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Managing the resilience of a common pool rangeland system in South Africa

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Abstract.

Livestock production on South Africa's commons strongly contributes to livelihoods of communal households offering status, food and income. Management innovations are generally top-down and informed by commercial practices such as rotational grazing in combination with conservative stocking. Implementations often ignore how the specific socio-ecological context affects outcomes and the impact on equity. Science now acknowledges that rangeland management must be context specific and a universally agreed-upon recommendation for managing semi-arid rangelands does not exist. We present a socio-ecological simulation model derived from a case study in South Africa. It is used to assess the socio-ecological effects of rotational vs. continuous grazing under conservative and opportunistic stocking rates. We find that continuous grazing under conservative stocking rates is best suited for the system under investigation. However, past legacy under apartheid and participants' expectations render its successful application unlikely.

Keywords

JEL codes: Q15, Q58, Q13

1 Introduction

Grazing livestock plays a vital role for livelihoods in southern Africa as it constitutes either a mean of subsistence or a financial buffer in unfavorable times (Dovie et al. 2006; Shackleton et al. 2001). In the case of South Africa, livestock is the most important agricultural capital good in the crowded areas of the former homelands where it is predominantly managed on common pool resources (Adams 2013; Vetter 2013). Increasing the economic benefits generated by these rangeland systems is thus becoming an important goal on the agenda of the South African Government (Department of Agriculture 2007). However, concrete projects in the communal rangelands are often top-down, ignore stakeholder participation and their expectations (Jakoby et al. 2014; Atkinson 2013), and are guided by the persistent assumption that rangeland commons are generally overstocked and degraded (Adams 2013; Naumann 2014; Harrison and Shackleton 1999). Improvements are thought to be achievable by imposing rotational grazing and conservative stocking rates as practiced in the commercial sector (Campbell et al. 2006). There is little concern how those measures can be adapted to fit to specific needs of heterogeneous stakeholders and how measures affect equity (Vetter 2013). Moreover, enforcing those measures by the community causes considerable transaction costs and the willingness to invest in suitable institutional processes (Campbell et al. 2000). In short, the human dimension of grazing systems is not yet adequately considered in management policies targeted at communal grazing systems in South Africa (Vetter 2005). According to Vetter (2013), the policy for the development and management of the rangeland commons should achieve

- better resource management for sustainable land-use activities
- greater contribution of rangelands to livelihoods,
- greater equity in distributing benefits from the rangeland

Another important aspect for livelihoods is economic risk and uncertainty (Martin et al. 2014). As livestock functions as a safety-net (Shackleton et al. 2001), huge fluctuations in herd size reduce their inherent capacity to buffer against unforeseeable adverse circumstances. Thus, we add “reduced variability in herd size and profits” as a fourth desirable goal of management. That is, livestock husbandry must remain a viable strategy in most of the years (Mace and Houston 1989). We further assume that benefits from management alternatives should match participant’s expectations in order to be sustainable and that past legacies impact the likelihood for success (Frey and Jegen 2001).

Using a simulation model for a community rangeland case in South Africa, we investigate if the introduction of rotational grazing and conservative stocking satisfies the outlined development goals and discuss the constraints for a successful change in management. Although the focus of this paper is on social benefits from rangeland management options, we first start presenting an outline of the ecological debate and its management implications in the next section.

2 The ecological debate and management implications

Next to social implications of top-down policies in the commons, ecological debates in rangeland science are not yet fully resolved (Briske et al. 2008; Campbell et al. 2006). Two areas of theoretical dichotomy in rangeland science have been the discourses of equilibrium vs. non-equilibrium systems (Briske et al. 2003) and of engineering vs. ecological resilience (Peterson et al. 1998; Vetter 2009). These theoretical debates relate to diverging management paradigms on stocking rates and spatial-temporal grazing strategies.

The equilibrium system understanding assumes that rangelands exhibit reversal and continuous dynamics. An optimal stocking rate is assumed above which increased competition for forage causes a decrease in animal performance (Oba et al. 2000). Livestock survival is density-dependent. Degradation occurs due to overstocking. Equilibrium theory is criticized to neglect the impact of climatic variability which is predominant in arid and semi-arid areas (Briske et al. 2003). Contrary, proponents of the "new thinking" in rangeland ecology propagating non-equilibrium theory for arid and semi-arid rangelands argue that abiotic factors, and here variability in rainfall in particular, to be a far more important cause for livestock mortality. Population crashes are inevitable and solely induced by droughts. That is, mortality is density-independent. Degradation is likewise not a result of grazing but induced by abiotic factors (Vetter 2005). Non-equilibrium theory is criticized to neglect any potential negative effect of intensive grazing (Wessels et al. 2007).

Management implications, derived from equilibrium and non-equilibrium theory, are conservative and opportunistic stocking rates respectively (Sandford and Scoones 2006). Conservative stocking tries to avoid crossing the carrying capacity of rangelands by employing relatively low and constant stocking rates (Holechek et al. 1999). In contrast, opportunism maximizes resource utilization in favorable years and assumes that the rangeland will recover under light stocking after an ecological crises occurred. Recovery is possible as livestock is either sold in drought years or due to unintended resting caused by events of high mortality (Müller et al. 2007). However, opportunism commands the absence of significant supplementary feeding or restocking in drought years (Campbell et al. 2006; Vetter 2005; Briske et al. 2003). There is a stark controversy which of the two grazing practices is more suitable in semi-arid rangeland systems. See for example the dispute between (Campbell et al. 2000) and (Sandford and Scoones 2006). From an economic perspective, arguments of high opportunity costs of conservative stocking are contrasted with increased losses under opportunistic stocking (Campbell et al. 2006).

A second pair of management strategies related to the discussion is rotational vs. continuous grazing. The rational of rotational grazing is to allow the vegetation to rest in order to recover. It was introduced in South Africa in order to mimic evolutionary grazing patters of traditional transhumance which was restricted by settlements in the early 20th century (Vetter 2005). However, the new rangeland science argues that rest times are not necessary as the resource will eventually recover after droughts under light grazing (Müller et al. 2007). Briske et al. (2008) found that empirical evidence from the past 60 years could not support the superiority of rotational grazing According to the authors, a key management dilemma with rotational grazing is the goal of simultaneously optimizing residual leaf area and utilization by livestock for production. Moreover, high quality forage is not utilized as pastures rapidly senescent in semi-arid areas. However, also the proponents of continuous grazing acknowledge that longer term rests, as practiced by rest-rotation where a part of the resource is rested during the growth period, might be ecologically beneficial (Briske et al. 2008; Bennett et al. 2010; Snyman 1998).

The notion of a single and multiple stable states associated with equilibrium and non-equilibrium systems is reflected in the discourse on ecosystem resilience (Vetter 2009). A classical ecological understanding of resilience is known as engineering resilience (Peterson et al. 1998). It assumes a single equilibrium and understands resilience as the “speed of recovery” and resistance as the ability to withstand disturbances (Adger 2000). Engineering resilience is criticized for ignoring sudden shifts in system states if system inherent thresholds are crossed (Peterson et al. 1998). Here, examples of lake eutrophication (Carpenter et al. 1999), and more relevant for rangeland systems, transitions from grassland to shrub-dominated systems are described and illustrated by simple ball-and-cup metaphors (Jeltsch et al. 1997; Anderies et al. 2002; Vetter 2009; Briske et al. 2003). Here, a system which did not change its fundamental functions in the face of external shocks is then considered to be resilient (Walker et al. 2006). From a social perspective, this definition does not consider the costs for being resilient in the first place (Béné 2013). Even in the absence of alternative states, grazing pressure and resting time of the vegetation might determine the costs for withstanding disturbance and enduring recovery time for stakeholders. However, management implications of the resilience discourses are as clear-cut as for the non-equilibrium discourse. At least for Harrison and Shackelton (1999), destocking and rotational grazing are not needed for resilient rangelands.

The scientific discourse is currently resolving the dichotomy of equilibrium vs. non-equilibrium rangeland systems and acknowledges that there is a gradient between these dynamics. Rangeland systems can exhibit both: equilibrium and non-equilibrium dynamics. Or, they exhibit a dynamic equilibrium (Briske et al. 2003, see also Huston 1979 for a detailed discussion on this matter). Likewise, voices are raised that those ball-and-cup metaphors of ecological resilience are "deceptively simplistic" and that there are indeed systems which are better described by continuous and reversible dynamics. Harrison and Shackelton (1999) found that South African "communal grazing areas are extremely resilient" (p.237) as they recover rapidly in less than 10 years after removal of grazing. Is it then not worthwhile to consider return time and resistance in those cases as they might be highly relevant from a management perspective?

The growing consensus resolving the dichotomy of concepts has, however, does not yet come with clear management implications. That is, the question remains unanswered if rangeland systems in semi-arid areas should employ conservative or opportunistic stocking and if rotational grazing should be emphasized over continuous grazing. At least for stocking regimes, an attempt for overcoming the polarization in the debate was suggested by Campbell et al. (2006) who differentiate between rangeland systems according to framing conditions. Or, as they term it: "one size does not fit all" (p.81) and went further to note that grazing policies need a case-by-case analysis. Likewise, Müller et al.'s (2007) findings support those of Scoones (1994) that "there are no universally applicable grazing strategies, because particular context-specific conditions have to be taken into account" (p.311). This observation might especially fit to those ecosystems which are on the threshold of what is considered to be a non-equilibrium system. Here, systems with a rainfall coefficient of variability (C.V.) above 33% belong to this category (Behnke 2000). Moreover, context-specificity is evident in the heterogeneity of households (HH) managing a common pool resource regime (Vetter 2005). Especially the impact of heterogeneity in HH assets on socio-ecological outcomes, and resulting positive feedbacks increasing stratification and thus inequality has, at least to our knowledge, not yet received any attention.

A way to test for the impact of management alternatives considering the socio-ecological context are simulation models. According to Briske et al. (2008), simulation modeling is well suited to "evaluate the managerial and ecological components of grazing management, both independently and in combination" (p.11). Simulation models are further useful to explore the combined effect of density-dependent and density-independent effects in these systems (Vetter 2005) and are thus able to overcome the polarization of the debate. Moreover, models can forecast outcomes of strategies which become only visible after decades in semi-arid regions (Müller et al. 2007). For representing the human dimension of the system, agent based models have been proven being able to account for heterogeneity, bounded rational decision making and social context (Chion et al. 2011; Chen et al. 2012; Heckbert et al. 2010; Jager et al. 2000; Bhattacharyya and Ohlsson 2010).

In the next section, we present a case of a communal rangeland system on the brink between equilibrium and non-equilibrium with a C.V. of 30% with a high recovery potential making it resilient towards droughts and grazing stress. Thereafter, a socio-ecological system model is presented according to the odd+d protocol. The model is then used to explore the effects of rotational grazing and destocking. We use the above stated policy goals for developing the rangeland commons as a benchmark to assess alternative management options.

3 The case

The case, a communal livestock production SES, is located within the former homeland of Bphuthatswana (Jacobs 2001) in the Free State, South Africa. The village community of Sediba uses a common pool resource rangeland for beef-cattle production. For the sake of reducing complexity in description and later model specification, we are ignoring more fine-grained differences in HH decision making and informal institutions which were identified but which are not the focus of this paper.

3.1 Ecosystem

The region is categorized as a semi-arid grassland biome (Rutherford and Westfall 1994), with a mean precipitation of 537 mm per annum (Swemmer et al. 2007; Woyessa et al. 2006) and provides forage as the main ecosystem service. The vegetation belongs to the “Moist Cool Highveld Grassland Type” (Bredenkamp and van Rooyen 1996), which covers the central eastern parts of the Free State province. Dominant species are perennial C4 bunchgrasses such as Themeda triandra, Eragrostis lehmanniana and Digitaria eriantha, and hence it is commonly referred to as “sweet veld” (Palmer and Ainslie 2005), with sweet referring to relatively good palatability of the vegetation and veld being a South African term for rangeland. Shrub vegetation is absent on the rangeland (Oomen). It is utilized for grazing purposes with cattle as the dominant grazer. The ecosystem dynamics are on the brink between equilibrium and non-equilibrium with a coefficient of inter-annual rainfall variability of 30% (Behnke 2000). García et al.’s analysis confirmed that of Harrision and Shackelton (1999) insofar as plant communities on the communal rangelands exposed to intense grazing are well adapted and “show fast growth rates and quick return strategies” (Moreno García et al. 2014). The regenerative potential for this grassland biome under communal management was also indicated by (Linstädter et al. 2014). The authors could only find small to no differences in the abundance of perennial grasses between commercially and communally managed systems in the area after a period of good rainfall. To summarize, the grassland biome under investigation is highly resilient (ecological resilience) towards droughts and grazing pressure and a clear alternative stable state due to e.g. bush encroachment cannot be identified. However, climatic variability and mean annual precipitation are characteristic for a semi-arid system. Thus, fluctuations in forage abundance, and even more important, in forage quality are high.

3.2 Social system

Around 160 HH are situated in Sediba and 83 HH are producing beef cattle. However, ownership is fluctuating as villagers are exiting and (re-)entering into livestock production due to herd losses or animal re-acquisitions after droughts. In accordance with Berzborn's (Berzborn 2007, p.679) findings, livestock is not perceived as a main source of income but as a "top-up" to off-farm income. However, the average herd size in Sediba is worth more than an average yearly per-capita income in the village. Thus, livestock is an important buffer against unforeseeable circumstances. Measured at an upper poverty line of 1000 Rand (949 Rand in 2008), the head count ratio is 61% although stratification is evident with individuals earning up to 3000 Rand per month (Leibbrandt et al. 2010). HH income is mainly generated by state grants and remittances. Income from wage labour is generally low due to scarce employment opportunities.

Off-farm income is a strong supporter of agricultural activities with respect to animal (re)-acquisitions after population crashes and for supplementary feeding, although for the latter to a lesser extent. Here, many low-income HH do not supply supplementary feeding. Livestock is only bought in case a HH wants to enter into production. Generally, HH use simple rules of thumb oriented at animal characteristics to decide which animal to sell. Sediba has no direct access to formal markets and livestock is sold to local traders or so called "fly-by-nights".

After the fall of Apartheid, all formal institutions of resource governance disintegrated. Participants have lost their adaptive capacity to reorganize their institutional environments after decades of external interventions, resettlements and betterment schemes (Naumann 2014). However, the rangeland is not an open-access resource as access for other villages is not permitted. Thus, management takes place on an individualistic basis and stocking rates are not regulated. The 2500 ha large rangeland is utilized under continuous grazing where livestock is homogenously distributed on the rangeland.

The acceptance of a rotational grazing scheme in the villages was very high with 95.5% of HH strongly welcoming it (Question H5, Table A.2). Moreover, most HH expect a significant increase of 50% in animal productivity (Question H6, Table A.2). However, 86.9% of the respondents state that the community is not able to enforce rotational grazing under self-governance but it should be enforced by an external institution (Question H6, Table A.2).

HH were reluctant when asked if they would agree to restrict their herd size. No formal institution is in place regulating stocking rates on a community level. Thus, the only viable opportunity to achieve a maximum stocking rate is a maximum herd size on HH level as practiced during Apartheid. This is, however, overshadowed by the way how past interventions were implemented (Naumann 2014). Massive culling operations have taken place which e.g. culminated 1983 in the “great Bphuthatswana Donkey Massacre” (Jacobs 2001). Those top-down interventions ignored people’s needs and their enforcement created resentments against reducing herds which is reflected in a 89.7% share of HH not agreeing with this measure today (Question H4, Table A.2).

To summarize, core elements of this case which need to be considered in a structurally realistic model are:

- High recovery potential of vegetation and variability in rainfall
- Differentiation between forage quantity and quality
- Importance of heterogeneous off-farm income for supplementary feeding and restocking
- Use of individualistic heuristics for selling animals

Other details are omitted in order to minimize model complexity. The next section presents the model structure according to the ODD+D protocol for agent based models (Müller et al. 2013). Obtained results from model analysis with respect to rotational grazing and destocking will then be discussed in the light of people’s expectations and perceptions in the last section.

4 ODD+D

This section utilizes a recent update of the ODD protocol (Grimm et al. 2010) for agent based model description. The ODD+D protocol has been developed to better account for describing human decision making (Müller et al. 2013). The ODD protocol is structured in a hierarchical way with respect to the complexity of model description. It starts with a general overview, reveals design concepts and concludes with a detailed presentation of the model. The resulting redundancy in the presentation is thought to be outweighed by enhanced replicability and comparability. Here, we follow the author’s recommendation to present the overview and design concepts and to provide the full ODD+D protocol, including details, as an online appendix (Table A.2).

4.1 Overview

4.1.1 Purpose

The purpose of the model is to assess the socio-ecological outcomes of spatial-temporal grazing and stocking strategies. Outcomes are evaluated against four defined goals for developing the rangeland commons. Strategies encompass rotational and continuous grazing combined with either opportunistic or conservative stocking. The model was designed for policy analysis of rangeland management options for a case in South Africa.

4.1.2 Entities, state variables and scales

Social agents are aggregated on the household (HH) level. Two HH agent types are present in the model: a livestock producing HH agent and a HH agent who does not own livestock. Cattle being heifers, cows or bulls are representing the livestock agent. A fourth entity is the common rangeland providing the ecosystem service of forage production. Biomass production is modelled in kg per ha.

Both HH agents are characterized by income, expenditures, savings, HH size and age of the HH head. Livestock producing HH agents are additionally characterized by number and types of livestock agents owned, the memory of past profits, and the selling rule. HH agents can switch their type during the simulation depending on entry and exit rules. Livestock agents have a bodyweight, age, gender and, in the case of cows, a value for the number of calves. Important state variables of the rangeland are shoot biomass green, shoot biomass senescent and basal cover. A list of state variables and parameters can be found in the appendix (Table A.1). References to the data files are given in the next section describing the empirical background.

Space is implicitly considered in the consumption and production of forage per ha. Here the resource size is constant but herd sizes vary over time. The model runs with daily (ecosystem) and monthly (social system) time steps over a period of 125 years.

4.1.3 Process overview and scheduling

The rangeland entity produces biomass on a daily basis which is reduced by monthly forage consumption. Livestock agents update monthly live-weight from forage consumption. All HH agents predict their expenditures at the beginning of each month. They decide on entering or might be forced to exit livestock production in every month. The amount of supplementary feeding is calculated once per year and is specific to agent attributes. Livestock is born and dies in one month of the year. Livestock producing HH agents draw a new heuristic selling rule in every fourth year (production cycle). Figure 1 depicts the time intervals and order of scheduled events. (Figure 1 here)

4.2 Design concepts

4.2.1 Theoretical and empirical background

A living standards and measurement HH survey was conducted in four villages of the rural area in the north of Thaba Nchu (Worldbank 15.11.2013). It encompassed 350 HH and was adapted to the local context. Individual data was aggregated on the HH level. The survey was administered to livestock producers and to HH not owning livestock. For the village of Sediba, which constitutes the case to be modelled here, the survey covered the whole population of livestock owing HH. Additionally, vegetation samples were taken in Sediba and a second village and used to calibrate the rangeland model. All field activities were conducted by a research group (http://www.fg1501.uni-koeln.de/) funded by the German Research Foundation from 2010 till 2013. HH survey templates, coding schemes, survey data, weather data and input data files used in the model can be found in the online-appendix (Table A.2).

The model was designed to account for the impact of abiotic (climatic) and biotic (competition) factors and their combined effect on herd survival (Vetter 2005). The ecosystem design (biomass growth) was guided by the need to account for climatic variability in semi-arid areas (McAllister et al. 2011, p.1). This was accounted for by means of a daily temporal resolution. The ecosystem model constitutes the adoption of the Lingra model to semi-arid rangelands (Schapendonk et al. 1998). Livestock dynamics in terms of mortality and reproduction are based on the notion of over-compensatory growth, forage quantity and quality as modelled in Gross et al. (2006). Stocking densities are an emergent outcome of ecosystem determined herd dynamics and social interaction.

Agents are assumed to be bounded rational (Carpenter and Brock 2004, p.5; Ebenhöh 2006; Ebenhöh and Pahl-Wostl 2008; Feola and Binder 2010, p.2324; Schlüter and Pahl-Wostl 2007; Schlüter et al. 2012, p.231; Janssen and Ostrom 2006, p.6). Agents do not have full information and lack the computational ability to plan decisions in a fully rational manner. They use adaptive heuristics instead.

Bounded rationality was assumed on the basis of empirical evidence from the case study. The HH survey revealed that respondents use simple heuristics or even random choice for selling cattle. Additionally, high climatic variability in semi-arid areas imposes constraints to full rationality in terms of information availability. Here, information about ecological outcomes is scarce and uncertain.

Other structurally relevant, but not focal, decisions are HH expenditures, the level of supplementary feeding and the decision to enter into livestock husbandry. Available data allowed for statistical estimation of expenditures, supplementary feeding and entries in the form of regressions.

A randomized twelve year weather data time series from the region was used to model the exogenous impact of the climate. Survey data from the village of Sediba was used to specify the number, types, state variables and parameters of HH agents in the model (Table A.2).

4.2.2 Individual decision making

This section, distinguishes between four decision making models. The first three relate to concepts behind modelling HH expenditures, supplementary feeding and entries. The third depicts the decision to sell livestock.

All HH agents decide on how much to spend from the monthly HH budget on the basis of income and HH size. HH agents not owning livestock decide whether to buy a cow in order to enter livestock production. However, HH agents need to have sufficient savings to do so. HH expenditures are determined by a linear regression on HH size and income which does not account for uncertainty in the prediction. The level of supplementary feeding is likewise computed by a linear regression on income and the herd size and does also not account for uncertainty in the prediction. Uncertainty in the entry decision is, however, reflected by a logistic regression predicting the probability to enter. HH only enter if a random number drawn from a uniform distribution is lower or equal than this probability. HH exit livestock production as a consequence of livestock mortality or the selling decision. In the decisions on expenditures, entries and in the case of exits no temporal or spatial aspects are considered.

Livestock producers decide if, how much and which type of livestock to sell. Survey data revealed that 83% of all sales are leaving the village as livestock is mostly sold to butcheries or speculators visiting the villages regularly (Table A2). Livestock sold within the village is often slaughtered by the buyers for ritual usage during funerals. Only a minority of cattle is sold to HH who want to enter livestock production and HH don't buy livestock to increase their herds[1]. Thus, sold livestock is reducing grazing pressure and does not just change ownership within the village. Producers decide which selling rule to use depending on the economic success during past production cycles. The probability to keep a distinct selling heuristic increases with the economic success associated with the heuristic. Lower profit of the past production cycle increases the probability to experiment with the selling rule for the next cycle. The objective is to maximize economic success which is done by inductive reasoning on the basis of limited information. The described decision making process is implemented with a genetic algorithm (Goldberg and Holland 1988). Here heuristic rules and values for applying these rules are encoded. Economic success determines fitness values of solution

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[1] Less than 2% of the total herd size was bought by HH during the last 12 months before the interview (Table A2)

chromosomes. Solution chromosomes are chosen depending on a roulette-wheel draw with probabilities weighted according to the fitness values. The random draw of solution chromosomes mimics uncertainty in the decision of rule adoption and updating of fitness values reduces uncertainty. The temporal aspect plays a role in the agent’s memory of past economic successes. The decision model does not account for spatial aspects.

4.2.3 Learning

The selling decision makes use of reinforcement learning. A distinction is made between heuristic rules and the values used for applying these rules. Here, agents decide to sell bulls and cows according to their age, cows according to the number of calves or according to which of the two conditions is satisfied first[2]. The genetic algorithm produces new combinations of heuristics and values by means of crossover and mutation. Fitter rule-value combinations survive during the process. Here, fitness refers to economic success of rule-value combinations. Thus, agents using this decision model aim to increase profits. However, they are not optimizers as they use the non-optimizing strategy of reinforcement learning (Gigerenzer and Selten 2002). Agents don’t compute an optimal strategy beforehand rather than choosing what worked best in the past. With Wilson et al.’s words, agents are “assumed to be boundedly rational, profit maximizers” (Wilson et al. 2007, p. 15213).

4.2.4 Individual sensing

HH agents know all own attributes including livestock attributes of their own herds.

4.2.5 Individual prediction

HH agents predict their HH expenditures, the level of supplementary feeding and their probability to enter into livestock husbandry.

4.2.6 Interaction

Interactions of livestock agents are indirectly via the rangeland. Cattle compete for forage. Similarly, Livestock producing HH agents compete with each other indirectly via resource appropriation of their herds.

4.2.7 Collectives

There are no agent collectives in the model.

4.2.8 Heterogeneity

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[2] Ranges for values are derived from survey data (Table A2)

Livestock producing HH agents are heterogeneous in the use of selling heuristics.

4.2.9 Stochasticity

Random numbers are used in assessing if probability thresholds of the following variables are reached: cattle mortality and births, HH entering livestock production and selling heuristics chosen.

4.2.10 Observation

Basal cover (%), average agricultural profit (Rand) and the monetary value of the current herd (Rand) are collected on a monthly basis.

4.3 Details

The details of the model and its submodels can be found in the full ODD+D in the appendix (Table A.2).

5 Scenarios and measures of performance

The following section outlines modeled scenarios and according evaluation criteria.

5.1 Scenarios

5.1.1 Continuous grazing and opportunistic stocking- Baseline

The baseline scenario reflects the current strategy mix of continuous grazing and opportunistic stocking. Here the opportunistic strategy is based on die-offs and slow recovery rather than on de- and restocking, or tracking (Müller et al. 2007). According to Toulmin (1994), slow recovery is ecologically superior to immediate restocking but is, however, a “waste of grazing resources” (Müller et al. 2007). Results for the baseline scenario are used in the analysis as a reference indicating the relative impacts of alternative grazing schemes.

5.1.2 Rest-rotation under opportunistic stocking

To assess the impact of rest-rotation on the system, we implemented a version of rotational grazing which is currently practiced by farmers in the commercial sector (Figure 2). This specific system was recommended by a local expert from the South African department of Agricultural development (pers. comm. H. J. Fouché). The rangeland is divided in three land categories which are grazed over different time periods over the year. Here, it is important to note that rotational cycles are not of equal lengths such that one of the three land categories is rested over the whole vegetation phase from October till April. The other two parts are grazed during half of the vegetation phase. Full resting in the critical phase of rapid plant growth is applied sub-sequentially for the three land categories over a three-year schedule. This system is adapted to the ecological context in terms of inter-annual climatic variability by accounting for rainy and wet seasons. (Table 1 here)

For this scenario, we divided the Sediba rangeland (2500 ha) in three equal parts which are utilized in the described manner. Rule conformance of HH is assumed.

5.1.3 Restricting opportunism under continuous grazing

As outlined before, imposing a maximum or conservative stocking rate is problematic for several reasons. First, no formal institution is in place to regulate stocking rates on a community level. Second, the rangeland is not sufficiently large for allowing big herds for all HH. Third, each HH must be able to sustain a large-enough herd for sustaining production in case of high mortality incidences. The first argument implies that maximum herd sizes can only applied on HH level. The dilemma between the second and third argument calls for a compromise with respect to the maximum stocking rate per HH. For our analysis we used a maximum of 15 cattle which is above the current average but below the current maximum per HH. Arguably, this “soft” conservative stocking rate, reducing peaks in grazing pressure, was chosen on the basis of plausibility considerations and should be target to further investigation in future analysis. However, a sensitivity analysis of this variable goes beyond the scope of this paper. Our aim is to test for a general effect of restricting opportunism in the system.

5.1.4 Rotational grazing and opportunistic stocking

A last scenario combines the outlined strategies of rational grazing and conservative stocking in order to test for potential interaction effects between the two management alternatives.

6 Measures of system performance

In the following sub-section, operationalizations for measures of ecosystem state, productivity, economic variability and equity are presented.

6.1 Ecosystem state

We measure ecosystem state with an indicator for rangeland condition (Walker et al. 2002). Here, we use the slow changing ecological indicator of basal cover which measures the % area of surface covered by plants. Basal cover, as an indicator for rangeland quality, has been used by Wiegland et al. (2004) and Snymann (2005) to assess the quality for semi-arid grassland ecosystems in South Africa. In order to detangle the impact of grazing stress from drought shocks and climatic variability, we compute a reference time series of basal cover in an un-grazed state as a benchmark for the different scenarios. As grazing can have a negative or positive effect on rangeland condition, this reference scenario is not an optimal state but one which shows the impact of climatic variability in isolation. Figure 2 shows an example time series comparing basal cover dynamics of an un-grazed system with a system under high grazing pressure. All modeled scenarios, as well as the un-grazed reference system, are driven by a deterministic weather file (Table A.2) based on empirical data from the region. The main climatic shock to the system is a multi-annual drought occurring in the middle of the simulation. The use of a single weather file allows comparing basal cover dynamics for different management regimes under ceteris paribus conditions with respect to abiotic factors. (Figure 2 here)

In the forthcoming analysis we refer to the basal cover dynamics of the un-grazed state as the "resilience pattern" as it resembles the magnitude of distortion and recovery of the ecosystem resulting solely from the multi-annual drought periods and inter-annual climatic variability.

Deviations from the resilience pattern due to grazing show the additional impact of grazing on ecosystem state. The % deviations from the resilience pattern are computed for each month over multiple runs which results in a certain frequency distribution for each management scenario. Frequency distributions allow for quantification beyond a mere graphical presentation of deviating patterns.

6.2 Productivity

To asses if alternative grazing management increases the contribution of rangelands to livelihoods, we measure system performance in terms of total generated profits over the specified time frame. Profits are summed over all HH and are the result of subtracting costs for supplementary fodder and animal (re)-acquisition from sale revenues. Thus, we account for the costs of capital as suggested by Campell et al. (2000) and by Sandford and Scoones (2006).

6.3 Economic variability

As livestock production should remain a viable strategy over time, we measure the average monthly variability in the value of HH based livestock production (Martin et al. 2014). That is, the variation of what can buffer any HH from economically unfavorable circumstances which can occur anytime. This is defined as the monetary value of herds in any month plus monthly generated profits from sales which we refer to as HH buffer capacity from now on. We assume that increased variation in buffer capacity reduces planning security and thus increases uncertainty. We measure the variation as the standard deviation of HH buffer capacity.

6.4 Equity

To arrive at a measure for the goal of achieving greater equity among resource users, we observed the level and change of buffer capacity over different income classes and time. Resulting time series allow to visually comparing the evolution of HH buffer capacities along off-farm income gradients. Moreover, an investigation of time series can give an indication if there are differences in how HH recover from population crashes by utilizing off-farm income.

7 Results

In the following section, simulation results from the four scenarios are presented for ecosystem state, productivity, economic variability and equity.

7.1 Ecosystem state

The effect of different grazing strategies with respect to sustainable land-use activities (first goal) is assessed by quantifying the impact of grazing on the resilience of the ecosystem.

Table 2 shows a summary statistic of deviations from the resilience pattern under grazing stress for the four scenarios. Monthly percentage deviations were computed over multiple runs to account for stochasticity in the model. All scenarios show a negative mean percentage deviation from the resilience pattern of the un-grazed system albeit a considerable difference between the baseline and the other three scenarios. That is, grazing stress under continuous grazing with opportunistic stocking results in a negative mean deviation from the resilience pattern of -31.4% whereas the other scenarios result in mean negative deviations ranging from -2.3 % till -1.2%. (Table 2 here)

A similar discrepancy between the baseline and the three alternative scenarios is the variation of deviations. Here, continuous grazing under opportunistic stocking results in a standard deviation of 27.8% whereas the next higher standard deviation was found to be 5.8% for continuous grazing under conservative stocking. It is furthermore worth to note that all scenarios, except for the baseline, show improvements of the rangeland condition in 20% of the months (see 80% percentile, Table 2). This result resembles Briske et al.'s empirical findings that grazing increased primary production in 20% of investigated rangeland cases (Briske et al. 2008).

Figure 3 shows the frequency distribution of monthly percentage deviations from the resilience pattern for continuous grazing under opportunistic stocking. Here, grazing stress significantly lowers the resistance of the ecosystem and leads to events of severe ecological collapse. The latter is e.g. evident in a small cluster of negative percentage deviations above 95%. Here, basal cover is substantially reduced but recovery can take place as the system does not remain in the severly depleted state for longer time spans. (Figure 3 here)

Figure 4 shows the percentage deviations for the other three scenarios; rotational grazing under conservative (1) and opportunistic stocking (2) as well as continuous grazing under conservative stocking (3). All three distributions show a similar resistance under grazing stress resulting in a percentage deviation from the resilience pattern above -6.6% in 80% of all months. The lowest negative deviation of the three distributions is found for continuous grazing under conservative stocking with -18%. (Figure 4 here)

To summarize, all three alterations in grazing strategies result in an improvement of the ecosystem's drought resistance compared to the currently practiced system of continuous grazing under opportunistic stocking.

However, an improved rangeland condition does not necessarily translate into socially preferred outcomes as resources might be underutilized. Moreover, the presented frequency distribution for the baseline scenario does only implicitly account for the speed of recovery, or resilience. The latter might have an impact on social outcomes which will be investigated in the next sections.

7.2 Profits

As outlined, we assess the contribution of rangelands to livelihoods as relative changes in profits. Here, we used an aggregate measure of mean total profits over all livestock producing HH generated over the time span per simulation run. Profitability per HH is measured as total revenues from livestock sales minus expenses for supplementary feeding and (re)-acquisition of animals after. Livestock lost due to mortality is not considered to contribute to profits or costs. Note that the analysis focuses on relative differences in profitability instead on absolute figures as the model uses fixed input prices and selling prices which vary in a pre-determined range. That is, a ceteris paribus approach with respect to the macro-economic framework is not suitable to predict absolute values with sufficient certainty. However, the focus of this analysis lies on the relative superiority of alternative grazing strategies related to distinct management goals.

An analysis of variance and subsequent post-hoc S-N-K tests were conducted to asses if differences in group means over multiple runs are significant. Significant differences between the four grazing strategies with respect to the total average profitability of livestock production where found with F(3, 1196) = 9733.873, $p<0.05$. A S-N-K post-hoc test on group differences found three homogenous sub-groups (Table 3). One is formed by both rotational grazing scenarios and the other two are represented by the two continuous grazing scenarios. That is, no differences could be found between the rotational grazing strategies but differences between rotational grazing and both continuous grazing strategies were significant with respect to profitability. Here, the lowest profitability was found for rotational grazing followed by a medium profitability for continuous grazing under opportunistic stocking (baseline). The most profitable strategy is continuous grazing under conservative stocking. (Table 3 here)

7.3 *Economic variability*

Reducing the variability in HH buffer capacity equates to the social goal of decreasing uncertainty and risk in a fluctuating environment. In analyzing the variability of HH buffer capacity, we follow the same approach as used for profitability. That is, an analysis of variance and sub-sequent post-hoc tests were conducted for the four scenarios in order to asses if differences in groups are significant. Please note that this measure is complementary to those of profitability and equity dynamics of HH buffer capacity which are presented in the previous and forthcoming sections respectively. Arguably, a certain variability of a profitable system might be considered to be socially more desirable compared to the same variability of a less profitable grazing strategy.

Significant differences between the four grazing strategies with respect variability in HH buffer capacity where found with F(3, 1196) = 16254.798, $p<0.05$. A S-N-K post-hoc test on group differences found three homogenous sub-groups (Table 4). One homogenous sub-group is formed by the results for rotational grazing under opportunistic stocking together with continuous grazing under conservative stocking. The other two strategies form their own sub-groups. The lowest variability in buffer capacity, measured at its standard deviation, is found for the rotational grazing strategy under conservative stocking. This is followed by a slightly higher variability for both; rotational grazing under opportunistic stocking and continuous grazing under conservative stocking. The highest variability in HH buffer capacity, and thus the least predictable system, emerges with the currently practiced strategy of continuous grazing under opportunistic stocking. (Table 4 here)

7.4 Equity

The following analysis relates to the social goal of achieving greater equity in the distribution of benefits from the rangeland. Here, off-farm income was identified as an important supporter of agricultural activities. Thus, richer HH have a competitive advantage over poorer HH in establishing and maintaining their herds in favorable times and during ecological crisis. Figures 5 and 6 present HH buffer capacity, as the monetary value of the individual herds in each month plus monthly profits from livestock production, along the time axe for the highest (Figure 5) and for the lowest income quintile (Figure 6). Time series for monthly HH buffer capacities are shown for each of the four grazing strategies in order to indentify stylized facts in evolving patterns. That is: which grazing strategies are superior in enabling the poorest HH to benefit from ecosystem services in the long-run? Results are shown for an example run as averages would blur the effect of ecological collapse in specific time steps.

Figure 5 shows the evolution of HH buffer capacity over time for the highest off-farm income quintile for the four grazing strategies. The high variability in ecosystem state of the baseline scenario is also reflected the evolution of HH buffer capacity for the highest off-farm income quintile. That is, HH in the highest income category show significant gains from continuous grazing under opportunistic stocking before and after the multi-annual drought period in the middle of the simulation. However, overstocking leads to two density-dependent collapses of the livestock population during and after the drought. After the second collapse, the livestock population needs over a decade to recover to the levels sustained by the other management strategies. Short term benefits in terms of HH buffer capacity were achieved at the cost of lowering the resistance and resilience of the ecosystem resulting in poor productivity for a prolonged time span after collapse. The three strategy alternatives show a positive trend over time which is stabilizing after the drought. Here the lowest outcome was found for rotational grazing under conservative stocking and the highest outcome for rotational grazing under opportunistic stocking.

To summarize, the management alternatives for the currently practiced strategy avoid severe population crashes but are not able generate the tremendous gains from continuous grazing under opportunistic stocking during ecologically favorable times. Overall, richer HH are able to stabilize or increase their gains from the rangeland over time and are able to recover after the multi-annual drought period. However, the unrestricted recovery after drought in the baseline scenario creates a socio-ecological crisis with a secondary, even longer recovery period for the richest HH. (Figure 5 here)

Figure 6 shows the HH buffer capacities for the poorest part of livestock producing HH for the four grazing strategies. Analog to the highest income quintile, HH achieve significant gains by practicing continuous grazing under opportunistic stocking over the three alternatives until the set-in of the drought period. However, a recovery after drought does not lead to new highs in HH buffer capacities for the poorest HH. Moreover, the second collapse leads to a de-facto extinction of this income group from livestock production. The most sustainable level of HH buffer capacity for poor HH is achieved by continuous grazing under conservative stocking. Except for an initial phase at the beginning of the simulation, the two rotational grazing scenarios always yield lower values for HH buffer capacity with a negative trend towards the end of the simulation. (Figure 6 here)

To summarize, the most viable grazing strategy in terms of long-term participation of poor HH in resource appropriation is found to be continuous grazing under conservative stocking. The highest income quintile is able to generate an average HH buffer capacity under this scenario which is more than five times as high. However, it is worth to note that gains from opportunism with continues grazing are tremendous for poor HH until the drought sets in.

8 Discussion

The presented results are supporting earlier findings that stocking rate is the most important management variable (O'Reagain and Turner 1992; van Poollen and Lacey 1979). Our results show that a maximum cap on herd sizes increases profits while preserving a stable ecosystem and yields low economic variability. Moreover, this simple measure of a quasi-conservative stocking rate on HH level applied to the local context is able to support a more equal distribution of rangeland benefits. This management strategy does not involve the costs associated with the creation and maintenance of fenced-off paddocks needed for rotational grazing. Our results are furthermore supporting empirical studies which could not find that rotational grazing increases livestock productivity (Briske et al. 2008). At the same time, we could show that rest-rotation is an adequate mean to maintain ecosystem resilience and resistance which is also reflected in more predictable economic outcomes. This is, however, not translated into increased profits in the case presented here. Also the combination of rotational grazing with conservative stocking could not increase profits above those of the baseline scenario. The specific conditions in Sediba might contribute to that fact as the resource size is limited and a separation in fenced-off camps considerately increases competition on smaller land units (Müller et al. 2007). Live-weight gain is limited by giving resting time to the vegetation. However, key resource biomass provided by rested camps functions as a buffer to fodder shortage in drought years (Vetter 2013). The restriction of livestock to separated camps moderately increases mortality, decreases reproduction and body-weight in favorable years compared to continuous grazing. The maximum stocking rate per HH used in this model is thus not a binding constraint for most HH in the rotational grazing scenario and has thus only a marginal effect on outcomes. The increased selling rate due to the conservative stocking rate under continuous grazing outperforms profits generated from opportunistic stocking as re-acquisition of animals is too costly. However, the tremendous gains of opportunism with continuous grazing in terms of peeks in buffer capacity indicate that there might be a lot to win if livestock is sold prior to collapse. That is, our results suggest that a tracking scenario has some potential with respect to profitability. However, the investigation of tracking was beyond the scope of this paper. We believe that the latter is a worthy endeavor for future research.

Although it is tempting to arrive at a clear cut management recommendation based on our results, any such attempt must be viewed in the light of local and social context (Vetter 2013). Assuming the absence of any informal institutions regulating resource use, a social dilemma is evident. That is, people don’t want to be externally forced to restrict their herd sizes considering past experiences during apartheid. At the same time, villagers expect significant gains in profits from the introduction of rotational grazing. Such heightened expectations have been reported earlier (Heady 1961). Thus, it is unlikely that villagers will burden the maintenance and institutional costs associated with rotational grazing which renders any investment in the infrastructure as useless. That is, a restriction of herd sizes is not wanted and rotational grazing will not meet expectations. A potential path-way to solve this dilemma is to consider academic and governmental support for (1) the development at early-warning indicators for imminent population crashes, (2) establishing ecosystem monitoring and (3) implementing buy support to prevent the loss of capital bound in livestock.

The applicability of our findings to this case is, however, limited as the model ignores any informal institutions regulating resource governance in non-obvious ways. Thus, further research is needed to detangle the social fabric in order to identify the existence and mechanisms of informal institutions and to translate those into quantifiable measures.

Tables

Table 1: **Rotational grazing system for Sediba**

Year	Sep	Oct - Dec	Jan - Apr	May	Jun - Aug
1	A	B	C	B	A
2	B	C	A	C	B
3	C	A	B	A	C

Table 2: **Summary statistics - % deviations from resilience pattern under the four grazing scenarios**

Statistics		Continuous Opportunism	Continuous Conservative Stocking	Rotation Opportunism	Rotation Conservative Stocking
N	*Valid*	443100	443100	443100	443100
	Missing	0	0	0	0
Mean (%)		-31.3500	-2.2678	-2.0237	-1.1712
Std. Deviation (%)		27.77924	5.84562	4.11339	3.68388
Percentiles	*20 (%)*	-60.0570	-6.6357	-4.5643	-3.6838
	40 (%)	-32.3945	-4.4887	-3.1114	-2.5360
	60 (%)	-15.6916	-1.8097	-1.9520	-1.3502
	80 (%)	-6.5105	2.1962	.9380	1.5200

Table 3: **SNK - post-hoc test on differences in means of total generated profits for the four grazing scenarios**

Scenario	N	Subset for alpha = 0.05		
		1	2	3
Rotation conservative stocking	300	66.17 Mio Rand		
Rotation opportunistic stocking	300	66.66 Mio Rand		
Continuous opportunistic stocking	300		85.65 Mio Rand	
Continuous conservative stocking	300			108.24 Mio Rand
Significance		.086	1.000	1.000

Table 4: **SNK - post-hoc test on differences in mean variation of HH buffer capacity for the four grazing scenarios**

Scenario	N	Subset for alpha = 0.05		
		1	2	3
Rotation conservative stocking	300	3262 Rand		
Continuous conservative stocking	300		4061 Rand	
Rotation opportunistic stocking	300		4086 Rand	
Continuous opportunistic stocking	300			10896 Rand
Significance		1.000	.526	1.000

Figures

Figure 1: **Scheduling of steps – process flow**

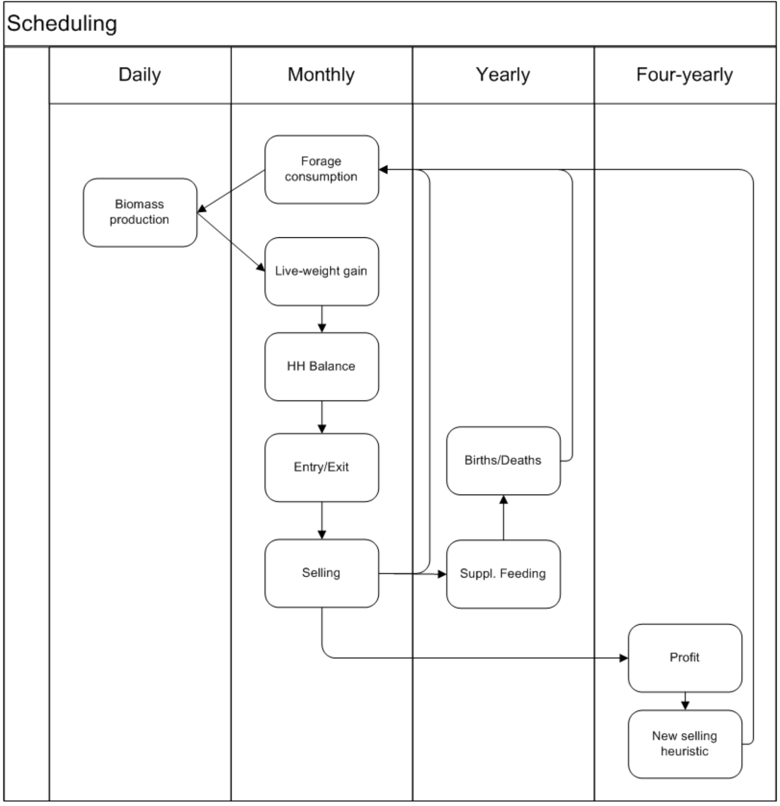


Figure 2: **Basal cover dynamics in the absence and presence of grazing pressure**

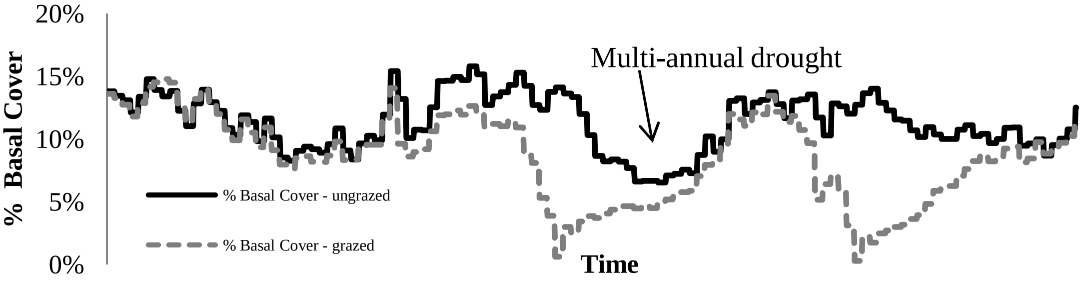


Figure 3: **Frequencies of % deviations from resilience pattern under continuous grazing and opportunistic stocking**

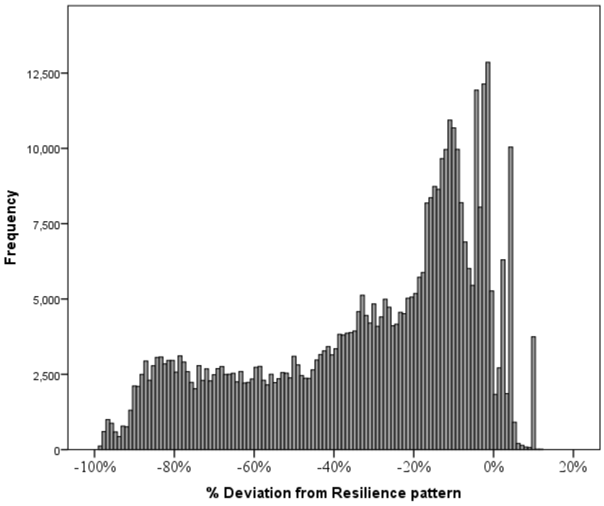
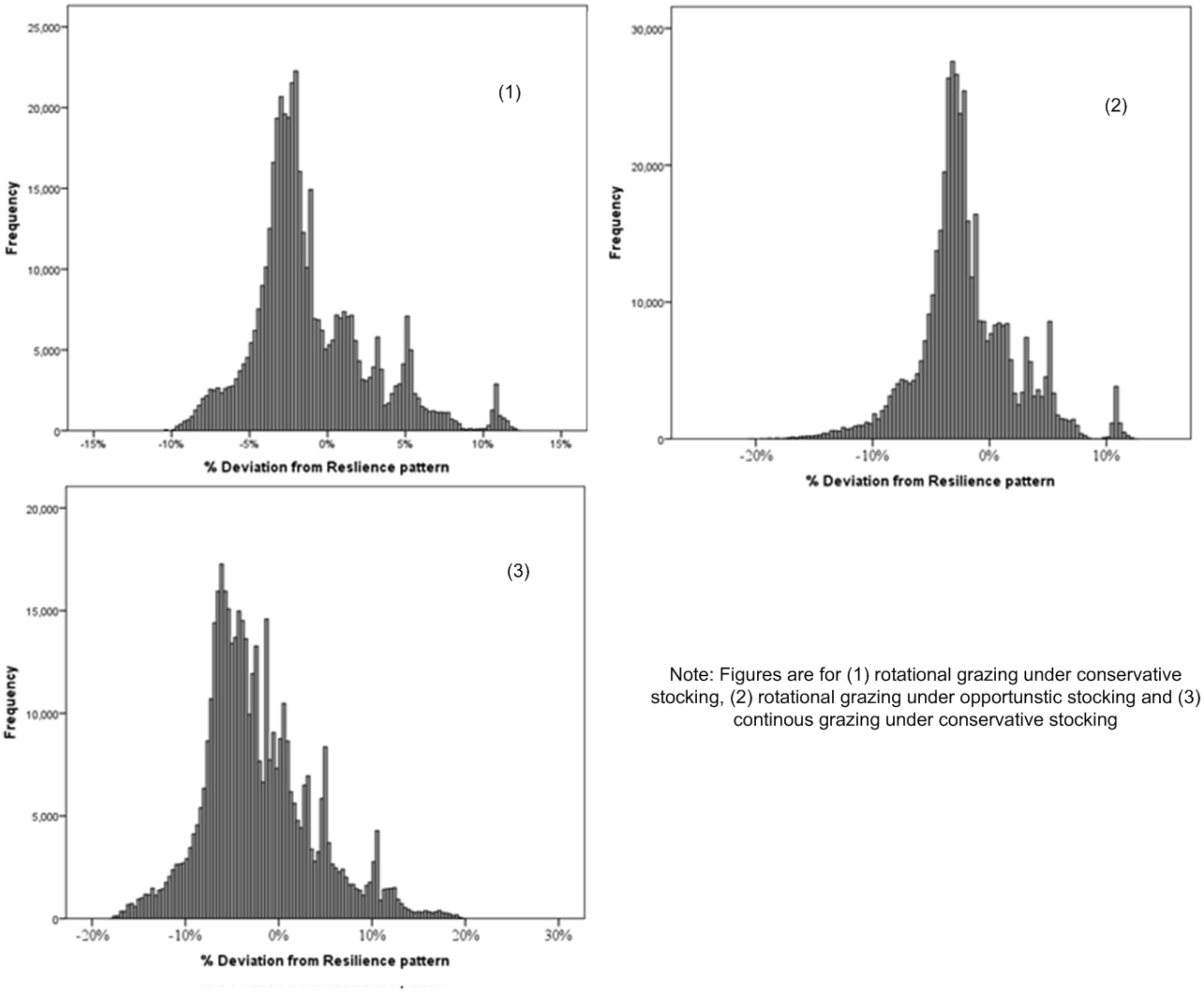


Figure 4: **Frequencies of % deviations from resilience pattern for alternative management strategies**



Note: Figures are for (1) rotational grazing under conservative stocking, (2) rotational grazing under opportunstic stocking and (3) continous grazing under conservative stocking

Figure 5: **Time series – evolution of HH buffer capacity of the highest income quintile for the four grazing scenarios**

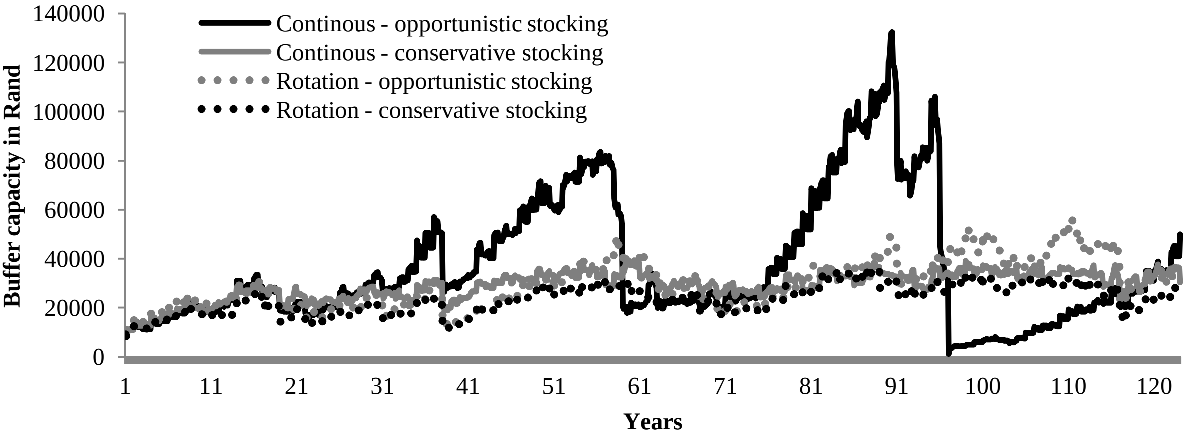
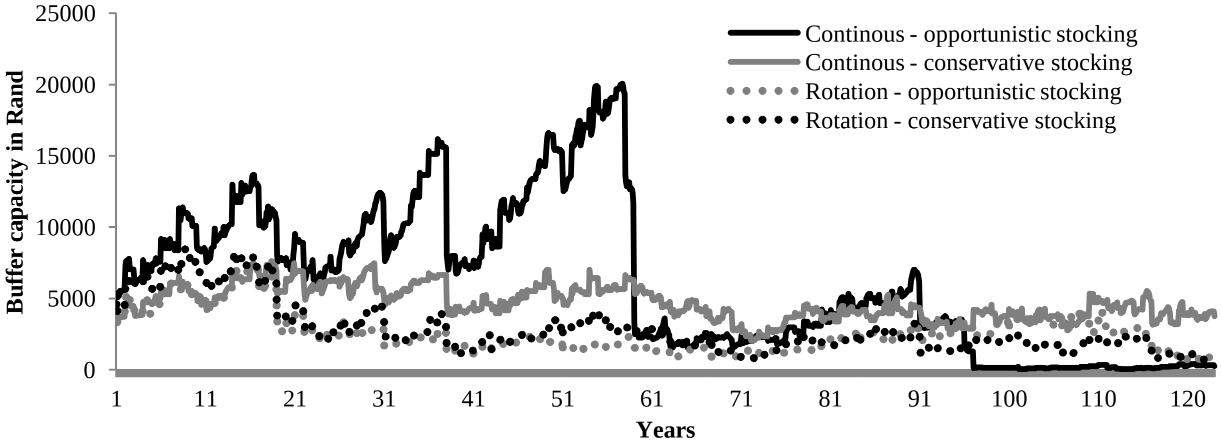


Figure 6: **Time series – evolution of HH buffer capacity of the lowest income quintile for the four grazing scenarios**



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Appendix

Table A1: State variables and parameters of entities

	State variables	Parameters
Livestock producing HH	Livestock, farm-income, expenditures, savings, reciprocity, cooperativeness, norm compliance	Off-farm income, HH size, age
HH not owning HH	Expenditures, savings	Off-farm income, HH size, age
Livestock	Age, bodyweight, #calves	Sex
Rangeland*	Basal area, green standing crop, senescent standing crop	Temperature, precipitation, irradiance, wind speed

*Note: The rangeland model is a complex stand-alone model designed by the crop scientists of the research group (forthcoming). Here, only those state variables which are directly interacting with the agent-based model or used in the analysis are listed. Parameters are only listed if they are part of the weather file.

Table A2: Links to online appendix

Template HH survey – Livestock owners	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=16
Coding scheme HH survey – Livestock owners	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=36
Data HH survey – Livestock owners	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=37
Input data file – Livestock owners	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=43
Template HH survey – HH not owning livestock	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=17
Coding scheme HH survey – HH not owning livestock	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=38
Data HH survey – HH not owning livestock	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=44
Weather file	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=42
Extended figure of rangeland submodel	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=45
Parameter input file rangeland submodel	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=46
ODD+D protocol	http://www.fg1501db.uni-koeln.de/index.php?navi=8&id=51