to

avoid catastrophically losses. Furthermore, resources like savings, time, or farm structure limit his possibilities. In summary, the variety of different objectives is as manifold as the diversity in management strategies itself. Although the objective and the management goal of a farmer are important variables in the choice of the appropriate strategy, moreover, it is limited by local factors such as climate conditions or available resources.
In this paper we explore several grazing strategies for rangeland management in an uncertain environment, characterised by an uncertain and variable precipitation and observe how they match with different farmers' objectives. We also analyse the range of robust strategies in order to shifting objectives and climate change.

2 MATERIALS & METHODS

Rangeland management in semi-arid areas depends on multitude of different factors such as precipitation, vegetation growth, livestock grazing as well as farm structure, management strategy, and risk perception of a farmer. To cover these aspects we developed a generic ecological-economic simulation model. The model consists of two submodels: An equation-based ecological submodel describing the dynamics of the grazed vegetation and a spatially explicit, rule-based economic submodel describing the farmer's management strategy. The ecological part of the system is represented by a physiology-based model of grass biomass production. The biomass is mainly affected by both unpredictably fluctuating precipitation, and the grass consumption of livestock. The way a farmer is managing his livestock has a direct feedback to the ecosystem providing his livelihood. This links the ecological to the economic part of the system. The economic submodel comprises both the management strategy of the farmer and the evaluation of the economic risk at the end of the time horizon. The management strategies considered in this study are characterised by: the rules for selling livestock, and the implemented farming system described by the number of fenced pastures (paddocks), and the rules of herd rotation.

2.1 Ecological Submodel

In the present study, each paddock is described as a grid of small homogeneous cells of rangeland. The ecological submodule describes the dynamics in a single cell that is the result of local interactions of the biotic (vegetation and livestock) and abiotic (precipitation) environment. As major interest of this study is in the effectiveness of different management strategies that are all working with weekly management decisions, the dynamics are described at a weekly time scale. The processes are affected by precipitation and livestock grazing, that are known as the main drivers of arid and semi-arid rangelands dynamics [Walker, 2002].

Precipitation. In accordance with the seasonal rainfall pattern in semi-arid rangelands that is characterised by a low and erratic annual rainfall of 250 - 500mm, we distinguish two different phases per year: (i) the rainy season with interannual fluctuating rainfall, and (ii) the dry season without rainfall. Each year the weekly amount of rain is drawn from a log-normal distribution $LN(\overline{r}, \sigma_r)$ [Sandford, 1982]. The mean $\overline{r}$ and variance σ_r of the distribution differs regarding to the different climate scenarios (Tab.1). The rainy season lasts on average four month (18 weeks). It consists of a fixed period of 14 weeks and a flexible beginning and end phase. These are drawn from a uniform distribution of four weeks each.

Vegetation dynamics. The vegetation dynamics within a homogeneous rangeland cell are based on a set of three difference equations that are simulated at a weekly time scale. The plant biomass is subdivided into three components (Fig.1A): The (1) storage biomass (q.v. crown or reserve biomass) represents the vigour of the vegetation [Noy-Meir, 1982]. Further, the (2) green photosynthetically active and (3) brown, dead biomass form the grazeable parts of the plants. The storage biomass is supposed to contribute to the initial growth of green biomass by providing carbohydrates (after the first rainfall or a strong grazing event). If the amount of green biomass increases, the green parts of the plants maintain their growth independently from the storage due to photosynthesis. The growth rate of the green biomass is linearly increasing with the amount of precipitation. Towards the end of the growing season, carbohydrates formed by photosynthesis are transferred to the storage as reserves for regrowth in the next year. After a severe depletion of

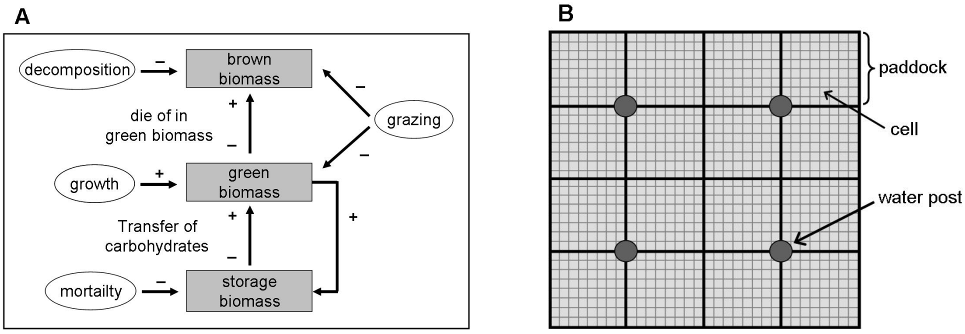

Figure 1: (A) Conceptional description of the vegetation biomass submodel. (B) Spatial layout of the farm in the economic submodel.

green biomass by grazing the return of carbohydrates to storage biomass is diminished resulting in a poorer regrowth in the following year. Brown biomass emerges from dying of green biomass at the end of the rainy season. Both brown and green biomass can be consumed by livestock.

Livestock grazing at the local scale. Biomass consumption by large herbivores, i.e. domestic livestock like cattle or sheep has a major effect on the rangeland condition. Furthermore, the impact of different kinds of livestock varies as they differ in dietary preference, nutrient requirements and foraging abilities [Stuth, 1991]. However, in this study we neglect those species specific differences as the main focus lies on the effect of amount and distribution of livestock in general. We presume a general definition of livestock in terms of Large Stock Units (LSU).
Thereby, the biomass loss due to grazing within one cell depends on the amount and the palatability of grazeable biomass. Green biomass has a higher palatability than brown biomass [Stuth, 1991]. Therefore, the biomass discharge is weighted with palatability and quantity of the two types and multiplied by the amount of livestock on the cell.

2.2 Economic Submodule

This submodel describes the spatially explicit farm structure and the farmer's livestock management. It uses the ecological model (see 2.1) for simulating vegetation dynamics in each rangeland cell. Moreover, it describes the livestock dynamics, the spatial grazing behaviour of livestock on one paddock, as well as the set of management strategies considered, and the rules for the economic risk assessment that provides the basis for the farmer's strategy choice.

Spatial farm structure. The modelled rangeland is subdivided into 1024 cells on a rectangular grid (Fig.1B). The biomass production in each cell is simulated on a weekly basis. The cells are grouped to paddocks that serve as grazing units. Each paddock has access to one water post. As several paddocks use the same water source it is located in one corner of each paddock.

Spatial grazing behaviour of livestock. The farmer chooses the paddock that is grazed at a certain time, but he cannot influence the grazing pattern within a grazed paddock. Here, the impact of large herbivores, in particular the degree of herbage defoliation, is largely influenced by the distance from a water source [Andrew, 1988]. Furthermore, livestock has a preference to graze fresh, green biomass [Stuth, 1991]. In the model we assume the relative grazing activity per cell G predicted by a negative exponential decay function [Pringle and Landsberg, 2004]:

$$G = \exp(-D) \cdot P \tag{1}$$

where D is the distance of a cell from a water post and P is the preference for grazing in a cell. P is depending on the amount of available biomass weighted with a preference for green biomass.

Livestock dynamics, stocking and selling rules. The number of livestock on a farm is determined by intrinsic population growth and the management of the farmer (Eq. (2)). Usually, most decisions regarding the stocking rates are made at the end of the growing season [Holechek, 1988].

Therefore, we assume one calving season per year that is timed towards the end of the growing season. At the same time, the farmer makes the decision to sell livestock to cover his expenses and regulate the stocking density.
In this study we apply an opportunistic stocking rule [Campbell et al., 2006]. This means the farmer varies the maximal number of livestock according to the temporally variable forage supply on the grazed paddocks in the next year, and the stocking rate that correspond to the percentage of available forage that should be used. We assume that the farmer only raises own animals and never purchases livestock. To cover at least some of his expenses he definitely sells 10% of his livestock at the end of each rainy season. Additionally, he sells the surplus of animals that exceed his calculated maximal herd size. In the following, we use the terms sold livestock and income synonymous, as the farmers derives his income only from selling livestock and the livestock prices are defined constant over time.
Moreover, the herd size is determined by its intrinsic population growth. It is based on a linear relationship between growth rate and amount of forage intake during the last year (Eq. (3)):

$$H_{t+1} = H_t + g_t \cdot H_t - S_t \tag{2}$$

$$g_t = g_{max} \cdot \left[2 \cdot \left(\frac{1}{52} \cdot \sum_{k=0}^{51} \frac{F_k}{H_t} \right) - 1 \right] \tag{3}$$

H_t is the number of livestock in the current year, and S_t is the number of livestock sold. The population growth rate g_t depends on the maximal population growth rate g_{max} and the cumulated amount of grazed forage F_k per week k.

Rotation rules. Most livestock ranches in semi-arid areas apply one of various kinds of rotational grazing schemes. That means the farmland is subdivided into multiple paddocks, and grazed in rotational sequence allowing recovery of rested areas. Here, we analyse a non-adaptive rotation management. The herd is shifted from one paddock to the next after a fixed period in time (ST). The selection of the next paddock follows a fixed sequence.

Evaluation of the management strategies. In order to evaluate the different management strategies in terms of their appropriateness and to provide insight into the role of the farmer's management objectives, two different management aims were assumed and compared. In the first case, we consider a risk-averse, utility maximizing farmer whose utility positively depends on the mean number $\overline{S}$ of livestock sold and negatively on the coefficient of variation $CV(S_t)$ (Obj_1). In the second case, we assume that the farmer follows a safety-first approach and intends to avoid the economic risk that the yearly number of sold livestock S_t falls too often below the minimum threshold S_{min} required for securing his livelihood (Obj_2). "Too often" means more frequently than a critical number of years Y_{max} that can be tolerated at maximum within 10 years. Note that this number Y_{max} can also be interpreted as indicator of risk aversion: low/large Y_{max}-values indicate high/low risk aversion.

2.3 Scenarios for model simulations

Many different management strategies exist (and are applied) for livestock farming in dry rangelands [e.g. Heady and Child, 1994]. External factors, such as climate conditions, determine the potential management strategies. However, the adequacy of a strategy depends mainly on the preferences and the objectives of a land manager. Therefore, we test different sets of management rules under several climate scenarios and observe how they match with different objectives.

Management scenarios. Heitschmidt and Taylor [1991] point stocking rate, number of paddocks and rate of rotation as the important variables in rotational grazing systems. Here, we analyse the impact of paddock number and rotation rate on the success of rangeland management and focus on a medium stocking rate of 50%. Thereto, we define different rotational grazing strategies by combining several paddock numbers (4, 8, 16, 32) with fix standing times (1, 2, 4, 8, 17, 52 weeks). Additionally, we simulate continuous grazing on one paddock.

Climate scenarios. The rainfall pattern in drylands differs widely between geographical locations. Moreover, a decrease in precipitation is expected for many parts of the arid and semi-arid

Table 1: Table of climate scenarios. The values were transformed that a medium rainfall is expected to be 1.

Scenario	Mean rain $\overline{r}$	Variance of rain σ_r	Description
R1-V25	1	0.25	normal rainfall with normal variance
R1-V40	1	0.4	normal rainfall with increased variance
R08-V25	0.8	0.25	decreased rainfall with normal variance
R08-V40	0.8	0.4	decreased rainfall with increased variance

regions over the next century [IPCC, 2008]. Generally, an increased frequency of extreme weather events is predicted. Therefore, it is crucial to know which management strategies perform well under which range of climatic conditions. We evaluate, if the success of different strategies change for different regions or rather under the influences of a locally changing precipitation regimes. Hence, we analysed rainfall scenarios differing in interannual variance σ_r and mean precipitation $\overline{r}$ (Tab.1).

Simulation experiments. We simulated all management strategies for a period of 100 years. For each climate scenario the simulations were repeated 100 times with differing stochastic precipitation. For the analysis we calculated the mean number of livestock sold ($\overline{S}$) and their coefficient of variation (CV) for each run and averaged the two quantities over of all 100 runs.

3 Results

3.1 Management aiming at maximum stable income

We start with the assumption that the farmer aims at maximizing the mean income from livestock sales by minimizing its variation, i.e. follows an optimisation approach. Therefore, we evaluate the different management strategies from the point of view of the resulting mean $\overline{S}$ and the coefficient of variation $CV(S_t)$ of the livestock sold.

Influence of paddock number and standing time. The combination of paddock number (PN) and standing time (ST) shows a strong impact on both $\overline{S}$ and CV (Fig.2). An increasing standing time leads to a typical shape of the resulting curve in the $\overline{S}$-CV-space. Evidently, the CV decreases, except for very long grazing periods on small paddocks, while the mean income $\overline{S}$ shows a unimodal response. This indicates the existence of an optimum ST that balances the trade-off between increasing mean and decreasing variation. We also see that the entire curve and the optimum ST shift with the PN. A simultaneous increase in paddock number and standing time cause both an increase in the mean income $\overline{S}$ and a decrease in CV. Therefore, a higher subdivision

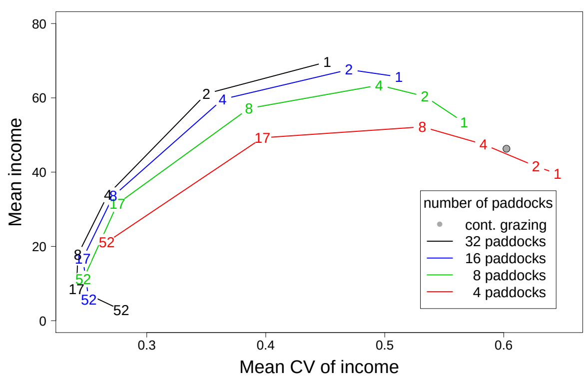

Figure 2: Relation between mean ($\overline{S}$) and coefficient of variation (CV) of sold livestock for different management strategies. The numbers on the curves indicate the standing time per paddock in weeks. (A) The relation is plotted for different paddock numbers indicated by different colours. The gray dot shows the outcome for a continuous grazing strategy.

of the farm combined with an appropriate (and higher) rotation speed improves the success of a farm enterprise in terms of higher income and lower CV. However, in return the farmer's effort in management increases with more paddocks and faster rotation. Therefore, he is subject to a trade-off between mean income, the degree of fluctuation in his mean income (related to his risk aversion), and the effort cost. Additionally, a continuous grazing strategy performs very poorly (Fig.2). It provides a rather low mean income at an extremely high degree of uncertainty. This means that most rotational grazing strategies perform much better for risk management.

3.2 Management for sustaining a minimum income

We now change the perspective and repeat the analysis for a different specification of the farmer's objective (Obj_2). This means that we consider a farmer who intends to secure a certain minimum income from livestock S_{min} but tolerates a maximum number of years Y_{max} where this minimum is fallen below.

For this analysis, we assess all management strategies regarding their suitability to meet the management objective (Fig.3). This is repeated for different values of S_{min} and Y_{max} to assess the influence of the farmer's minimum requirements and his capacity to tolerate failing the minimum. Figure 3A reveals that both the income requirements and the tolerance of failure of the farmer markedly limit the range of suitable strategies. If these requirements are low or the tolerance is high, almost every strategy is found to be suitable. In face of increasing requirements or decreasing tolerance, however, the range of opportunities is shrinking. Long ST or small PN become increasingly critical. The suitable strategies are characterised by an appropriate ratio of paddock number and standing time (i.e. the higher the PN the shorter the ST). Altogether, there is only one type of strategy that is suitable for a large range of settings and so most robust: strategies with short standing time and a large number of paddocks. These strategies ensure that the rangeland can regenerate after short-term grazing.

3.3 Influence of climate changes

Additionally, we analysed the influence of the scenarios of climate change listed in Table 1. As far as management objective Obj_1 is concerned, we found that alterations in the distribution of precipitation $LN(\bar{r}, \sigma_r)$ cause a shift in the functional response of the strategies in terms of mean

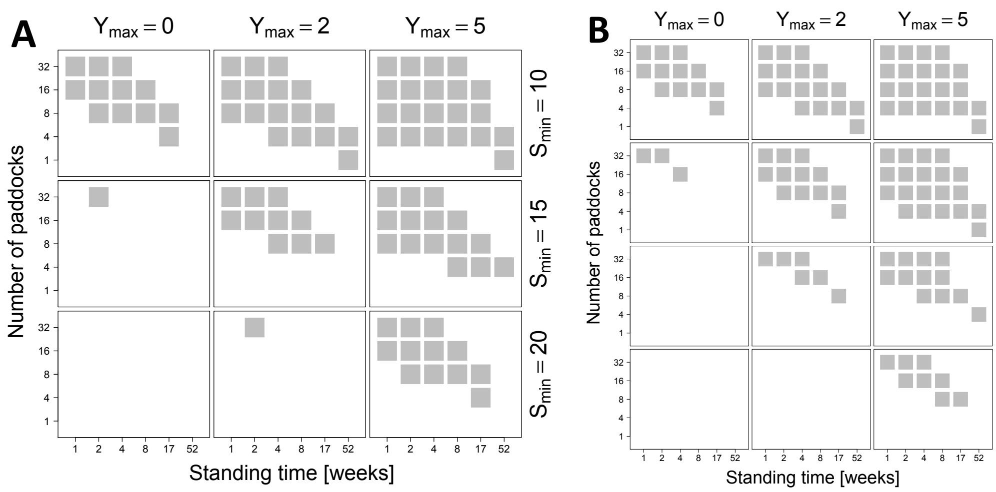

Figure 3: Possibility space of rotation strategies for farmers with different management aims. Strategies are said to be suitable, if 95% of the simulation runs match the objective. (A) Changes in the possibility space for different minimum incomes (S_{min}) and maximal numbers of years that are manageable to fall below (Y_{max}). The figure shows an average climate scenario (R1-V25). (B) Suitable management strategies under different climate scenarios (see Tab.1) and a defined minimum income of $S_{min} = 10$.

and CV in the income gained from livestock sales, but did not change the shape of this relationship (results not shown). All changes to lower $\overline{r}$ and higher σ_r result in an increase in the CV of income. Further, in scenarios with lower $\overline{r}$ the mean income $\overline{S}$ is diminished as a whole.
Figure 3B shows the performance of the management strategies under the same scenarios of climate change from the perspective of management objective Obj_2. Evidently, the climatic conditions influence the range of suitable management strategies. A decrease of 20% in the mean precipitation $\overline{r}$ causes a dramatic shrinkage of this range. For example, it is not even possible to achieve a fairly low minimum income S_{min} on a regular basis, regardless of the standing time or the number of paddocks. Also, an increase in the variability of precipitation results in a smaller set of possible options. Again, the more flexible strategies are characterised by an accurate combination of PN and ST, with dominance of a management on many paddocks with a fast rotation. This shows that the climate conditions limit the chance to manage the income risk by appropriately designed adaptive management strategies

4 Discussion and conclusions

We used a generic ecological-economic simulation model to incorporate the feedback between the vegetation dynamics in semi-arid rangeland and the management activities taken by a livestock farmer. We evaluated different management strategies from the perspective of different management objectives (maximize stable income (Obj_1), ensure minimum income (Obj_2)), and we assessed the robustness of the results against different scenarios of climate change.
We have shown that a higher subdivision of the farm combined with an appropriate (and lower) standing time improve the success of a farm enterprise in terms of higher mean income $\overline{S}$, lower CV, and the coverage of a certain minimum income requirement. This is consistent with the statement of Hart et al. [1993] that an intensive rotational grazing system has to be coupled with pasture subdivision to produce a grater stocking rate and more uniform grazing. The more homogeneous distribution of grazing in small paddocks [Barnes et al., 2008] is one of the major reasons for the success of a higher number of paddocks in our model. Altogether, our results supports to some extend the findings of Savory and Parsons [1980].
In connection with the management objective Obj_2 considered, a whole range of suitable management strategies can be determined. Here, the farmer has more opportunities than a single optimum strategy. Nevertheless, the two management objectives (Obj_1 and Obj_2) are interlinked with each other. We have shown that, whenever the minimum income requirements of the farmer are increasing or his economic capacity to tolerate is decreasing, the range of opportunities is shrinking. The most robust strategy that, to a certain extent, stands increasing economic demands or decreasing precipitation is the strategy with short standing time and a large number of paddocks - the strategy that has also been found as promising under management objective Obj_1.
The range of strategies suitable for ensuring minimum income markedly depends on the farmer's economic requirements but also on his resources. For example, a full-time farmer with low abilities to stand bad years depends on a continuous and relative high income from livestock farming. He has only a few management options and would be best with a high degree of subdivision and a fast rotation. On the other handthe farm business is just extra income. He can set a lower required income and accept a higher variability as he diversified the risk and can buffer low income years. Here, the economic possibility space would be large, and the selected strategy depends on other resources. Assuming he has limited time due to his main business he cannot put much effort in an advanced management system and would choose a small paddock number, a long standing time, and a low stocking rate.
Further we could show, that a decreasing mean and an increasing variability of precipitation leads to a shrinkage of the range of suitable management strategies that allow an adaptation. To some degree a farmer can follow such changes by adjusting his management system. However, as functional aspects in rangeland management remain constant regardless of social and economic factors [Connor, 1991], after strong changes he has to scale down his requirements, or take other options, such as an increase of the farm size or a diversification of income.
Our study implies feedback loops on different levels of the socio-ecological system. The major feedback in semi-arid rangeland systems couples the availability of natural resources directly to livestock dynamics and management actions. An increasing number of livestock leads to a decrease in green biomass, which in turn causes a decrease in the herd size either by destocking or

by death of livestock. This interaction is connected with two more feedback mechanisms: On the level of the vegetation a positive feedback exists between the vigour of the vegetation and the amount of green biomass. Furthermore, the amount of livestock positively effects the population growth that in turn results in a larger herd size.

Regarding to the huge amount of possible management options, we had to restrict our selection of strategies in this study. So far, we assumed an opportunistic stocking strategy with a fixed selling rule. This management takes into account the negative feedback loop between amount of green biomass and herd size. However, it did not explicitly comprise the positive feedback in livestock production. In this context, an interesting question for future research would be the impact of different stocking and selling rules on the achievability of the management goals. Also, we used the simplest rotation strategy and neglect the feedback between green and storage biomass. To assess the potential of more adaptive rotation strategies that adapt to the recent state of the environment is therefore another task for future research. Overall, this would allow comparing the effectiveness of different approaches of risk management and adaptation. It would strengthen the knowledge base for the design of the institutional framework for sustainable grazing in semi-arid regions.

Conclusively, we can detect cases of management strategies at which the farmer is definitely better of, than in others. Furthermore, we can distinguish areas in the strategy space which are not suitable at all. Altogether the optimal management strategy will vary widely with management objectives and environmental constraints, albeit in our study a relative high paddock number with an adequately high rotation speed appears to be the most robust management strategy. However, it is not suitable to advocate dogmatic a certain kind of management system, as there are plenty different individual needs and goals among livestock farmers.

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