Institut für Lebensmittel- und Ressourcenökonomik der
Rheinischen Friedrich-Wilhelms-Universität Bonn

Resilience, collapse and reorganization of a rangeland socio-ecological system in South Africa

I n a u g u r a l - D i s s e r t a t i o n

zur

Erlangung des Grades

Doktor der Agrarwissenschaften

(Dr.agr.)

der

Landwirtschaftlichen Fakultät

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vorgelegt am 25.06.2015

von

Sebastian Rasch

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Kurzfassung

Kommunale Weidewirtschaftsformen in semi-ariden Gebieten sind komplexe sozial-ökologische Systeme (SÖS). Ihre Komplexität ist in nicht-linearen Rückkoppelungsschleifen zwischen dem Sozial- und dem Ökosystem begründet. Die Untersuchung des sozialen Systems beinhaltet institutionelle Fragen bezüglich des Ökosystemmanagements von Allmendegütern. Darüber hinaus ist die hohe klimatische Variabilität in semi-ariden Gebieten für die Einschätzung von Ökosystemdynamiken zu berücksichtigen.

Die vorliegende Dissertation quantifiziert die Dynamiken eines kommunalen, Viehproduktions-SÖS in einem ehemaligen „Homeland" in Südafrika. In diesem Zusammenhang wurde ein soziales, agentenbasiertes Modell mit einem Biomassewachstumsmodell des Weidelandes gekoppelt. Die Koppelung der Modelle wurde durch eine vollständige Softwareintegration (Java) erreicht. Somit berücksichtigt das Gesamtmodel ökologische Komplexität. Letzteres stellt einen Beitrag zur methodologischen Verbesserung von bio-ökonomischen Modellen dar insofern als das jene ökologische Prozesse stark vereinfachen. Das SÖS-Modell basiert auf primären Fallstudiendaten.

Auf einer konzeptuellen Ebene untersuchen die drei Hauptkapitel dieser Dissertation die Aspekte von SÖS Resilienz, Kollaps und Reorganisation. Im Einzelnen untersucht das zweite Kapitel soziale Wohlfahrtsimplikationen einer (Wieder)-Einführung von Herdengrößenmanagement sowie von räumlich-zeitlichen Weidemustern. Das dritte Kapitel beschäftigt sich mit den Effekten einer lokalen Norm auf SÖS-Dynamiken hinsichtlich Kollaps versus Stabilität. Die Messung der Resilienz auf verschiedenen Skalen des SÖS – bezüglich Dürreperioden, einem Verlust an sozialer Verflechtung sowie einer signifikanten Veränderung der Subventionen – steht im Mittelpunkt des vierten Kapitels.

Die Ergebnisse zeigen, dass die Anpassung der Herdengröße höhere soziale Wohlfahrtsgewinne erzielt als die Einführung von Wechselweidewirtschaft. Dieses Ergebnis wurde unter der Annahme eines institutionellen Vakuums im SÖS erzielt. In einem zweiten Schritt wurde die Existenz einer informellen Institution, welche die Herdengröße endogen aber indirekt beeinflusst, festgestellt. Modellergebnisse zeigen den signifikanten Einfluss jener informellen Institution auf die Langzeitstabilität des SÖS insofern als dass sie die Wahrscheinlichkeit für einen Systemkollaps senkt. Die Emergenz von normgeleitetem Verhalten wurde durch Ökosystemvariabilität gefördert. Das SÖS war resilient gegenüber Dürren und einer Veränderung der Subventionen. Es war allerdings nicht resilient gegenüber dem Verlust an sozialer Verflechtung. Von den drei behandelten Szenarien verhinderte nur die Einführung eines bedingungsloses Grundeinkommen einen Strukturwandel mit erodierender Resilienz der Haushalten. Die Einführung eines bedingungslosen Grundeinkommens ermöglichte es ärmeren Haushalten sich erfolgreich im Wettbewerb um die Ressourcenutzung zu behaupten, ohne jedoch die Resilienz des gekoppelten Systems zu gefährden.

Schlüsselwörter*: Süd Afrika, Weideland, Allmende, Sozial-ökologisches System, Agenten-basierte Modellierung, Resilienz, Endogene Modellierung von Instutionen, Normen*

Abstract

Communal rangelands in semi-arid areas are complex socio-ecological systems (SES). Their complexity arises from non-linear feedbacks between the social- and the ecosystem. To understand the social system requires tackling institutional issues associated with common pool resource governance. Moreover, assessing ecosystem dynamics commands to acknowledge high climatic variability in semi-arid areas.

This thesis quantifies the dynamics of a communal livestock production SES in a former homeland of South Africa using a SES modelling approach. Here, a social agent based model is combined with a biomass growth model of the rangeland. The coupling of both models is achieved by full integration on software (Java) level. Accordingly, the resulting model does account for ecological complexity. The latter constitutes a contribution to the methodological advancement of bio-economic modelling insofar as bio-economic models strongly simplify ecological processes. The SES model is specified based on primary data from a case study.

On a conceptual level, the three main chapters in this thesis investigate aspects of SES resilience, collapse and reorganization. Specifically, chapter two assesses social welfare impacts from reorganizing resource use by the adjustment of stocking rates and alterations of spatio-temporal grazing patterns. Chapter 3 explores the effect of a local norm on SES dynamics with a focus on collapse vs. stability. Finally, chapter 4 quantifies the resilience on multiple scales of the SES towards droughts, a loss of social embededdness and a significant change in subsidization.

We found that the adjustment of stocking rates yields higher social benefits compared to the (re)-introduction of rotational grazing in a system assumed to be void of institutional arrangements. In a second step, we identified the existence of a local norm indirectly impacting resource use by endogenous stocking rate adjustments. The existence of the informal institution significantly contributes to the long-term stability of the SES by reducing the chance for collapse. The emergence of norm-following behaviour is fostered by climatic variability. The SES was resilient towards droughts and a change in subsidization. It was however not resilient towards a loss in social embededdness. At another level, only the introduction of a basic income grant was able to stop a process of structural change eroding household resilience. The introduction of a basic income grant enabled poorer households to successfully compete with richer ones without jeopardizing the resilience of the coupled system.

Keywords: *South Africa, Common-pool resource, Socio-ecological system, Agent based modelling, Resilience, Modelling of endogenous institutions, Norms*

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Abbreviations

ABM	Agent based model
CAS	Complex adaptive system
HH	Household
ODD	Overview, design concepts and details
ODD+D	Overview, design concepts and details + decision making
SES	Socio-ecological system

Chapter 1
Research Context

1.1 Motivation and structure

The sub-Saharan African rangeland commons are a vital contributor to income diversification (Berzborn 2007) and livestock serves as a safety-net (Vetter 2009). Apartheid's legacy and the socio-economic framework sets South Africa apart from its neighbours with respect to the social determinants of resource appropriation from rangelands. Massive resettlement programs targeted at the black population resulted in the creation of so-called “homelands”. Grazing land was assigned to individual settlements in those overcrowded reserves in order to provide a means for subsistence farming on a common-pool resource basis. Over decades, the management of the rangeland commons, including the constitution of institutions of resource governance, was top-down and coined by external intervention (Naumann 2014). The fall of apartheid resulted in a sudden dismantlement of formal institutions of resource use. At the same time, large scale and state backed financial assistance payments were introduced. The combination of small resource sizes, a decade long crowding out of intrinsic motivation together with the introduction of age-coupled social grants created a unique situation in those rangeland commons. Today, “livestock presents the largest monetary investment in agricultural assets in the former homelands” (Vetter 2013, p.1).

The empirical case investigated for this thesis is the village community of Sediba in rural Thaba Nchu, South Africa. Sediba is medium sized with 162 households (HH) of which 80 are producing livestock. Income is mainly generated by state grants. Livestock is kept either as a means of savings, sold for unforeseen expenses or is slaughtered during funerals. It furthermore serves as a status symbol. The share of agricultural profit relative to total income is small but the capital bound in livestock constitutes a major monetary resource for HH. Sediba's residents utilize a 2500 ha large rangeland for grazing. Beef cattle are the dominant grazers. Only residents from the village are entitled with access rights to the rangeland. This does not, however, exclude absentee herding.

This thesis goes beyond the socio-economic assessment of the described case as it analyses the dynamic interaction between the social and the ecosystem. The underlying scientific paradigm for the presented research is the notion of coupled socio-ecological systems (SES) as “rangelands are closely linked SES” (Gross et al. 2006, p.1265). Acknowledging the coupled nature of both systems introduces additional complexity arising from reciprocal feedbacks and non-linear dynamics (Liu et al. 2007). According to Vetter (2009), agricultural research has „generally remained focused on sustainable yields and reducing the effects of environmental variability, and agricultural policies and interventions in South Africa still lack an integrated approach which incorporates ecological and social dimensions of rangelands use” (Vetter 2009, p.32). To contribute to an integrated approach for a holistic investigation of rangelands was the overarching motivation for this thesis.

In rangeland systems, individual actions interact with resource dynamics (Milner-Gulland et al. 2006, p.24). The interaction of ecological with social processes leads to emergent properties, e.g. resilience, on system level. Such emergent outcomes in SES are path-dependent (Schlüter et al. 2012). Moreover, Gross et al. (2006) found that the interaction of the social- with the ecological domain introduces thresholds in addition to those already existent in the ecosystem. A central hypothesis for this thesis is that the complementary view to the latter statement is likewise valid. That is, socio-ecological interactions add thresholds to social dynamics.

The three chapters in this paper are dissecting the complexity of the SES in an iterative approach by investigating the effect of ecological (chapter 2), social (chapter 3) and socio-ecological thresholds (chapter 4).

There is an additional, more theoretical, distinction reflected by the structure of this thesis. A canonical framework for describing the dynamics of SES is the adaptive renewal management cycle by Holling (1986). Holling created the notion of dynamic feedbacks of human-nature coupled systems contrasting the command-and-control paradigm of maximal sustainable yield. According to the adaptive cycle, every SES passes four distinct phases in an infinitive loop. Forward dynamics within that cycle are constituted by the movement of SES from growth to conservation. The first phase of exploitation (r) is characterized by an abundance of resources, increasing appropriation and few connections between system elements. As the utilization of ecosystem services increases, growth slows down and structures are solidified in the conservation phase (K). More capital is needed to maintain the structure and the whole system becomes more vulnerable to external disturbances. Shocks are more likely to propagate in a highly connected socio-ecological network. Surprise is what shifts the system from the forward dynamics into the backloop. That is, disturbances lead to a disconnection of system elements in the release phase (Ω). Bounded capital is released from the disintegrating structure and reused by institutions coping with change in the reorganization phase (α) (Walker et al. 2006). A critical element within this backloop dynamics from Ω to α is embodied in the availability of adaptive capacity. Adaptive capacity is the ability of the system to incorporate or absorb disturbances. Viewed from the social perspective, adaptive capacity is present in the process of institutional (re)invention or innovation (Berkes et al. 2003).

Recent work on SESs attempts to operationalize the meta-model of the adaptive cycle such that it can be better used in disciplinary approaches and theories. E.g. Abel et al. (2006) equate adaptive capacity with forms of capital linking disciplines like ecology, economics and sociology. They also identify complex adaptive systems (CAS) theory as a:

“ […] strong foundation for understanding change in SESs, in particular in its recognition of self-organisation and non-linear change” (Abel et al. 2006)

However, processes of self-organization and non-linear change are not as well understood as the development phases of the for-loop of SESs (r,K) (Walker et al. 2002; Walker et al. 2006). Moreover, Cumming and Collier (2005) remind us to look for SESs which deviate from the adaptive cycle. In fact, deviations are becoming evident by recent empirical research on SESs (Anderies et al. 2006).

In Summary, the adaptive cycle is an *idealized* process elaborating the concepts of resilience, collapse and reorganization based upon the adaptive capacity of its sub-systems in a sequential manner. That is, SESs are assumed to be resilient towards change until collapse occurs which is followed by reorganization in an infinite loop[1]. However, the order of phases is case specific and difficult to project in its entirety. The latter becomes, at least in our view, infeasible when the aim is to quantify the dynamics over time.

Generally, this thesis focuses on each of the three named concepts in its separate chapters albeit acknowledging the linkage to the other two. The three main chapters are dedicated to reorganization, collapse and resilience analyzed through the lens of CAS. In CAS, highly non-linear dynamic processes connected over different scales are triggered by perturbations resulting in cascading effects if system inherent thresholds of change are crossed. New cascading effects can only occur if a certain degree of connectivity is re-established by the self-organizing property of the complex system (Abel et al. 2006).

Contrary to the adaptive cycle, we don’t imply a sequence of events rather than analyzing the mutual impacts of resilience, collapse and reorganization. Thus, we avoid assuming fixed temporal trajectories in favour for casual interdependence and their potential consequences. This is done by acknowledging ecosystem resilience and SES collapse in the assessment of reorganizing resource use (chapter 2), by analyzing the role of multiple stable social states and institutional evolution in mitigating collapse (chapter 3) and in quantifying multi-scale resilience by measuring systemic change impacted by the infusion and reduction of economic and social capital, respectively (chapter 4). The general research questions answered by the three chapters are:

1. What are the effects of management changes in spatiotemporal grazing and stocking rates on agricultural profits, economic variability, equity and ecosystem resilience?
2. What is the effect of a "resource-blind" social norm on SES stability vs. collapse and how does norm guided behaviour evolve?
3. How resilient are the different scales of the SES towards bio-physical and socio-economic shocks?

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[1] We use the term “collapse” in the sense of “release” as previously done by Abel et al. (2006)

1.2 The approach – SES modelling

We approached these research questions by empirically based SES modelling with the aim to arrive at quantifiable measures. SES modelling differs from traditional, disciplinary approaches by explicitly taking the coupling of the ecosystem with the social system into account, and by acknowledging the complexity of the overall system. According to Schlüter et al. (2012), traditional ecosystem models treat the social realm as exogenous whereas bio-economic models endogenize the actions of resource users. In bio-economic models rational actors are maximizing utility under resource constraints, but "[...] diverse actors of the social system are not considered and resource dynamics are generally very simple" (Schlüter et al. 2012, p.224). SES models, however, account for heterogeneous decision making and rich ecological dynamics. In SESs, “slowly evolving institutional rules and infrastructure systems interact with faster resource dynamics and even faster economic decisions” (Schlüter et al. 2012, p.248).

Ecological modelling as part of SES modelling has reached some maturity during the last decades, but social models accounting for heterogeneity of agents are still in need of further development. SES modelling attempts are increasingly focusing on human behaviour e.g. (Smajgl et al. 2010; McAllister et al. 2011). Actors in SES models are considered boundedly rational in contrast to the assumption of a homo oecononomicus underlying traditional bio-economic models (Carpenter and Brock 2004; Ebenhöh and Pahl-Wostl 2008; Feola and Binder 2010; Heckbert et al. 2010; Schlüter and Pahl-Wostl 2007; Janssen and Ostrom 2006; Sun and Müller 2013), who thinks too much compared the thoughtless efficiency of heuristic decision making and norm guided behaviour (Epstein 2006, p.226). Moreover, conceptual and computational models of collective action are likewise deviating from the assumption of rational egoism in common pool settings (Ostrom 2003; 2005; Deadman 1999; Ebenhöh 2006). Ostrom (2005) stresses the important role of non-monetary incentives like normative sanctioning for successful common-pool resource governance – i.e. for avoiding a tragedy of the commons described in Hardin (1968). Most social models incorporating bounded rationality are agent based models (ABMs).

The term ABM describes a set of social simulation modelling approaches which share a common paradigm. That is, agent-based modelling is "bottom-up" by "growing" the social phenomena under investigation. Epstein termed this approach generative social science (2006). ABMs avoid the "top-down" approach of traditional (bio)-economic simulation models. That is, without relying on a unified objective function and restricting equilibrium constraints[2], ABMs generate emergent outcomes from local interactions of heterogeneous agents. Such emergent outcomes on system level might be dynamic patterns, distributions or multiple stable states. Moreover, ABMs are capable to capture the non-linear nature of SESs. They generate path-dependent outcomes as they are explicitly dynamic and adaptive. That latter allows for second-order emergence or immergence. That is, the emergent properties are immerging back into the local interactions in a path-dependent manner. Moreover, the non-aggregate nature of ABMs allows incorporating qualitative relationships into the quantitative framework. Decision making in ABMs can follow any paradigm but allows for relaxing rationality assumptions which is a common approach.

Accordingly, the social sub-models presented in this thesis are ABMs and their design is guided by the principles of bounded rationality. Agents use heuristic rules for livestock production (chapters 2-4) and for those decisions impacting collective action (chapters 3 and 4). Agents are heterogeneous with respect to decision making rules and parameters. They interact indirectly via resource appropriation (chapters 2-4) and directly via normative sanctioning (chapters 3 and 4). The models are coded in Java using the Repast framework (North et al. 2013) and utilize a learning classifier library (Hufschlag 2010). The ABMs contain a re-implementation of a livestock model by Gross et al. (2006).

The ecological sub-model was designed by crop scientists at the University of Bonn[3] (forthcoming). The biomass growth model accounts for high climatic variability symptomatic for the study region by means of a high temporal solution (daily). It is written in the Scala programming language under the Simplace framework (http://www.simplace.net/). Both sub-models, including the Simplace

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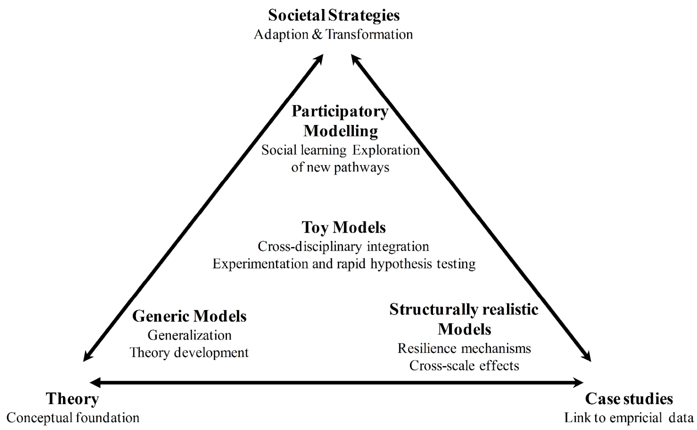
[2] Kuhn et al. 2014 is a recent exception to this definition as their approach allows for heterogeneous agents embedded in the toolset of equilibrium modeling

[3] http://www.lap.uni-bonn.de/home?set_language=en

framework, are fully integrated in Repast. That is, the SES model is dynamically exchanging data between its components during any model run.

The reference frame MORE (modelling for resilience thinking and ecosystem stewardship) offers a conceptual framework for classifying SES models with regard to three objectives (Schlüter et al. 2013). Accordingly, SES models can either contribute to the elucidation of societal strategies (participatory modelling), to the advancement of theory (generic models) or deliver insights in the structure of real-world cases (structural realistic modelling). Toy modelling serves a cross-cutting objective (Figure 1.1). The three objectives are not mutual exclusive rather than informing each other. The SES model designed for this thesis can be categorized as a structurally realistic model. However, in chapter three, a generic model by (Ebenhöh and Pahl-Wostl 2008) was adapted to the case and integrated in the SES model.

Figure 1.1 Reference frame MORE (Modelling for Resilience Thinking and Ecosystem Stewardship) (Schlüter et al. 2013)



The SES model here explores resilience mechanisms, investigates dynamics over socio-ecological scales and builds upon a theory of bounded rationality and collective action. The structure of the model is informed by empirical case study data collected from 2010 until 2013 in several villages of rural Thaba Nchu, South Africa. A team of crop and soil scientists, economists and anthropologists conducted field research funded by the German Research Foundation (DFG)[4]. This included soil and vegetation sampling, surveys and qualitative research. A living standard and measurement survey (Worldbank) was adapted and conducted with the specific aim of SES modelling in mind. The same accounts for vegetation and soil sampling. Anthropologist's field observations supported modelling by face validation of stylized social values and processes.

The three main chapters of this thesis are supplemented by an extensive online appendix (http://www.ilr.uni-bonn.de/agpo/publ/techpap/Techpap15-01.pdf) containing model descriptions according to the ODD+D protocol for describing human behaviour in agent based models (Müller et al. 2013). Being a standardized protocol for model description, the ODD+D protocol aims to enhance model replicability and comparability with a focus on decision making. The contents of the ODD+D protocols are somewhat redundant owed to the re-use of larger model parts when moving from chapter to chapter. We opted to not rephrase reoccurring paragraphs as the ODD+D is meant to be a technical model description only complimented with the theoretical and empirical justification of model assumptions. Chapter 2 and 3 contain excerpts from the respective ODD+D protocol. That is, the two chapters contain the overview and design concept elements from the protocol. To exclude the details part of the protocol from research manuscripts was also recommended by the authors of the ODD+D protocol. In chapter 4, only changes to the previous model are mentioned[5] in favour of readability.

[4] DFG Research Group FOR 1501, Grant nr. HE 2854/3-1

[5] Ideally, also chapter 3 should only contain changes to the previous model. However, we included the excerpts from the ODD+D protocol in the third chapter due to the sequence in the publication process. That is, the third chapter represents an accepted paper in Environmental Modelling & Software (Rasch et al. 2014). We apologize for the resulting redundancy in model descriptions in the first two chapters.

1.3 **Contribution**

This section summarizes the three main chapters of the dissertation. It furthermore elaborates on the model set-ups from a complex adaptive system perspective and relates findings and limitations to the progressive sequence of chapters. The distinct roles of resilience, collapse and reorganization are highlighted and put into a joint perspective.

1.3.1 *Reorganizing resource use in a communal livestock production SES in South Africa*

The second chapter lays out the computational foundation for the quantitative analysis of the coupled system by presenting a fully integrated SES model. It furthermore investigates pathways for reorganizing the SES. An earlier version was presented at the Resilience & Development Conference 2014 in Montpellier.

Reorganization of formal institutions of livestock related resource use has not yet happened two decades after the fall of apartheid (Naumann 2014). The social system resides in a state of institutional collapse with respect to formal rules-in-use. The only exceptions are access rules preventing the transformation of the common-pool to an open-access good. We lack the relevant theories and empirical ground to model the process of endogenous institutional *innovation* for this case. However, quantitative data regarding the acceptance and expectation for two relevant institutional reorganizations were gathered. These were the (re)-introduction of (1) rotational grazing rules and (2) of a rule determining a maximum cap on herd sizes per HH.

Rotational grazing and maximum stocking rates relate to two scientific discourses. First, to the debate regarding equilibrium vs. non-equilibrium theory in rangeland science (Briske et al. 2003). Second, to the dichotomy between engineering and ecological resilience (Peterson et al. 1998; Vetter 2009). Equilibrium theory suggests maximum stocking rates below a (static) grazing capacity. Contrary, the non-equilibrium paradigm emphasizes opportunistic stocking in order to maximize production in rainy periods. The dichotomy of resilience concepts does not relate to straight-forward management advices. However, the assumptions of stable alternative states made in the ecological resilience concept depict an irreversible transition to degradation if the resource is not properly rested (e.g. done in rest rotation schemes). The latter is only valid for un-resilient ecosystems. The investigation of social welfare benefits in resilient ecosystems might well benefit from the concept of return time which is a feature of engineering resilience. That is, continuous grazing might be superior under certain circumstances. It is the latter notion of case specificity which informed the approach in the second chapter. That is, the chapter makes an attempt to overcome the dichotomy in concepts in the rangeland literature by following Campbell et al.'s suggestion that ”one size does not fit all” (2006, p.81).

The chapter analyses social welfare effects under the consideration of ecosystem resilience with respect to alternative grazing strategies (Vetter 2013). We found that the ecosystem is highly resilient (Moreno García et al. 2014). We utilized the concept of resistance and return time in order measure the *degree* of ecosystem resilience which is highly relevant from a management perspective (Ruppert et al. 2014). The analysis in chapter 2 is based on the assumption that agents fully conform to institutional prescriptions or prohibitions. Here, we modelled the combinations of opportunistic vs. conservative stocking with rotational vs. continuous grazing in a baseline and three alternative scenarios. We related the socio-ecological outcomes of reorganization to participant acceptance and expectation and discussed the likelihood of reorganization in that light.

Our findings suggest that all three management alternatives to the status quo increase ecosystem resilience preventing SES collapse and decrease economic variability. The most beneficial strategy is conservative stocking under continuous grazing as it additionally increases profitability and equity. This outcome constitutes a border case between what is typically recommended for temperate and semi-arid zones. That is, either rotational grazing *and* conservative stocking (temperate) or continuous grazing *and* opportunistic stocking[6] (semi-arid) is suggested.

The results arising from the introduction of formal rules are contrasting participant acceptance and expectation. That is, villagers expect a significant increase in animal productivity from rotational grazing. Such (over)-expectations

[6] According to the new Rangeland science paradigm

were also noted by Briske et al. (2008). Our results do likewise not support the assumption of increased animal production. This questions the long term conformity of participants towards rotational grazing rules and their commitment in the maintenance of the needed infrastructure. Moreover, a formal rule enforcing a maximum herd size per HH is not welcomed as participants had bad experiences with the enforcement of that rule under the apartheid regime (Jacobs 2001). Future research might investigate the impacts of monitoring grazing pressure and ecosystem state combined with buying support for animals during the advance of ecological crisis (Scoones und Graham 1994). Contrary to current unintended resting, such a "tight tracking" for emergency sales has the potential to avoid severe losses of the capital bound up in livestock (Campbell et al. 2006).

The modelling approach in the second chapter favoured model transparency and communication. However, it is limited in two ways: First, it only allowed for the evaluation of formal rules. Second, it assumed full conformity of agents. From a complex adaptive systems perspective, the scenarios of management alternatives (social determinants) change thresholds in the ecosystem. However, the introduced social rules are not adaptive and thus do not lead to a second-order emergence into the social sphere. An adaptive institution is in the focus of the third chapter. Interviews with stakeholders, anthropologic field observation as well as the relative egalitarian herd structure indicated the existence of an informal institution; a norm impacting resource utilization.

1.3.2 *Collapse and cooperation in a communal livestock production SES model - a case from South Africa*

The third chapter is a published paper in *Environmental Modelling & Software* and extends the approach in chapter two by modelling the endogenous emergence of cooperation due to the interaction of agents wavering between cooperation and defection in the context of a local norm (Rasch et al. 2014). Computational modelling of norms and institutional evolution has been applied in generic, or theory based models in the past; e.g. (Staller and Petta 2001; Saam and Harrer 1999; Smajgl et al. 2010; Thebaud and Locatelli 2001). A rare exception is Wilson et al. who used real-world case study data from a lobster fishery case in Maine to show the self-organizing property of collective action (2007).

The generic approach is based on Ebenhöh and Pahl-Wostl (2008) who presented a computational implementation of Ostrom’s theory of collective action (2003). They successfully replicated results from economic experiments. Its adaption is constituted by the application to a local norm, by coupling it to SES dynamics and by using empirical data for the agent attributes of cooperativeness and reciprocity. We furthermore introduce the concepts of vividness and severity of norm violations in the computational model.

Agents defect or cooperate with respect to an action prescribed by a norm and the normative sanctioning of norm violators. Here, a simple norm to "not have much more cattle than others" is enforced by normative sanctioning. That is, no formal punishment rather than the disapproval by others is what's driving agents into mutual cooperation. This assumed negative reciprocity was based on survey data and anthropologic field observation. The latter confirmed the important role of enviousness as a driver of many social interactions in the study villages. People are afraid to raise concerns of inequality as this might result in being bewitched by others. Thus, inequality raises the incentive for normative sanctioning. The severity of existing norm violations, on the other hand, serves as an antagonist driver. That is, agent's hope to draw defectors into mutual cooperation decreases with an increased concentration of herds.

SES dynamics are considered as cooperative agents reduce their herd sizes and thus grazing pressure. Ecosystem dynamics, on the other hand, impact inequality and the severity of norm violations due to variable forage availability and resulting herd growth. The latter means that the ecosystem endogenously changes thresholds in the social model. The modelled norm is an adaptive institution; adapting to socio-ecological dynamics and impacting those. The impact of this non-linear SES feedback loop on the probability of SES collapse is the focus of investigation in chapter three. A second research question relates to the role of heterogeneity in agent attributes regarding model outcomes. That is, is it possible to reduce model complexity without changing results?

Our results indicate that the emergence of cooperation in following and sanctioning the norm significantly reduces the likelihood for SES collapse constituting an incident of 100% livestock mortality. Collapse proves to be path-dependent and only occurs after decades of unrestricted resource use. We could furthermore show that cooperation is an alternative stable state exhibiting hysteresis. That is, reducing the factor that triggered a systemic change to the level before the change does not reverse the system to the previous state. This characteristic is documented for showcases of ecological resilience e.g. the eutrophication of lakes by phosphorus input (Carpenter et al. 1999) or shrub invasion on rangelands (Briske et al. 2003). The analogous phenomena of hysteresis in the endogenous formation of alternative *social* stable states was, at least to our knowledge, not shown before. We furthermore found that ecological crisis fosters cooperation (McAllister et al. 2011). During crisis, social reorganization became feasible as self-enforcing SES dynamics, opening a window of opportunity.

A sensitivity analysis of the impact of agent heterogeneity on the probability of cooperation showed that heterogeneity in agent attributes is a prerequisite for cooperation. Moreover, the level of heterogeneity matters. That is, we found that the up-scaling technique of specifying agent attributes by means of random draws from normal distributions changes model results (Smajgl and Barreteau 2014). Thus, using available HH specific data for specifying agent attributes is advisable.

The approach in chapter three was to integrate a generic model based on a theory of collective action into the existing, structurally realistic model, followed up by a detailed analysis of model behaviour. However, agent specification remained relatively simple. In order to test the modelled system with respect to real-life disturbances, the model must exhibit a certain level of granularity. Chapter four presents a more detailed model expanding agent heterogeneity with respect to structurally relevant differences. This allows investigating multi-scale resilience of the SES towards surprises because some scales involve processes of structural change within the social dimension of the SES. The importance of heterogeneity for structural change is also attested by Zimmermann and Heckelei (2012).

1.3.3 *Measuring multi-scale resilience of a communal livestock production SES in South Africa*

Chapter four presents the most detailed model. Here, a HH typology introduces additional agent heterogeneity regarding timing of selling livestock and ecological feedbacks into the decision to sell, fertility management and HH expenditures. All sub-models are based on empirical data, which is also reflected by the more extensive description of the case compared to the previous chapters. The objective is to quantify multi-scale resilience towards external disturbances (Miller et al. 2010). We lay out a framework of SES scales and develop dynamic indicators, or surrogates, in order to quantify resilience. The resiliencies on the ecological, HH, community and socio-ecological scale were put into a joint perspective during analysis. The system is subject to the external disturbances of a multi-annual drought shock, a significant shift in ownership due to a high share of absentee herders and a fundamental change in anti-poverty policy. The general research question is the following:

How do the external disturbances affect resilience on each scale and how are the resiliencies coevolving?

Another objective of chapter four was the development of multi-scale resilience measures as there are no unified concepts available for quantifying resilience in the first place (Carpenter et al. 2005).

The lack of a resilience measurement framework may in part come from the multitude of resilience definitions in the literature. It offers definitions for engineering vs. ecological resilience (Ludwig et al. 2001; Peterson et al. 1998), social resilience based on concepts of HH vulnerability (Miller et al. 2010) or adaptive institutions (Adger 2000) and for socio-ecological resilience (Walker et al. 2002).

Moreover, there are interpretations of resilience being normative contrary to being positivistic. Janssen et al. maintain a normative view on resilience when they state that rangeland managers try to “maintain the resilience of the system […]” (2002, p.103). For Carpenter et al., resilience is distinguished from theories of sustainability by separating the judgment of desirability of system states from its denotation (2001). Holling describes a negative resilience as a “perverse resilience, preserving a maladaptive system” (2001, p.400). Hawes and Reed view resilience as a measure of system health (2006). Here, it is important to note that “health” is related to the capacity of a system configuration to absorb change – desirable or not.

In summary, resilience is not clear-cut in its definitions and interpretations. The concept is also used differently depending on the scale of investigation and is often not directly observable (Carpenter et al. 2005). We defined resilience in two ways: First viewed from a system identity perspective constituting a non-normative concept (Cumming and Collier 2005). Here, resilience is the persistent identity of dynamic patterns emerging over different SES scales. A change in the *type* of dynamic pattern constitutes a loss of resilience. Second, we use normative resilience definitions specific to the scales of investigation. With this approach, we aim at a multi-faceted view on resilience avoiding the dichotomy in the literature.

In order to quantify resilience we identify resilience surrogates (Carpenter et al. 2005) for each SES scale (ecosystem, HH and social or community resilience) based on the literature and implement them as dynamic measures. Furthermore, we apply Walker et al.'s proposal to measure SES resilience by mapping the dynamic patterns of ecological with social resilience surrogates (Walker et al. 2002). This approach is similar to Janssen et al. who applied it to different ecological scales (2002). To our knowledge, chapter four is the first application of Walker et al. to the socio-ecological scale (2002).

The multi-scale perspective on resilience allowed us to investigate if there exists a trade-off between resilience on one scale with resilience on another. This view puts *desirability* into the context of scale and thus introduces a meta-normative approach to the resilience analysis. For example, not everything serving the community is also beneficial to individuals and sustaining ecosystem resilience might only be achieved at the costs of decreasing HH resilience. Moreover, our approach to identify a *change* in resilience is non-normative by observing the change in the identity of dynamic patterns.

For the baseline scenario (status quo), we find that SES dynamics are in a limit cycle pattern. Here, we identify the initial stable attractor around which SES dynamics are fluctuating. The latter implies stable ecological and social states. We use that basin of attraction for comparing the impact of disturbances (or surprises for that matter) on SES resilience. HH resilience shows a negative trend, not co-evolving with SES resilience.

A multi-annual drought pushed the system towards the boundary of attraction but the SES remained resilient and returned to the limit cycling pattern. However, the drought accelerated the decline of HH resilience. Neither ecological nor social resilience was lost.

A second disturbance scenario mimics a significant increase in absentee herding in the community. Absentee herders are assumed to be not socially embedded with respect to the receptivity to normative sanctioning (see chapter 3) as they follow management rules determined by herd owners who are not residing in the community anymore. A share of 50% absentee herders in the village resulted in 20% of the runs in SES collapse with a total distinction of herds. Resilience was lost on all scales in those cases. Emergent patterns disintegrated.

The introduction of a basic income grant (third scenario) did not affect SES resilience albeit a slightly increased grazing pressure. However, the negative trend of HH resilience changed towards a converging pattern. That is, long term HH resilience was established and co-evolved with SES resilience. An investigation of individual HH found that the basic income grant enabled poor HH to successfully compete with richer HH for ecosystem services. The latter stopped the continuing exit of poorer HH from livestock production and resulted in stable states along all scales of the SES.

A limitation of the model structure in chapter four is its complexity. The complexity arises from additional modules introducing agent heterogeneity. This limits the sensitivity analysis in terms of the doable coverage of parameters. The trade-off between achieving structural realism and model complexity led us to recommend an intermediate level of complexity for future SES models.

1.4 **Conclusion**

1.4.1 *Summary of results*

With our empirically based SES modelling approach, we find that a "resource-blind" norm, reducing the peaks in grazing pressure, mitigates SES collapse. The social process modelled exhibits alternative stable social states. Regulating stocking rates is shown to be the most important management variable and the informal institution is doing exactly that. According to our results, institutional reorganization prescribing rotational grazing rules reduces socio-ecological variability but fails to meet the social criteria of increased animal productivity and equity among participants. We furthermore find that SES dynamics are in the basin of a stable attractor but HH resilience follows a downward trend. The ecosystem is resilient towards droughts. However, droughts are accelerating the degradation of HH resilience. A loss of social embededdness, modelled as an increase in the share of defectors, increased the likelihood for SES collapse. The introduction of a basic income grant leads to a converging pattern in HH resilience while sustaining the resilience on other scales of the SES.

1.4.2 *Limitations and outlook*

We find that the structurally realistic modelling approach applied throughout the chapters of the thesis is an appropriate way to capture relevant entities and dynamics of the underlying case study. However, the closeness to the case study is preventing the generalization of findings. In our view, the presented approach is a mean for triangulation in case study research aiming at theory building rather than theory testing (Vaus 2001).

In this sense, our results indicate the importance for negative reciprocity and “resource-blind” norms for the resilience of SES. Self-organizing institutions of resource governance are key for robust common-pool resource systems (Ostrom 2005). However, they might not solely depend on the “good” efforts to organize resource use in order to be successful. That is, normative sanctioning based on "negative" emotions like enviousness can be of significant influence in establishing SES robustness. The latter complements the, at least in our view, over-stressed aspect of "good" governance of SES with its notions of strong leadership, cultural identity, trust and resource-targeted constitutional efforts.

Next, our results question the benefit of rotational grazing for the rangeland commons and stress the importance of local specificities like HH heterogeneity and resource size. That is, research on developing the rangeland commons must take the socio-ecological context into account. Finally, we lay out a measurement framework for multi-scale resilience. This framework is transferable to other cases as it uses surrogates that are universal for the rangeland commons.

Another limitation of our modelling approach is that it lacks the ability to mimic the processes of institutional *innovation*. That is, theories on how agents come up with new rules in response to socio-ecological surprises. Future research is needed to explore pathways of integrating theoretical models of this kind without bloating model size. One way to achieve this is to reduce model complexity to stylized facts and to aim at an intermediate level of complexity as in stylized, or toy modelling approaches.

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Chapter 2
Reorganizing resource use in a communal livestock production SES in South Africa[7]

Abstract. Livestock production on South Africa's commons contributes significantly 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 leads to the most favourable outcomes from the social and the ecological perspective. However, past legacy under

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apartheid and participants' expectations render its successful application unlikely as enforceability is not ensured.

Keywords: Governance, Land Ownership and Tenure, Environment and Development, Simulation Modelling

JEL classification codes: **Q010, Q150, Q560, C630**

2.1 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 unfavourable 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). Considering the high population density and poverty in the former homelands, the South African government has emphasized the need to increase the economic benefits generated by those rangeland systems. (Department of Agriculture 2007). However, projects in the communal rangelands are often implemented 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. The third section presents the case. Thereafter the simulation model is described in a condensed manner according to the ODD+D protocol for social agent based models. Scenarios and measures of performance are outlined in section five. This then followed by model results (6) and a discussion of results (7).

2.2 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). Proponents of the “new thinking” in rangeland ecology propagating non-equilibrium theory for arid and semi-arid rangelands argue that abiotic factors, and here rainfall variability 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 favourable years and assumes that the rangeland will recover under light stocking after an ecological crisis. Recovery is possible as livestock is either sold in drought years or due to un-intended 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, temporally high opportunity costs of conservative stocking has to be weighed against reduced average productivity under opportunistic stocking (Campbell et al. 2006).

A second pair of management strategies related to the discussion is rotational vs. continuous grazing. The rationale 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. found that empirical evidence from the past 60 years could not support the superiority of rotational grazing (2008). 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. This is especially relevant for semi-arid areas where high quality forage of under-utilized pastures does rapidly senescent.

However, also the proponents of continuous grazing acknowledge that longer term rests ("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 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). A system is considered resilient in this context, if it does not change its fundamental functions when facing external shocks, (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 not as clear-cut as for the non-equilibrium discourse. At least for Harrison and Shackelton, conservative stocking rates and rotational grazing are not needed for resilient rangelands (1999).

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 that are better described by continuous and reversible dynamics. Harrison and Shackelton found that South African "communal grazing areas are extremely resilient" (1999, p.237) as they recover rapidly in less than 10 years after abandoning grazing. Therefore, it seems worthwhile to consider return time and resistance in those cases, as they might be highly relevant from a management perspective.

The growing consensus, 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 is favourable over continuous grazing. At least for stocking regimes, Campbell et al. offer an attempt to overcome the polarization in the debate differentiating between rangeland systems according to framing conditions. Or, as they term it: "one size does not fit all" (2006, 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 that are on the threshold of what is considered a non-equilibrium system. Here, systems with a rainfall coefficient of variability (CV) 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.

One way to test for the impact of management alternatives considering the socio-ecological context are simulation models. According to Briske et al., simulation modelling is well suited to "evaluate the managerial and ecological components of grazing management, both independently and in combination" (2008, 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 that become only visible after decades in semi-arid regions (Müller et al. 2007). For representing the human dimension of the system, agent based models demonstrated already their ability 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 CV of 30% and 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 subsequently serves 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.

2.3 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.

2.3.1 *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 providing 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 (pers. comm. Roelof Oomen), which is grazed by cattle as the dominant grazer. The CV for the region is 30% (Behnke 2000). García et al.’s (2014) analysis confirmed that of Harrison 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”. Linstädter et al. also indicated the regenerative potential for this grassland biome under communal management (2014). The authors only find small or no differences in the abundance of perennial grasses between commercially and communally managed systems 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, for example due to bush encroachment, cannot be identified. However, climatic variability and mean annual precipitation are characteristic for a semi-arid system. Thus, fluctuations in forage quantity, and even more important in forage quality, are high.

2.3.2 *Social system*

Sediba comprises about 160 HH and 83 HH own cattle. However, ownership is fluctuating as villagers are exiting and (re-)entering into livestock production due to herd losses or animal re-acquisitions in the context of droughts. In accordance with Berzborn’s findings, livestock is not perceived as a main source of income but as a “top-up” to off-farm income (2007, p.679). However, the average herd size in Sediba is worth more than the 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 mainly consists of 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 to purchase supplementary feeding, although for the latter to a lesser extent. Many low-income HH do not practice supplementary feeding. Livestock is only bought in case a HH wants to enter into production. Generally, HH use simple rules of thumb based on animal characteristics to decide which animal to sell. Sediba has no direct access to formal markets and owners sell livestock 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, individual herders decide on their own management without formal regulation of stocking rates. The 2500 ha large rangeland is utilized under continuous grazing with livestock roaming freely on the rangeland.

The villagers' acceptance of a rotational grazing scheme was very high with 95.5% of HH strongly welcoming it (Appendix A). Moreover, most HH expect a significant increase of 50% in animal productivity if this scheme is adopted (Appendix A). However, 86.9% of the respondents state that the community is not able to enforce rotational grazing under self-governance and support enforcement by an external institution (Appendix A).

A share of 89.7% of the HH did not agree to restrict their herd size (Appendix A). Thus, the only possibility to achieve a maximum stocking rate is an externally enforcement of a maximum herd size on HH level as practiced during Apartheid. However, this is overshadowed by the way past interventions were implemented (Naumann 2014). Massive culling operations have taken place that culminated 1983 in the "great Bphuthatswana Donkey Massacre" (Jacobs 2001). Those top-down interventions ignored people's needs and created the observed resentments against reducing herd sizes.

To summarize, core elements to be considered in a structurally realistic model of this case 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 individual heuristics for selling animals

We omit to implement other details of the case in the model 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). Results from model analysis of rotational grazing and destocking scenarios are presented then and discussed in light of people’s expectations and perceptions in the last section.

2.4 **ODD+D protocol**

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 hierarchically 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 Müller et al.’s recommendation to present the overview and design concepts in the text and to provide the full ODD+D protocol, including details, as an online appendix (http://www.ilr.uni-bonn.de/agpo/publ/techpap/Techpap15-01.pdf).

2.4.1 *Overview*

Purpose

The purpose of the model is to assess the socio-ecological outcomes of spatial-temporal grazing and stocking strategies for a case in South Africa. 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.

Entities, state variables and scales

Social agents are aggregated at the household (HH) level distinguishing two HH agent types: a livestock producing HH agent and a HH agent who does not own livestock. Cattle being heifers, cows or bulls represent the livestock agent. A fourth entity is the common rangeland providing the ecosystem service of forage production. Biomass production is modelled as photosynthetic and senescent biomass in order to mimic fluctuations in forage quality.

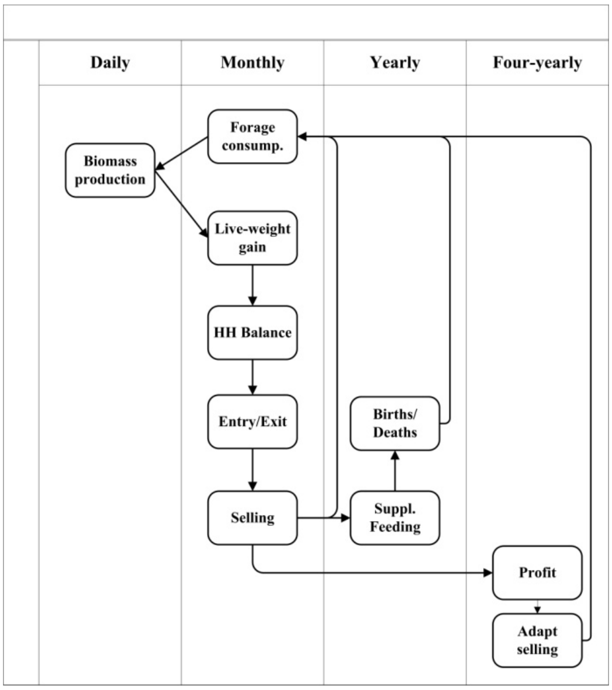
Income, expenditures, savings, HH size and age of the HH head characterize both HH agents. Livestock producing HH agents are additionally described by number and types of livestock agents owned, the memory of past profits, and the selling rule. HH agents can switch their type during the simulation depending 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. Appendix (B) provides a list of state variables and parameters. The next section with the empirical background refers to the data files.

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.

Process overview and scheduling

The rangeland entity produces biomass on a daily basis that 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 (August). Livestock producing HH agents draw a new heuristic selling rule in every fourth year (production cycle). Figure 2.1 depicts the time intervals and order of scheduled events.

Figure 2.1 Model flow and scheduling



2.4.2 *Design concepts*

Theoretical and empirical background

A living standards and measurement HH survey (Worldbank 15.11.2013) was conducted in four villages of the rural area in the north of Thaba Nchu. It encompassed 350 HH and was adapted to the local context. The survey was administered to livestock producers and to HH not owning livestock. For the village of Sediba, the case to be modelled here, the survey covered the whole population of livestock owning 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 until 2013. Links to HH survey templates, coding schemes, survey data, weather data and input data files used in the model can be found in the appendix (A).

The model is 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) is guided by the need to account for climatic variability in semi-arid areas (McAllister et al. 2011, p.1). This is achieved 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 employs 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 boundedly 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. The according analysis can be found in the sub-model section of the extended ODD+D protocol (http://www.ilr.uni-bonn.de/agpo/publ/techpap/Techpap15-01.pdf).

A randomized twelve-year time series on weather data from the region serves to model the exogenous impact of climate. Survey data from the village of Sediba allows specifying the number, types, state variables and parameters of HH agents in the model (Appendix A).

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 based on 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 that 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 also not accounting for uncertainty in the prediction. A logistic regression predicting the probability to enter reflects uncertainty in the entry decision. HH only enter if a random number drawn from a uniform distribution is lower or equal than this probability. HH exit livestock production due to livestock mortality or the selling decision. No temporal or spatial aspects are considered in the decisions on expenditures, entries and exits.

Sold livestock is reducing grazing pressure and does not just change ownership within the village. This assumption is based on survey data which revealed that 83% of all sales go to butcheries or traders visiting the villages regularly (Appendix A). 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[8].

Livestock producers decide if, how much and which type of livestock to sell. 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 chromosomes. Solution chromosomes are chosen depending on a roulette-wheel draw with

[8] Less than 2% of the total herd size was bought by HH during the last 12 months before the interview (Appendix A)

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.

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[9]. 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 choose what worked best in the past rather than computing an optimal strategy beforehand. With Wilson et al.'s words, agents are "assumed to be boundedly rational, profit maximizers" (Wilson et al. 2007, p. 15213).

Individual sensing

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

Individual prediction

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

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[9] Ranges for values are derived from survey data (Appendix A)

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.

Collectives

There are no agent collectives in the model.

Heterogeneity

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

Stochasticity

Random numbers ensure implementation of probabilities regarding the following variables: cattle mortality and births, HH entering livestock production and choice of selling heuristics.

Observation

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

2.4.3 *Details*

For the details of the model and its submodels, we refer to the full ODD+D in the online appendix (http://www.ilr.uni-bonn.de/agpo/publ/techpap/Techpap15-01.pdf).

2.5 **Scenarios and measures of performance**

The following section outlines modelled scenarios and evaluation criteria.

2.5.1 *Scenarios*

Continuous Opportunism - 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, slow recovery is ecologically superior to immediate restocking (1994). It is, however, a “waste of grazing resources” (Müller et al. 2007, p.314). Results for the baseline scenario are used in the analysis as a reference indicating the relative impacts of alternative grazing schemes.

Rotational Opportunism

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 (Table 2.1). 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 into three land categories grazed over different periods during 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 until April. The other two parts are grazed during a certain time span in the vegetation phase each. Full resting in the critical phase of rapid plant growth is applied 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 in terms the division of grazing camps during the specific months of the year.

Table 2.1 Rotational grazing system

Year	September	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**

note: Letters and shades indicate a specific area of the rangeland. Shades only serve visual clarity.

For the scenarios testing rotational grazing, we divided the Sediba rangeland (2500 ha) in three equal parts which are utilized in the described manner. Rule conformance of HH is assumed. In this scenario, no restrictions on herd size are in place.

Continuous Conservative Stocking

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 be 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 use 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, is based on plausibility considerations and should be further investigated 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. In this scenario, no spatio-temporal grazing patterns are applied.

Rotational Conservative Stocking

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

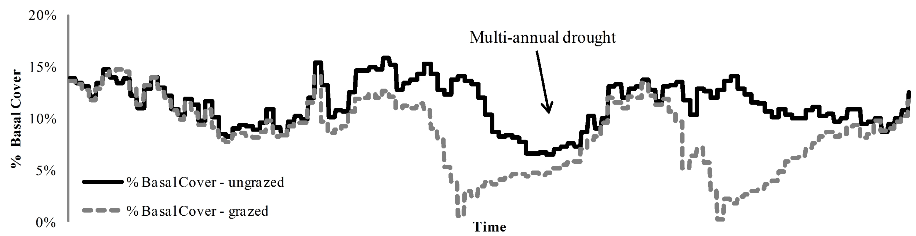
2.5.2 *Measures of system performance*

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

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 measuring the percentage surface area covered by plants. Basal cover is 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 2.2 shows an exemplary time series comparing basal cover dynamics of an un-grazed system with a system under high grazing pressure. All modelled scenarios, as well as the un-grazed reference system, are driven by a deterministic weather file based on empirical data from the region (Appendix A). 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 2.2 Basal cover dynamics in the absence and presence of grazing pressure



In the analysis, we refer to the basal cover dynamics of the un-grazed state as the "resilience pattern" atess 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 percentage deviations from the resilience pattern for each month over multiple runs result in a certain frequency distribution for each management scenario. Frequency distributions allow for quantification beyond a mere graphical presentation of deviating patterns.

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 simulation period. 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).

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 buffers any HH from economically unfavourable circumstances that can occur anytime. This is defined as the monetary value of herds in any month plus monthly generated profits from sales and we refer to it 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.

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.

2.6 **Results**

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

2.6.1 *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 2.2 shows a summary statistic of deviations from the resilience pattern (baseline) under grazing stress for the four scenarios. Monthly percentage deviations were computed over 300 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 % until -1.2%.

Table 2.2 Summary statistics - % deviation from resilience pattern under the four grazing scenarios

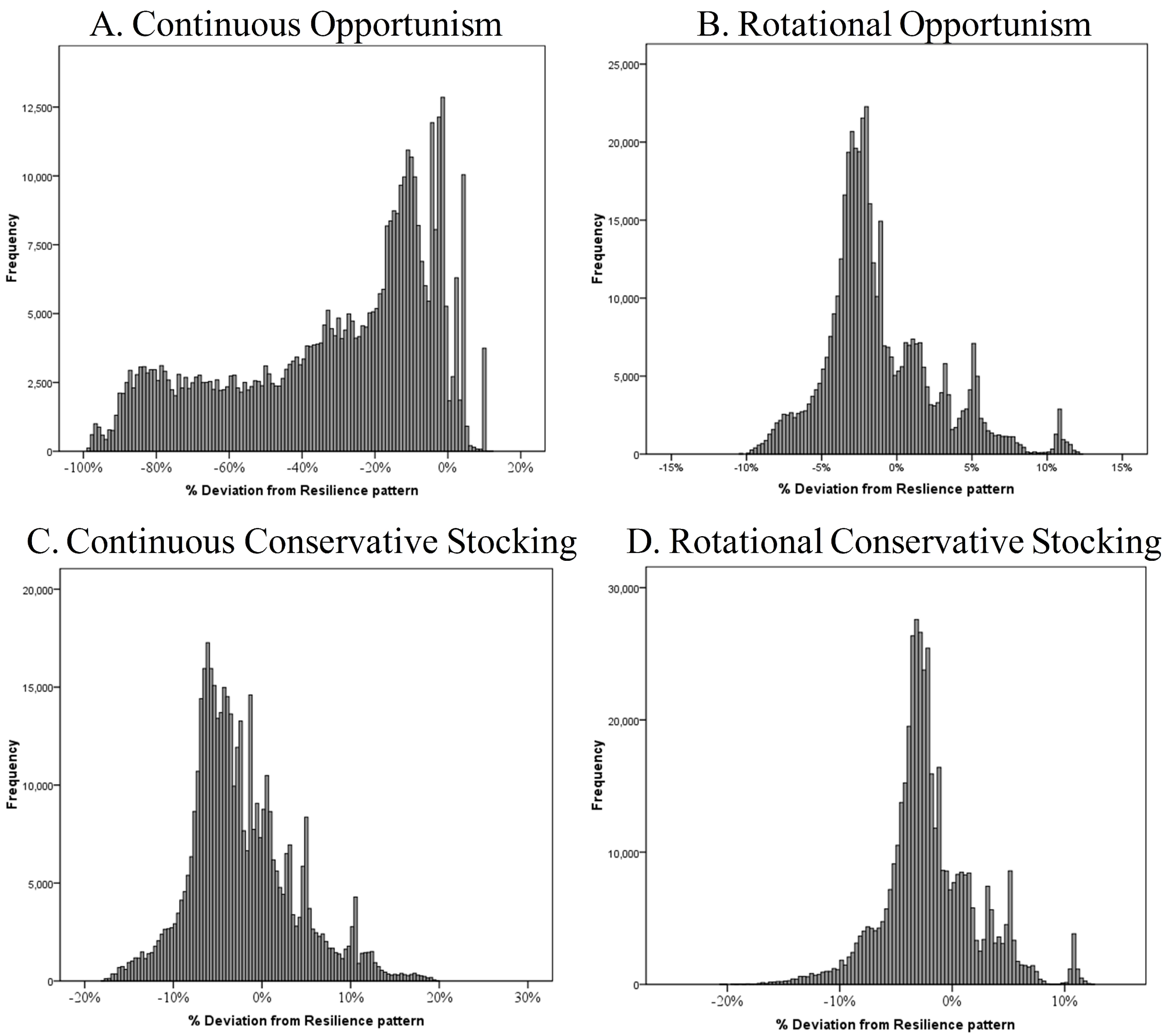
Statistics		Continuous Opportunism	Rotational Opportunism	Continuous Conservative Stocking	Rotational Conservative Stocking
N	*Valid*	443100	443100	443100	443100
	Missing	0	0	0	0
Mean (%)		-31.35	-2.02	-2.27	-1.17
Std. Deviation (%)		27.78	4.11	5.85	3.68
Percentiles	*20 (%)*	-60.05	-4.57	-6.63	-3.68
	40 (%)	-32.39	-3.11	-4.49	-2.54
	60 (%)	-15.69	-1.95	-1.80	-1.35
	80 (%)	-6.51	.94	2.2	1.52

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 2.2). This result resembles Briske et al.'s empirical findings that grazing increased primary production in 20% of investigated rangeland cases (2008).

Figure 2.3 (A) shows the frequency distribution of monthly percentage deviations from the resilience pattern for continuous grazing under opportunistic stocking as currently practiced in the village. 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 severely depleted state for longer time spans.

Figures 2.3 (B), (C) and (D) shows the percentage deviations for the other three scenarios; rotational grazing under opportunistic (B) and conservative stocking (D) as well as continuous grazing under conservative stocking (C). 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 occurs for continuous grazing under conservative stocking with -18%.

Figure 2.3 Frequencies of % deviations from resilience pattern under (A) continuous grazing and opportunistic stocking, (B) rotational grazing and opportunistic stocking, (C) continuous grazing under conservative stocking and (D) rotational grazing under conservative stocking.



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 only implicitly accounts for the speed of recovery, or resilience. The latter might have an impact on social outcomes that will be investigated in the next sections.

2.6.2 *Productivity*

As said above, we assess the contribution of rangelands to livelihoods as relative changes in profits. Here, we use an aggregate measure being the average of total profits over all livestock producing HH generated over the simulation period. Profitability per HH is measured as total revenues from livestock sales minus expenses for supplementary feeding and (re)-acquisition of animals. Note that the analysis focuses on relative differences in profitability instead on absolute figures as the model uses fixed input and selling prices varying 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 were 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 2.3). Both rotational grazing scenarios form one group and the two continuous grazing scenarios represent the other two. That is, no profit differences are found between the rotational grazing strategies but differences between rotational grazing and both continuous grazing strategies were significant. 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 2.3 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
Rotational conservative stocking	300	66.17 Mio Rand		
Rotational opportunism	300	66.66 Mio Rand		
Continuous opportunism	300		85.65 Mio Rand	
Continuous conservative stocking	300			108.24 Mio Rand
Significance		.086	1.000	1.000

2.6.3 *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 approach is complementary to those of profitability and equity dynamics of HH buffer capacity presented in the previous and forthcoming sections, respectively. Arguably, a certain variability of a profitable system might be considered socially more desirable compared to the same variability of a less profitable grazing strategy.

Significant differences between the four grazing strategies with respect to variability in HH buffer capacity were 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 2.4). One homogenous sub-group is 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 as standard deviation, is found for the rotational grazing strategy under conservative stocking. Rotational grazing under opportunistic stocking and continuous grazing under conservative stocking show a slightly higher variability. 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 2.4 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
Rotational conservative stocking	300	3262 Rand		
Continuous conservative stocking	300		4061 Rand	
Rotational opportunism	300		4086 Rand	
Continuous opportunism	300			10896 Rand
Significance		1.000	.526	1.000

2.6.4 *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 is 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 favourable times and during ecological crisis. Figures 2.4 and 2.5 present HH buffer capacity over time for the highest (Figure 2.4) and for the lowest income quintile (Figure 2.5) under all four grazing strategies. We present exemplary runs instead of averages to not blur the effect of ecological collapse in specific time steps.

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. The respective HH 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 takes more than 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 alternative strategies show a positive trend over time stabilizing after the drought. The lowest outcome is recorded for rotational grazing under conservative stocking and the highest for rotational grazing under opportunistic stocking.

To summarize, the management alternatives for the currently practiced strategy avoid severe population crashes but are not able to generate the large gains from continuous grazing under opportunistic stocking during ecologically favourable 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 2.4 Time series – evolution of HH buffer capacity of the highest income quintile for the four grazing scenarios

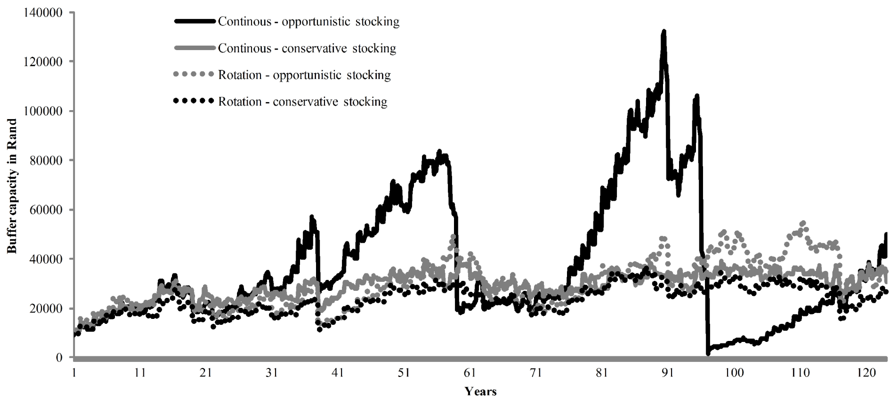
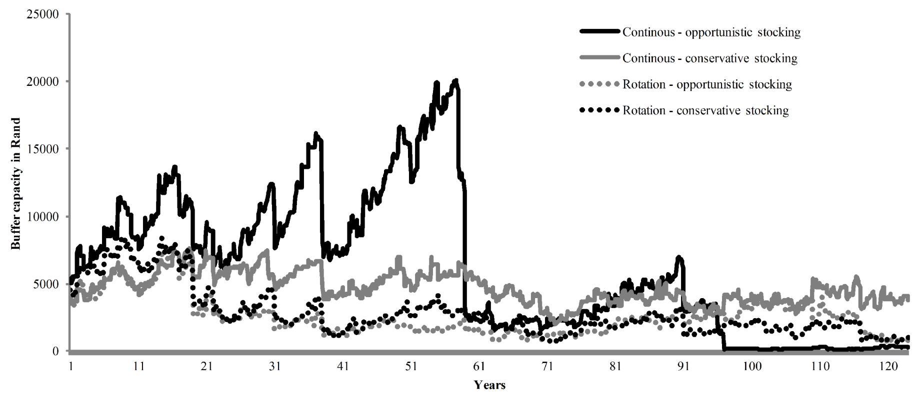


Figure 2.5 shows the HH buffer capacities for the poorest part of livestock producing HH for the four grazing strategies. Analogous to the highest income quintile, HH do considerably better by practicing continuous grazing under opportunistic stocking compared to the three alternatives until the set-in 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 2.5 Time series – evolution of HH buffer capacity of the lowest income quintile for the four grazing scenarios



To summarize, the most viable grazing strategy in terms of long-term participation of poor HH in resource appropriation is 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 noting that gains from opportunism with continuous grazing are tremendous for poor HH until the drought sets in.

2.7 Discussion

The presented results support 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 furthermore support 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 also reflected by more stable economic outcomes. This does not translate, however, into larger profits when aggregated over time for 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 be responsible for this as the resource size is limited and a separation in fenced-off camps considerably 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 compared to continuous grazing in favourable years. 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 resulting lower stocking rate combined with "reserved" forage on rested camps offers, however, a higher probability of herd survival in unfavourable years. Moreover, 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.

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). Under the absence of 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, which has been reported earlier (Heady 1961). However, it is unlikely that villagers will carry the maintenance and institutional costs associated with rotational grazing rendering any investment in the infrastructure useless. To summarize, a restriction of herd sizes is not wanted by villagers and rotational grazing will not meet their economic expectations.

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 and might be a potential path-way to tackle the described dilemma. Tracking would involve monitoring stocking rates and ecosystem state as well as opportunities to sell and re-buy large parts of the herd. However, the investigation of tracking was beyond the scope of this paper. We believe that the latter is a worthy endeavour for future research.

Here, further research is needed to derive early-warning indicators for imminent population crashes, optimal de- and restocking strategies and a careful benchmark of socio-ecological outcomes for this management scheme against other management alternatives. The success of tracking would furthermore require the integration of local markets into national or global supply chains in order to not distort prices due to over-supply or demand.

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. The next chapter in this thesis is devoted to the identification of mechanisms of informal institutions and their translation into quantifiable measures for the case under investigation.

2.8 References

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2.9 **Appendix**

Appendix A: 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

Appendix B: 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

Chapter 3
Cooperation and Collapse in a communal livestock production SES[10]

Abstract: Institutional arrangements are considered necessary for successfully governing the commons. They are considered to be most effective if they are self-organized rather than imposed from outside. However, endogenous institutional arrangements, such as local norms, are specific to a particular socio-ecological system (SES). This paper presents a SES model of communal livestock producers in South Africa. Its bio-physical component accounts for the impact of biotic and abiotic factors on livestock population. The social agent-based component models individual and socially determined behaviour, the latter of which is a social norm specific to the case. Model results show that when cooperative agents obey and sanction the norm, there is less likelihood of SES collapse in terms of livestock population crashes. However, cooperation among agents only emerges in times of ecological crisis where social reorganization is fostered. The crisis creates an opportunity for initializing a self-enforcing process of mutual cooperation. Model specifications are based on survey data, and agents were parameterized according

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[10] This part is published as Rasch, S., Heckelei, T., Oomen R. and Naumann C. (2014): Cooperation and collapse in a communal livestock production SES model – A case from South Africa, *Environmental Modelling & Software*, in press, doi:10.1016/j.envsoft.2014.12.008

to individual household data. A sensitivity analysis shows that this empirical heterogeneity cannot be reduced without changing model outcomes.

Keywords: SES, agent-based modelling, rangelands, norms, cooperative behaviour, bounded rationality, South Africa

JEL classification codes: Q2, **Z13, C9, C63**

3.1 **Introduction**

Recent debates in rangeland science have focused on resolving the dichotomy between equilibrium and disequilibrium models (Vetter 2005, p.334). Equilibrium models stress the importance of density-dependent livestock mortality that results from competition for forage. The contrasting idea of disequilibrium models is that mortality is primarily density-independent and driven by abiotic factors. Although rangeland science now acknowledges that both elements are evident in rangelands, an integrated approach still misses a third element (Vetter 2005, p.323). This element is the social dimension, which is interwoven with the ecological system. Such a coupled system, accounting for both social and ecological complexity, is described as a socio-ecological system (Gross et al. 2006, p.1265). Social complexity is evident when social interactions contribute to relevant outcomes at the system level, such as where the decisions of several individuals contribute to resource appropriation. A classical case for social complexity arising from multi-stakeholder settings is a communal livestock production system (Milner-Gulland et al. 2006, p.24). If common access to the resource is restricted to the community, it is characterized as a common-pool good (Ostrom 2005, p.24).

A characteristic threat associated with common-pool resources is ecological degradation due to over-appropriation. In such cases, the actions of rational individuals have external effects on other actors, which was predicted to result in a “tragedy of the commons” (Hardin 1968). However, the classical view on the inevitability of the tragedy of the commons has also changed (Deadman 1999; Feeny et al. 1990; Allsopp et al. 2007). This paradigm shift is based on the acknowledgement that actors are not necessarily “*rational egoists*” (Ostrom 2005, p.101). Economic experiments have shown that participants are “*more trusting than homo economicus*” (Heckbert et al. 2010, p.41), are strong reciprocators

(Gintis 2000, p.313) and are thus conditional co-operators (Gintis 2000, p.316) rather than purely self-interested free-riders in common-pool resource settings. An essential element for successfully governing the commons is the existence of institutional arrangements constraining individual behaviour (Vetter 2013; Ostrom 2005, p.137). Ostrom (2005, p.137) presents an institutional syntax based on the notion that institutional arrangement can be distinguished as shared strategies, norms or rules. The three types of institutions differ in how they treat sanctioning of violations of the arrangement. A rule is enforced with a formal sanction; a norm by normative sanctioning and a shared strategy is not enforced. Normative sanctioning does not include a formal fee but is expressed in disapproval from others. Moreover, institutional arrangements are seen to be more effective in the long run if they are revised and enforced by the community instead of being externally imposed (Frey and Jegen 2001).

SES modelling has emerged as a new field to study the interplay of ecology with the social dimension of SES. According to Schlüter et al. (2012),

“Modeling SESs as coevolving systems acknowledges that history matters, i.e., the system’s dynamics are path-dependent, such that previous developments and states of the system constrain possible future developments” (2012, p. 48)

A prominent example of an SES model applied to rangeland systems that considers the social dimension is in Walker and Janssen (2002), which was based on a model from Janssen et al. (2000). Here, the authors find that rangelands, including their livestock and managers, are complex adaptive systems (CAS) characterized by individuality of components, localized interactions and autonomous processes. The authors stress that future research needs to better understand “the rules that govern change and the conditions under which change occurs” in those self-organizing systems (Walker and Janssen 2002, p. 724). Other SES rangeland models have addressed pastoralist behaviour (Milner-Gulland et al. 2006), assessed management alternatives for rangelands (Müller et al. 2007; Campbell et al. 2000; Beukes et al. 2002) and identified robust strategies for rangeland management (Janssen et al. 2004). Gross et al.’s rangeland model emphasised the interaction between learning and environmental heterogeneity (Gross et al. 2006). An ecological-economic model by Jakoby et al. (2014) found that individual risk preferences of rangeland managers have to be taken into account to find a viable strategy. The assessment of HH (Household) viability in terms of risk in the rangeland context was modelled by (Martin et al. 2014). Another rangeland model focuses on the importance of gift-giving institutions for risk pooling (Aktipis et al. 2011). The impact of underlying rationality assumptions is another important element (Rouchier et al. 2001), and SES models typically assume bounded rational decision making (Schlüter et al. 2012).

However, most SES models that account for institutional aspects and social rules impose them as exogenous constraints for individual behaviour (Schlüter et al. 2012). Endogenously evolving institutional processes have only been modelled by a few scholars and have seldom been applied to real-world SES cases. Early examples encompass the computational study of norms e.g., by Staller and Petta (2001) as well as by Saam and Harrer (1999). Saam and Harrer (1999) focus on “norms as solutions to problems of inequality [...]” and operationalize norms in this context as behavioural constraints on interacting, artificial agents. Smajgl et al. (2010) modelled the evolution of institutional arrangements between farmers extracting water from a common pool. Both Ebenhöh and Pahl-Wostl (2008) and Castillo and Saysel (2005) modelled the endogenous formation of cooperation based on norms of reciprocity and trust. Another agent-based model by Wilson et al. showed that self-organizing processes can result in the emergence of successful collective action based on competition (Wilson et al. 2007). The collective action restrains individuals from unsustainable resource appropriation. The spontaneous emergence of a resource-sharing convention was modelled by Thebaud and Locatelli (2001). Using evolutionary game theory, Tavoni et al. (2012) modelled endogenously emerging cooperation in an artificial common pool resource setting driven by other-regarding preferences and the pressure of the conformist.

The models cited above are important steps towards a better understanding of endogenously evolving institutions based on social interaction.

Our aim is to make a further step in this direction by modelling an endogenously evolving social process in a real-world SES. We investigate the impact of a norm in a livestock producing community in South Africa, focusing on the social dimension of the SES. An agent-based model is used to test the basic hypothesis that endogenously evolving institutional arrangements can alleviate the threat of degradation and system collapse in a rangeland system. The emergence of self-governance has already been found to support this hypothesis for a fishery case in Wilson et al. (2007). A second research question examines the circumstances and conditions under which the modelled norm evolves. Here, we are interested in small changes propagating through the system and leading to systemic changes (Abel et al. 2006). Systemic changes are measured with outcomes at the system level. We differentiate between system configurations that sustain the link between the social and the ecological dimension and those that are marked by a loss of the link. The link itself is the livestock population, which allows the use of the ecosystem services provided by the common-pool resource. The loss of this link represents a change in identity (Cumming and Collier 2005) and is thus a collapse of the SES under investigation. With the aim to contribute to the field of empirical agent-based modelling, the model is further analysed with respect to the effect of empirical detail in parameterization on the emergence of cooperation (Janssen and Ostrom 2006; Smajgl and Barreteau 2014). Cooperation is understood as collectively obeying a norm and normatively sanctioning norm violators such that they are drawn into mutual cooperation.

The next section (3.2) presents a brief description of the underlying case followed by a (3.3) model description based on the ODD+D protocol. Thereafter, (3.4) results are presented and (3.5) discussed in the light of the existing literature on collective action and norms in common-pool resource settings.

3.2 **Case Study**

Sediba, a village community near Thaba Nchu, South Africa, is modelled here. Sediba’s residents use a 2500 ha rangeland as commonage for beef cattle production. However, only 80 of the 162 HH are currently engaged in livestock husbandry. 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). 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. Herd sizes of

HH are generally small with a maximum of 25 cattle (Journal Appendix A). In accordance with Berzborn's (2007, p.679) findings, livestock is not perceived as a main source of income but as a "top-up" to off-farm income. HH income is mainly generated by state grants and remittances. Income from wage labour is generally low due to scarce employment opportunities. Livestock production is predominantly a phenomenon of the middle class, which is more likely to own livestock than poorer or richer HHs. There are no formal institutions regulating stocking rates in Sediba. However, a social norm restricts the over-usage of the resource. This norm and its underlying social processes are described in the ODD+D protocol presented in the next section.

3.3 **ODD+D protocol**

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 describe 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 (doi:10.1016/j.envsoft.2014.12.008).

3.3.1 *Overview*

Purpose

The purpose of the model is to investigate how social norms affect the stability of a communal livestock production SES in South Africa. The underlying hypothesis is that the SES faces the threat of collapse in the absence of institutions regulating appropriation from the common-pool resource. The institutional arrangement is a norm to "not have much more cattle compared to other families". Although it is not targeted at preserving system stability, this norm might have positive effects on sustainability or resource use because it slows the growth rates of herds. The model was built to answer two research questions.

1. Does a “resource-blind” norm have a stabilizing effect on SES dynamics? RQ1
2. Under which conditions does norm compliance emerge? RQ2

Another objective is to detect whether heterogeneity in agent attributes derived from a HH survey significantly impacts model outcomes. That is, does the use of empirical data on a detailed level add information to the model or can complexity be reduced by using averages or random values?

The model was designed for scientists who study the impact of social norms on SES dynamics in common-pool resource settings.

Entities, state variables and scales

Social agents are aggregated on the 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 representative of 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 the number and type of livestock agents owned, memory of past profits, cooperativeness, reciprocity, norm compliance and 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 (1) biomass of green shoots, (2) senescent biomass, and (3) basal area. A list of state variables and parameters can be found in the appendix (Journal Appendix B). References to the data files are given in the next section describing the empirical background.

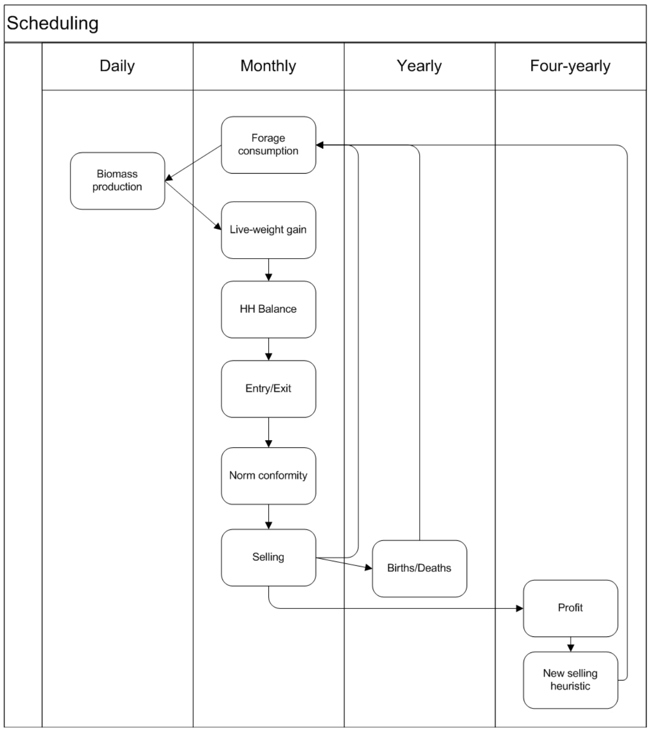
Space is implicitly considered in the consumption and production of forage per ha. Here the resource size is constant but herd sizes vary over time. The model runs with daily (ecosystem) and monthly (social system) time steps over a period of 100 years.

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 are potentially forced to exit livestock production every month. They decide if they obey a rule prescribed by a norm and whether to sell livestock on a monthly basis.

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 3.1 depicts the time intervals and order of scheduled events.

Figure 3.1 Model flow - scheduling



3.3.2 *Design concepts*

Theoretical and empirical background

A living standards and measurement HH survey was conducted in four villages of the rural area of Thaba Nchu in South Africa (Worldbank 2013). It encompassed 350 HH and was adapted to the local context. Individual data were aggregated on the HH level. The survey was administered to livestock producers and to HH not owning livestock. For the village of Sediba, the survey covered the whole population of livestock owing HH. The social mechanisms driving the dynamics of the modelled norm, as well as the norm itself, were face-validated by an anthropologic researcher who lived in the village for 9 months (pers. comm. Christiane Naumann). Additionally, vegetation and soil samples were taken in two villages 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, input data files used in the model and the full ODD+D protocol can be found in the journal appendix (doi:10.1016/j.envsoft.2014.12.008).

The hypothesis to be tested with the model was informed by the theory of collective action (Ostrom 2003) in the context of rangeland systems. Regarding the latter, 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). The most important abiotic driver for semi-arid rangelands is sporadic rainfall with high precipitation on a few days during the wet season. This was accounted through the daily temporal resolution of the ecological model. 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 idea of over-compensatory growth, forage quantity and quality, as modelled in Gross et al. (2006). Stocking densities emerge from the interaction of ecosystem, herd and social dynamics.

The general concept underlying the design of the social dimension is based on the insight that institutional arrangements constitute constraints for individual behaviour (Ostrom 2005, p.137). Accordingly, the social model is designed in a two-tier manner. Individuals know and perform actions in an isolated fashion to pursue individual goals. However, individual actions can be overruled by a collective action in case an individual is drawn into mutual cooperation (Ebenhöh and Pahl-Wostl 2008).

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). This accounts for the individual as well as for the collective level. On an individual level, agents do not have full information and lack the computational ability to plan decisions in a fully rational manner. They use adaptive heuristics instead. On the collective level, agents are conditional cooperators in cases where normative sanctioning is perceived to be more costly compared to the loss of monetary value (Ostrom 2003). Thus, they are not rational egoists.

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. Moreover, many respondents (47%) stated that a significant increase in their herd size would result in a form of normative sanctioning. That is, others would “become envious and make problems”. Thus, decision makers are considering norms of reciprocity. The existence of a strong social valuation of negative reciprocity was confirmed by the anthropologic researcher of the team. She observed negative reciprocity in the social interactions during her nine months stay in Sediba. One villager even stated that “*others would kill me if I double my herd size*”.

Additionally, the 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. The same holds for actions of other HH in a common-pool setting.

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

Survey data from the village of Sediba was used to specify the number, types, state variables and parameters of HH agents in the model (Journal Appendix B).

Individual decision making

This section distinguishes among four decision-making models. The first two relate to concepts behind modelling HH expenditures and entries. The second set depicts the economically and socially driven decisions 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 that do not own livestock decide whether to buy a cow to enter livestock production. However, HH agents need to have sufficient savings to do so. HH expenditures are determined by a linear regression on the HH size and income, which does 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.

The decision to sell livestock is determined by individual goals, which may change depending on aggregated decision-making on the community level. Thus, decision-making with respect to sales of livestock takes place on two levels. Livestock producers decide if, how much and what type of livestock to sell. Survey data revealed that 83% of all sales are leaving the village, as livestock is mostly sold to butchers or speculators that regularly visit the villages (Journal Appendix C). Livestock sold within the village is often slaughtered by the buyers for ritual use during funerals. Only a minority of cattle is sold to HH who want to enter livestock production, and HH do not buy livestock to increase their herds[11]. Thus, sold livestock reduces grazing pressure and does not simply change ownership within the village. Producers decide which selling rule to use

[11] Less than 2% of the total herd size was bought by HH during the last 12 months before the interview (Appendix C)

according to the economic success during past production cycles. The probability of keeping a distinct selling heuristic increases with the economic success associated with the heuristic. A lower profit of the past production cycle raises the likelihood of experimenting with the selling rule for the next cycle. The objective is to maximize economic success, which is performed 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 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.

Additional sales are triggered if producers obey a norm and have a herd size above a threshold prescribed by the norm. The implementation of cooperative behaviour in the context of a norm is inspired by the model of Ebenhöh and Pahl-Wostl (2008).

In their model of bounded rational agents engaging in collective action, the authors differentiate among three types of agent behaviour: (1) cooperative, (2) defective and (3) wavering between the first two. They focus on the latter, which stresses that social embededdness matters as outlined in Ostrom's theory of collective action (Ostrom 2003). Ostrom states that "individuals enter situations with an initial probability of using reciprocity based on their own prior training and experiences" (Ostrom 2003, p.49). *Reciprocity* means to "[...] react to the positive actions of others with positive responses and to the negative actions of others with negative responses" (Ostrom 2003, p.42). *Reciprocity* is strongly path-dependent on the trust that others will be reciprocators. Ebenhöh and Pahl-Wostl enrich this conceptual model by additional attributes, such as *cooperativeness*. The degree of *cooperativeness* among individuals differs according to their own preferences and is expressed by public commitment to an agreement or by signalling the assurance to be trustworthy in terms of obeying institutional arrangements (Ostrom 2003, p.45). However, *cooperativeness* can also change if agents lack "the assurance from others that their trust will be returned" (Ostrom

2003, p.45). In short, *cooperativeness* is degraded if others are violating institutional prescriptions in form of rules, norms or shared strategies. Ebenhöh and Pahl-Wostl model this behaviour with agent attributes and heuristics. Agents have, in addition to the named attributes, values for *expected reciprocity* and *expected cooperativeness* that correspond to the trust of individuals in that others will be reciprocators and cooperators, respectively. Trust in others then feeds back into its own attributes, which determine *conditional cooperativeness*. Agents with a high *conditional cooperativeness*, based on *reciprocity* and *cooperativeness*, have a higher probability to be drawn into mutual cooperation which in turn increases the reputation of the group (trust).

In SES, human actors rely on norms being "highly context specific social institutions" (McAllister et al. 2011). In the SES model presented here, as opposed to Ebenhöh and Pahl-Wostl's model (2008), agents cooperate with respect to a context-specific norm and are only drawn into mutual cooperation if the situation is vivid and promising. According to Ostrom (2005), vividness relates to the acuteness of a situation. That is, a high vividness increases the likelihood for action because "paying attention is costly" (Ostrom 2005, p.107). We further assume that the situation must also be promising in the sense that agents believe to be *able* to draw others into mutual cooperation. Both aspects relate directly to observable outcomes of resource extraction, which has been shown to influence cooperation (Tavoni et al. 2012). That is, agents consider the inequality of herd sizes and the severity of norm violations in their decision-making process. The latter is measured as the number of livestock in large herds. Both livestock-related variables are strongly impacted by forage availability on the common rangeland. Thus, the collective action modelled here accounts for SES feedbacks.

The incentives for agents to cooperate in the normative process are fourfold. First, agents are inequality averse, which increases the probability for those agents to put up social pressure to reduce inequality. Second, agents want to avoid normative sanctioning. Third, once they have publically committed to obey a norm, agents try to deter others from violating the norm, as they feel that this is just. Fourth, a high degree of norm violations decreases social pressure, as agents have lower expectations that violators will obey the norm. Agents are heterogeneous in their values for the parameter of initial cooperativeness. Details on the implementation of this process can be found in the full ODD+D protocol in the journal appendix (doi:10.1016/j.envsoft.2014.12.008).

This set-up represents a threshold model similar to innovation-diffusion models (Deffuant et al. 2005; Schreinemachers et al. 2009; Berger 2001; Abrahamson and Rosenkopf 1997), wherein early adopters trigger cascading effects of innovation-diffusion in the population. The process of social diffusion is influenced by endogenously evolving norm violations and inequality. There is a temporal lag of information diffusion. That is, agents consider the relevant decision variables of the past month in their current decision. Uncertainty and spatial aspects are not considered in this decision model.

Learning

The selling decision on an individual level 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[12]. 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 because they use the non-optimizing strategy of reinforcement learning (Gigerenzer and Selten 2002). Agents do not compute an optimal strategy beforehand, rather they choose what worked best in the past. With Wilson et al.'s words, agents are "assumed to be boundedly rational, profit maximisers" (Wilson et al. 2007, p. 15213).

Individual sensing

HH agents know the share of cooperating HH agents, how unequal herd sizes are and how severe norm violations are.

[12] Ranges for values are derived from survey data (Appendix C)

Individual prediction

HH agents predict their HH expenditures and their probability of entering into livestock husbandry. They furthermore implicitly predict the chances of drawing others into mutual cooperation based on the severity of norm violations.

Interaction

Interactions of livestock agents are indirect via the rangeland. Cattle compete for forage. Similarly, livestock producing HH agents compete with each other indirectly via resource appropriation of their herds. Moreover, they interact directly by normative sanctioning. HH agents not owning livestock are not interacting.

Collectives

There are no agent collectives in the model.

Heterogenity

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

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 the chosen selling heuristics.

Observation

The percentages of co-operators in the normative process and livestock mortality are collected on a monthly and on a yearly basis, respectively. Those variables were used to identify system collapse and the emergence of cooperation. Emergence of cooperation, measured as an incident of one-hundred percent of norm followers, was also used as a binary measurement variable for the sensitivity analysis investigating the effect of empirical heterogeneity on model outcomes. Other variables collected for visual analysis are the gini coefficient

(Pyatt 1976) of herd sizes, stocking density (ha/LSU), basal area (%) and green standing crop (kg/ha).

3.3.3 *Details*

The details of the model and its submodels can be found in the full ODD+D in the journal appendix (doi:10.1016/j.envsoft.2014.12.008). The source code for the model is published on openabm.org https://www.openabm.org/model/4293/version/1/view.

3.4 Results

In the following section, the results from a two-stage model analysis are presented. First, a typical run in the baseline configuration is described. This is followed by a descriptive analysis with respect to the frequencies of cooperation and SES collapse. Thereafter, two runs are presented to exemplify relationships between social and ecological variables in the cases of collapse and cooperation. In a second step, a sensitivity analysis based on design principles of experiments (DOE) is presented (Sanchez and Lucas 2002). The latter investigates the impact of empirical complexity in parameterization on model outcomes.

3.4.1 *Baseline configuration*

The baseline configuration for a typical run is specified according to individual HH data. That is, the heterogeneity of HH, reflected in the data, is directly assigned to agent attributes and rules. All livestock-producing agents are using heterogeneous and adaptive heuristics as they implement the genetic algorithm for the selling decision. Every run encompasses 100 years. The run starts with 80 livestock producing HH and 83 HH not owning livestock. There is no in- or outmigration. HH dynamics are not considered to avoid increasing the model complexity. Thus, the demographics remain constant. Prices, off-farm-incomes and HH structures are fixed. In total, 443 cattle are initially grazing on the rangeland. A warm-up period of 59 months is used for initializing the rangeland model. During warm-up, no grazing takes place as the rangeland model must first establish root biomass. The agent based model is started after this initial phase.

Cooperation and Collapse in the baseline configuration

To answer the first research question, which examines the effect of the norm on SES dynamics, we defined two basic configurations for measurement; *cooperation* and *collapse*.

For a single run, *cooperation* has emerged if there was an incidence during the run with 100% norm followers. We use the term *cooperation (italic)* to describe the public commitment of all agents to follow the norm and to cooperate in sanctioning norm violators. The simulation results show that the measure of an incidence of 100% norm followers captures 99.5% of all runs where the threshold of 61% norm followers was crossed in an earlier time step. A share of norm followers of above 81% leads to *cooperation* in any run.

Similarly, a *collapse* occurred if a total cattle population crash due an ecological crisis (100% mortality) was detected during the run. *Collapse* describes a state where the link between the social and the ecological system is lost. The defining link between the systems under investigation is the utilization of ecosystem services mediated via livestock production. The results show that any collapse in the simulation is path-dependent because it only emerges in later time steps of any run. The minimum year in which collapse occurred was year 52 (out of 1000 runs). Here, herd sizes slowly build up to an unsustainable critical threshold relative to the ecological condition.

Both *cooperation* and *collapse* are uncertain due to stochasticity in selling rules, mortality and reproduction. Small differences in earlier time steps can propagate through the system and lead to systemic change with respect to the final system configuration. To filter stochastic effects, a batch run encompassing 1000 runs was conducted and analysed. Descriptive statistics on the frequencies of four possible system configurations are presented in table 3.1. The four system configurations result from the combinations of cases of *collapse* and *cooperation* and their opposite states. That is, each run can be classified as *cooperation*, *defection*, *collapse* and *stability*.

Table 3.1 Frequency table of system configurations - 1000 runs

System configurations	Cooperation	Defection	∑
Collapse	1%	42%	43%
Stability	38%	19%	57%
∑	39%	61%	100%

Table 3.1 shows that *cooperation* emerges in 39% of the runs. *Collapse* occurred in 43% of the runs. However, a *collapse* only occurred in 1% of the runs where *cooperation* had emerged. In contrast, a *collapse* occurred most frequently (42%) in runs where *cooperation* had not emerged. Moreover, most cases of stable system configurations (38%), as the absence of system collapse, emerged in cases where agents fully cooperated.

To summarise, cooperation has a stabilizing effect on SES dynamics by significantly reducing the threat of population crashes (RQ1). However, two facts are notable. First, defection does not necessarily lead to a collapse. Second, cooperation emerges in less than 50% of the cases. Both facts indicate a sensitivity of the model towards differences in how variables evolve during the runs.

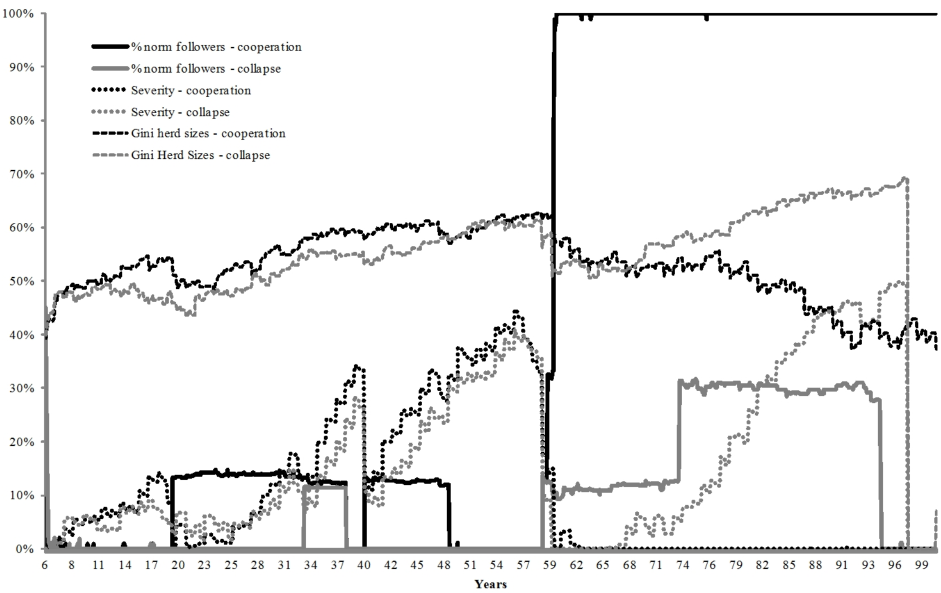
To inspect the conditions under which *cooperation* emerges (RQ2), two example runs are presented in the next sub-section

Dynamic patterns of cooperation and collapse

Figures 3.2 to 3.6 compare the social and ecological variables of a run where cooperation (black lines) has emerged and a run where a collapse (grey lines) occurred. Several typical patterns are described below.

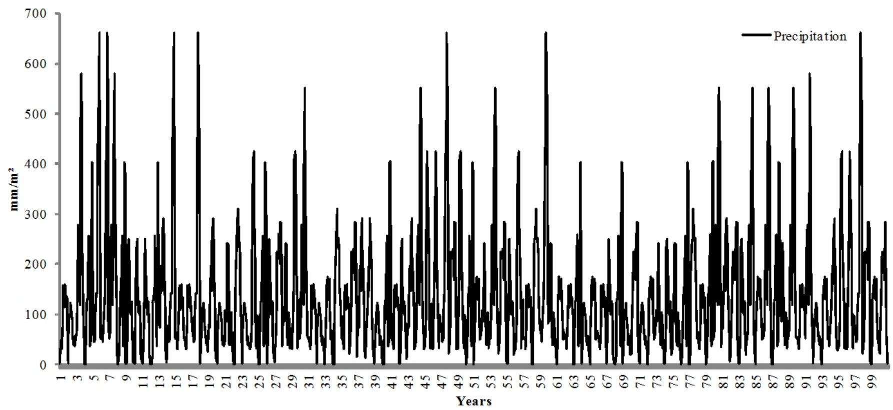
The system starts with moderate inequality (Gini herd sizes), low severity and no norm followers. Agents with the highest values of initial cooperativeness build up social pressure as inequality is rising. However, the severity of norm violations is increasing even faster, which suppresses other agents' participation in the collective action. The severity increases to a point (year 49), at which time all agents refrain from cooperation (Figure 3.2).

Figure 3.2 Cooperation, Severity and Inequality - Cooperation vs. Collapse



A rainy period (Figure 3.3) from year 45 till year 57 increases forage production and allows herds to grow substantially (Figure 3.6). However, total forage intake results in a steady decrease of basal area (Figure 3.4). The basal area describes the percentage of soil covered by plant surface, and it is a common indicator for rangeland degradation in South Africa (Snyman 2005).

Figure 3.3 Rainfall



Around year 57, the ecological crisis actualizes (Figures 3.4, 3.5 and 3.6) in the combination of low rangeland quality, low forage productivity and high grazing pressure in terms of livestock units (LSU) per ha.

Figure 3.4 Basal area - Cooperation vs. Collapse

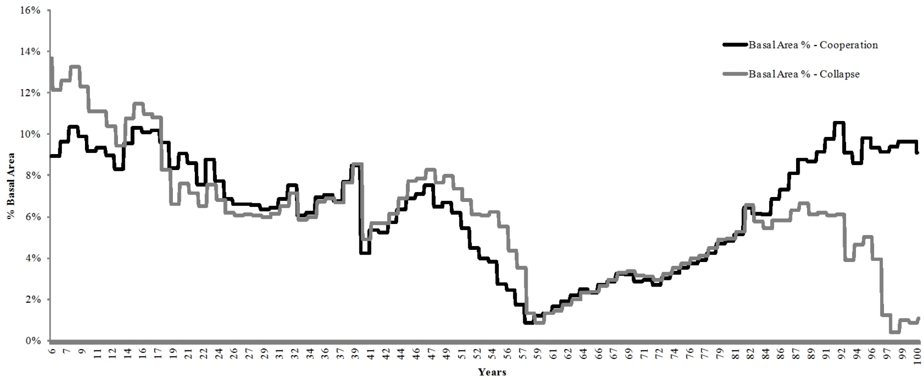
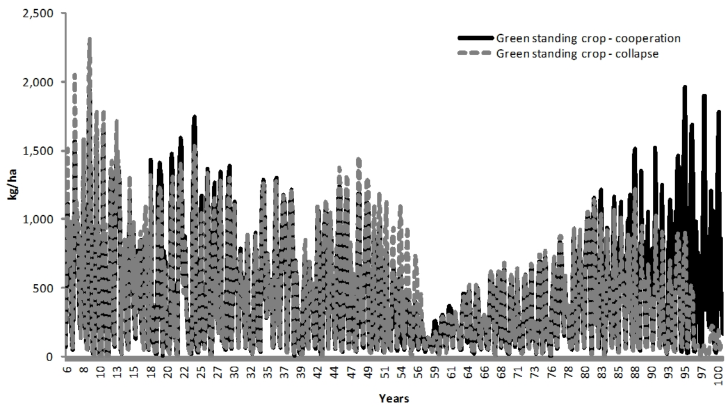
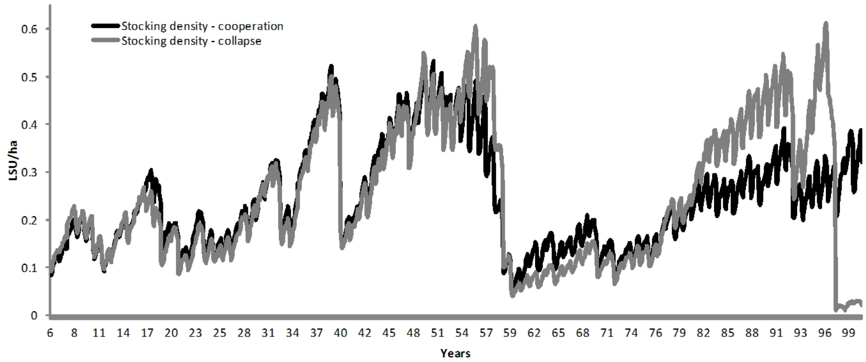


Figure 3.5 Green standing crop - Cooperation vs. Collapse



During this crisis, a high proportion of animals die off because forage production is not sufficient to feed the large herd (Figure 3.6).

Figure 3.6 Stocking densities LSU/ha - Cooperation vs. Collapse



The SES crisis is the critical phase for the emergence of *cooperation*. The death of substantial parts of the herd reduces both the inequality and the severity of norm violations. In cases where norm violations are not severe but inequality remains relatively high, the norm can fully evolve. Once established, the process is self-enforcing because normative sanctioning is at a maximum. There are still 100% norm followers at the end of the simulation when inequality is reduced back to its initial level (Figure 3.2). Additional sales, triggered by the action prescribed by the norm, result in slower rates of herd growths after the crises (Figure 3.6). The rangeland can recover (Figure 3.4) and provides sufficient forage (Figure 3.5) for herd survival.

In the absence of *cooperation*, the resource degrades to a point where forage production is insufficient (Figures 3.4 and 3.5) for herd survival and a SES *collapse* occurs (Figure 3.6). The collective action driven by the norm circumvented a second and more extreme SES crisis.

Figures 3.2-3.6 were computed from example runs. An investigation of the full run set revealed that *cooperation* is indeed an alternative stable state. In 61% of all runs, a very high share agents followed the norm until the end of the simulation. On average, norm-following remained stable for 86% of the remaining time until the end of the simulation, with an average duration of 334 months. During this time, the average percentage of norm followers was 96% and never below 61%. *Cooperation* never emerged if a critical threshold of 51% norm followers was not crossed. The emergence of cooperation is always erratic and occurs within a few years.

3.4.1 *DOE and sensitivity analysis*

In the preceding sub-sections, *cooperation* was identified as having a stabilizing effect on SES dynamics over the investigated time span. However, the emergence of *cooperation* is sensitive to path-dependent developments. Next, we investigate the model's sensitivity towards assumptions made with respect to agent parameterization from empirical data. In this subsection, we present a sensitivity analysis intended to investigate the impact of model assumptions on the likelihood of *cooperation* emerging, with a special focus on complexity and the necessary level of detail derived from empirical data. We would like to know if the empirically derived heterogeneity of agent attributes adds an explanatory value to model outcomes or if this complexity can be reduced without losing information.

A design of experiments (DOE) approach was conducted to capture the reaction surface of the model. There are several experimental designs established in the literature. Essentially, a full factorial design allows for a full exploration of the reaction surface, whereas all other experiments are trade-offs between the correlation between parameter vectors and computational effort (Kleijnen 2005, Sanchez and Lucas 2002). Here, a full factorial design was used because it was computationally feasible.

Explanatory variables in the analysis are the HH structure (*hhStruct*), initial cooperativeness (*iniCooperativeness*) and initial distribution of herd sizes (*iniHerds*). The HH structure encompasses the income, HH size and age of HH head. We apply three levels of empirical heterogeneity on the named variables to explain the likelihood of *cooperation*. As defined before, *cooperation* emerged if there was an incidence during the run with 100% norm followers. That is, *cooperation* is a binary variable.

Empirical heterogeneity in agent attributes is defined as one of three abstraction levels (variable level abbreviations are in brackets):

- Agents attributes exactly match with individual HH data (*full*)
- Agent attributes are set to the averages derived from HH data (*average*)
- Agent attributes are random within ranges informed by HH data (*random*)

The random factor level draws agent attributes from a normal distribution with a mean and standard deviation derived from survey data. Normal distributions are truncated according to the empirical minimum and maximum values. The average factor level uses the same means as used in the random level. All parameter values for the average and the random levels can be found in Appendix D (journal appendix).

The reaction surface generated by the full factorial design is used to specify a meta-model. Meta-modelling allows increased transparency in communicating model behaviour and is used to identify directions of influence (Kleijnen 2005, p.265). The latter refers to the sign of coefficients, which indicate the positive or negative influences of the explanatory variables on the response. As we are interested in the likelihood of *cooperation*, a probit regression model was used to measure *cooperation*. The analysis focuses on the statistical significance, general direction of influence and relative importance of variables. Those attributes are measured by the variable's p-values, signs of coefficients and marginal effects, respectively. In the model specification, dummy variables were used for the multinomial explanatory variables of HH structure and the initial distribution of herd sizes. *Random* was used as the reference level to assess whether additional information from the survey has an influence. The *average* level for initial cooperativeness resulted in a perfect prediction error in the probit estimation. That is, the same average value of initial cooperativeness for all HH agents results in 0% cooperation. This is plausible insofar as the structure of the threshold model relies on bandwagon effects based on agent heterogeneity, similar to Berger (2001). To avoid an omitted variables bias, experiments were conducted again without the *average* level for initial cooperativeness.

The coefficient table (Table 3.2) shows that all variables except the dummy variable of *iniHerds_average* are significant at a 0.05 level. Thus, there is no significant difference in the likelihood of *cooperation* with respect to a parameterisation of the initial herd size between random and average values. However, assuming full heterogeneity between herds of HH results in a significant and positive effect. The dummy variables assessing assumptions on the heterogeneity of HH structure are significantly different from each other. However, the average values of the HH structure decreases, and the full empirical heterogeneity of the HH attributes increases the probability for *cooperation*.

Finally, a random distribution of values of initial cooperativeness results in a higher probability for *cooperation* compared with a model specified according to data of individual HH.

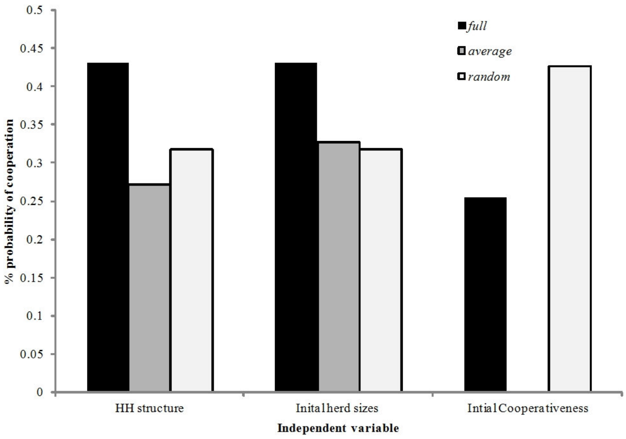
Table 3.2 Probit regression on the likelihood of Cooperation - coefficient table

Variable	Coefficient	p-value
const	-0.502851	.0000
iniHerds_average	0.043175	.4647
iniHerds_full	0.276913	.0000
hhStruct_average	-0.230648	.0001
hhStruct_full	0.505937	.0000
iniCooperativeness	-0.795022	.0000
F-test	468.2279	.0000
% correct prediction model		76.00
n		3600

In summary, the full utilization of individual HH data has a significant effect for all explanatory variables. However, the direction of influence varies along the variables.

Figure 3.7 shows the relative impact of the variables and compares their importance for the emergence of *cooperation*. Effects are calculated by computing the change in the average probability of *cooperation* if the value of one nominal variable is changed to another level (*ceteris paribus*). That is, the average probability of *cooperation* is computed over the complete reaction surface by altering the independent variable of interest.

Figure 3.7 Effects of different assumptions about empirical heterogeneity in agent attributes on the average probability of Cooperation



Full empirical heterogeneity of HH structures and initial herd sizes influence the probability of cooperation more than random or average parameter values for these variables.

The most important effect is attributed to alterations of a variable directly influencing the conditional cooperativeness of individuals. Here, using an average value for initial cooperativeness perfectly prevents cooperation. Using normally distributed random values for the variable results in a probability of cooperation that is 17.1 percent points higher compared to full empirical heterogeneity. In contrast, full heterogeneity in the HH structure results in a probability of cooperation that is 15.9 percent points higher than runs with average values for HH structure variables. The difference between the three levels of heterogeneity is lowest with respect to the initial herd size. Using random distributions for all explanatory variables smoothes out differences in the effect on cooperation. With respect to the chance for cooperation, the outcome on a system level resembles the one emerging under full heterogeneity. That is, an artificial population based on random distributions is predicted to result in a probability of cooperation in 38% of the runs.

3.5 **Discussion**

We conclude that cooperation in the process of norm compliance and sanctioning decreases the probability of SES collapse, even in the case of a “resource-blind” norm. Here, an unintended form of resource governance was modelled. The results support the findings of Thebaud and Locatelli's model (2001), which found that peer-pressure, or normative sanctioning, is an important aspect in the emergence of resource sharing conventions. This is also in line with Tavoni et al., who found that "when reputational considerations matter and a sufficient level of social stigma affects the violators of a norm, sustainable outcomes are achieved" (2012, p. 152)

Moreover, our results emphasise the importance of ecological rationality in norm-guided behaviour (Gigerenzer and Selten 2002). That is, norms are reducing computation (Epstein 2006). This also holds for the case presented here. That is, it is cheap and effective to follow the simple heuristics prescribed by a social norm leading to informal self-governance, as it does not involve ecosystem monitoring or the additional institutional costs associated with formal rules. In addition, self-governance itself is distinct from current top-down interventions in South Africa's commons, which have questionable benefits (Vetter 2013). This is in line with Schlüter and Pahl-Wostl, who state that "noncompliance and free riding are fundamental problems in common-pool resource management," and they are therefore best tackled by self-governance rather than by centralised regimes (2007, p.19).

Furthermore, our results suggest that some social processes in SES can be characterized as alternative stable states. The existence of the latter have been clearly identified for ecological states by, e.g., Janssen et al. (2004), in some biomes of rangeland systems. It remains, however, an open question whether all rangeland ecosystems systems exhibit alternative stable states (Vetter 2009). Our findings support earlier ones by Wilson et al. insofar that the collective action of a "continuing mutual restraint" is needed for conservation (2007, p. 15217) and that this continuity constitutes a social alternative stable state in the case presented here. The state of cooperation reduces noncompliance, free riding and the risk of ecological collapse.

Cooperation emerges in times of ecological crisis with a small window of opportunity. Systemic changes leading to collapse or cooperation are rooted in past disturbances. The latter represent opportunities for the social system to adapt and to reorganise. During the crisis, social interaction gains momentum and can stabilize in a self-enforcing manner. Or, as McAllister et al. have termed it: “what is more exciting is the evidence that variability and uncertainty can induce greater trust and reciprocity” (McAllister et al. 2011, p.7) and “trust is critical in that it is required to give some degree of confidence that cooperative behaviour will be reciprocated” (McAllister et al. 2011, p.2). This also in line with Tavoni et al. (2012), who found that ecological variability increases cooperation in their common-pool resource model.

Defection, on the other hand, increases the likelihood of ecosystem collapse. The investigation of system collapse in our model underpins Müller et al.’s (2007) assertion that inappropriate strategies in semi-arid rangeland systems unveil their negative consequences only after decades. Collapse, as the loss of the socio-ecological link constituted by the utilization of ecosystem services, occurred in the model only after decades. Thus, the path-dependence of mismanagement is evident in the SES, which stresses the usefulness of SES models per se.

The results of this analysis contribute to the emergent field of empirical agent-based modelling (Smajgl and Barreteau 2014; Janssen and Ostrom 2006). Smajgl and Barreteau (2014) understand parameterization not as a mere pinning down of numbers but rather as a process conveying information about the structure of a population needed for a potential up scaling towards an artificial society. A sensitivity analysis of the model examined the influence of heterogeneity in agent attributes on the emergence of cooperation, which constitutes an abstraction of parameterisation to a level above single agent attributes.

In our model, heterogeneity of agent attributes is a necessity for the emergence of cooperation because a uniform parameterization of agents with average values prohibits the cascading effects of social interaction. Using random distributions instead of individual HH survey data for agent parameterisation has significant effects on the probability of cooperation. These effects differ in their statistical signature, as some decrease and one increases cooperation. Their combined effect, however, is predicted to lead to cooperation with a percentage probability similar near to the one realised by parameterization with individual HH. Here, the difference was one percent. Thus, caution is advised when observing seemingly robust results on the system level for one state variable of interest, as the effect of individual variables might change. The latter might impact outcome variables of the model (e.g. profits), which were not investigated because such an endeavour was beyond the scope of this paper. Generally, the results from the analysis of agent heterogeneity support those of Castillo and Saysel (2005). They found that initial values of trust and heterogeneity in agent attributes have path-dependent effects in their model of collective action in a common pool resource setting.

Quantitative model validation is still difficult to achieve for any model without extensive time series data for matching model outcomes with historic patterns or resources to observe future behaviour. Unfortunately, the majority of data for the system was lost during the transition from Apartheid to democracy. Future research might be needed to follow up the developments of the SES, although it remains “a fundamental problem in our investigations [...] how to derive observations of a social system over time” as it is extremely difficult to obtain funding for repeated visits of communities (Janssen and Ostrom 2006, p. 5). For now, the empirical validation of model results is limiting.

However, our primary goal was to contribute to the first steps in integrating theoretical models of institutional evolution in empirical agent-based models to foster the development of an appropriate methodology rather than to predict outcomes for a real world case.

Modelling endogenous institutional processes of systems that couple humans with nature is still in its infancy, and there are no established methods for implementation. Thus, our approach has to be seen as an experimental one. It aims to generate hypotheses about how social interactions are related with ecological dynamics. At the same time, this paper attempts to emphasise the importance of local specificity embedded in empirical data. Generally, model results underpin the necessity of considering the socio-economic, ecological and institutional factors involved in the complexity of the rangeland commons if the ultimate goal is to arrive at management guidance (Moyo et al. 2008)

A major shortcoming of our model is its inability to model the emergence of novelty in constitutional institution building. That is, the normative behaviour modelled here builds on what was in place and cannot account for what might develop. To anticipate how bounded rational decision makers would create novelty in the face of exogenous disturbances is a limitation of the presented model here and, at least in our view, constitutes a major research frontier for SES modelling. In this field, companion modelling is a promising pathway (Étienne

2014). Companion modelling allows for the elucidation of adaptive responses in role-play sessions where stakeholders are actively engaged in the modelling process (Bousquet et al. 2007; Barreteau et al. 2003).

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Chapter 4 Multi-scale resilience in a communal livestock production SES[13]

Abstract: We present results from an agent-based model of a communal livestock production system. The underlying case is the village community of Sediba in rural Thaba Nchu, South Africa. Villagers use a commonly managed rangeland for beef cattle production. The objective is to measure resilience at different scales of the socio-ecological system (SES). That is, this paper investigates complementary and contradictory dynamics of household, community, ecological and socio-ecological resilience. A baseline scenario reveals that the SES remains in a stable attractor in terms of socio-ecological resilience. Household resilience, however, degrades in a process of structural change. Three scenarios are analyzed in order to investigate system reactions to disturbances: (1) A drought scenario shows an ecosystem able to recover and returning to baseline patterns but structural change at household level accelerated; (2) An increase in the number of defecting agents increases the likelihood for SES collapse and systemic change by eroding social embededdness within the community; (3) Anti-poverty policies as currently discussed in South Africa demonstrate that the SES is able to cope with

[13] This part is the submission to an international multi-disciplinary journal as Rasch, S., Heckelei, T., Oomen R. and Naumann, C.: Multi-scale resilience of a socio-ecological system of communal livestock production in South Africa

an increased number of resource appropriators by an endogenous redistribution of assets from wealthier to poorer households.

Keywords: Socio-ecological system, Resilience, Complex adaptive systems, Agent based models, rangeland systems, South Africa

JEL classification: Z13, C63, C62, Q2

4.1 Introduction

Resilience theory is currently replacing the notion of optimality in management strategies and the focus on single equilibria ignoring relevant non-linear dynamics in certain contexts (Lebel et al. 2006). This is especially evident in the analysis of socio-ecological systems (SES). A widespread agreement recently developed with respect to the nature of SES as complex systems (Berkes et al. 2003). In order to better understand the complexity of these human-nature coupled systems generating resilience on system level, SES modelling emerged as new field which contrasts disciplinary approaches treating either the social or the ecological dimension as exogenous factors. SES models have been applied to fisheries, wildlife and rangeland systems and are borrowing from complex system theory and resilience thinking (e.g. Barreteau et al. 2004; Dougill et al. 2010; Little et al. 2004; Milner-Gulland et al. 2006; Schlüter and Pahl-Wostl 2007; Schlüter et al. 2012; Winkler 2011). However, the field is still in its infancy when the task is to represent complex human decision making (Schlüter et al. 2012, p.248).

A major research task in SES modelling is therefore to understand "[...] the macro-scale effects of micro-scale drivers of human behaviour" (Schlüter et al. 2012, p.240). The interplay between individual decision making and normative constraints is an important research topic (Schlüter et al. 2012, p.249), but institutional dynamics are rarely endogenously modelled (McAllister et al. 2006, Smajgl et al. 2010, p.98). Schlüter et al. also remind us that models attempting to represent these aspects of human behaviour should be structurally realistic going beyond generic mathematical models (2013, pp.7-9). Structural realism can be achieved with bottom-up modelling approaches being able to consider bounded rationality.

Individual decision making and normative behaviour at group level strongly depend on the context of the SES (McAllister et al. 2011). However, existing SES models are often hypothetical and lack the empirical ground to deliver future trajectories of system paths for “real-world problems” (Schlüter et al. 2012, p.256). Baumgärtner et al. stress that the theoretical perspective underlying our models must be unified with, and based on the empirical reality of case studies (2008). Here, empirical agent based models are well suited to integrate case study data (Janssen and Ostrom 2006).

SES models with a resilience focus face the additional difficulty to arrive at quantifiable measures for this concept. Although conceptual models of coupled human-ecological systems are refined constantly within the domain of resilience theory, they fail to deliver quantifiable measures for real world cases (Walker et al. 2002). To measure resilience in field studies is very problematic, as it requires observing large time scales or external intervention as “the only sure way to detect a threshold in a complex system is to cross it” and research has “little experience with estimating resilience of SES” (Carpenter et al. 2005, p.941). In principle, SES models offer a pathway to explore the configuration space of SES by elucidating system inherent thresholds in silicio. However, measures of resilience in models incorporating more complex decision making are taken on a single scale and are snapshots in time (e.g. in Schlüter and Pahl-Wostl 2007; Schlüter et al. 2009; Carpenter et al. 2004). The acknowledgement of the complex nature of SES stipulates to take multiple scales of resilience into account (Miller et al. 2010).

In this paper we make an attempt to tackle the described issues in SES resilience modelling by presenting a communal livestock production SES model which offers quantifiable measures of multi-scale resilience under the consideration of heterogeneous decision making and institutional dynamics. The model design was based on empirical data from the case study in order to account for the socio-ecological context and constitutes an alteration of the model in Rasch et al. (2014). The purpose of the model is to answer three research questions relevant for the underlying case: What are the effects of

1. a drought shock,
2. a fundamental change in livestock ownership and,

3. of the introduction of a basic income grant

on the resilience at multiple scales of the system? In the next section, we outline the theoretical framework for measuring multi-scale resilience followed by a summary of case study results in the third section. The fourth section provides an outline of the model structure and results follow in the fifth. Section six presents a discussion on results and SES modelling for resilience research.

4.2 Theoretical framework for measuring multi-scale resilience

Resilience is an important measure in terms of the health of the SES (Hawes and Reed 2006, p.644). However, a multitude of resilience definitions exists in the literature. These range from highly abstract concepts on system level to social- or ecosystem specific indicators (e.g. Seixas and Berkes 2003; Hawes and Reed 2006, p.644; Holling 2001, p.400; Schlüter and Pahl-Wostl 2007, p.4). The growth of theoretical approaches to explain the resilience increases fuzziness (Pendall et al. 2010, p.72) and contradictions while not delivering a common framework to make it measurable. This shortcoming may originate from the fact that "important aspects of resilience might not be directly observable" (Carpenter et al. 2005, p.941). Carpenter et al. thus advice us to infer resilience indirectly which led them to use the term ‘surrogates’ instead of indicators for resilience (2005).

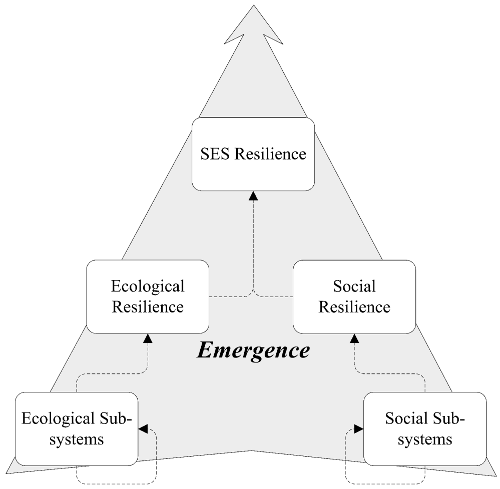
According to Miller et al., resilience measures should capture dynamic processes instead of being static indicators (2010). They are also in line with Carpenter et al. who stress that resilience indicators should “address multiple aspects of resilience” (2005, p.942) as resilience is "constructed simultaneously on more than one scale" (Miller et al. 2010).

In addition of being multi-scale, dynamic and measurable by means of surrogates, SES resilience is stated to be an emergent phenomenon:

> “Resilience may be considered an emergent property of a system, one that cannot be predicted or understood by simply examining the system’s parts.” (Berkes et al. 2003, p.5)

As we are concerned with resilience in SES, scales of emergence are naturally resembled by the ecological and social dimension generating ecological and social resilience from which SES resilience emerges (Figure 4.1). Moreover, the ecological and social dimension might be further detangled such that sub-dimensional scales of resilience are evident.

Figure 4.1 Emerging SES resilience scales



If we adopt Walker et al.'s definition of SES resilience as the

> "[...] capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore its identity" (2006),

we must understand system identity on SES level as exactly that: the identity of emergent phenomena and stylized facts of the coupled system measured by means of dynamic resilience surrogates emerging over different SES scales. The change in resilience can then be "visualized in different scenarios in an agent-based model" (Miller et al. 2010).

Following this line of argumentation, we present a synthesis of resilience surrogates on different SES scales. We exemplify this by applying those to a community based livestock production system in South Africa appropriating from a common rangeland. Here, we differentiate between ecological, household, social and SES resilience and seek to choose simple surrogates with the potential to be observable in field studies.

4.2.1 *Ecosystem resilience*

Some authors understand ecological resilience as the capacity of ecosystems to absorb disturbances without undergoing fundamental change (Drever et al. 2006). Others understand it as the rate of recovery from a disturbance (Adger 2000). An explanation for these seemingly controversial concepts might be found in the diversity of ecosystems themselves. The classical example of eutrophication of lakes is a good fit for the first definition of ecosystem resilience as aquatic systems can shift between clearly distinguishable states (Scheffer et al. 2001). The same, but in a less pronounced way, accounts for semi-arid rangelands which might shift from a grass dominated towards a shrub-dominated state (Sankaran et al. 2005). However, for highly resilient ecosystems like "sweet-" and "sour velds" in southern Africa we might go beyond the binary assessment of resilience (Harrison and Shackleton 1999, p.226) and assess the degree of resilience by measuring the time of recovery in such ecosystems characterized by reversible transitions.

Walker et al. suggested using the ecosystem state responsible for producing ecosystem services as a measure of ecological resilience in SES (2002). Ecosystem state is represented by variables associated with potential thresholds causing changes in dynamic patterns; being temporal or irreversible. Examples are the amount of P in lake sediments or woody vegetation biomass in rangelands. For our application, we propose to quantify ecosystem resilience by means of two variables serving as surrogates for (reversible) grassland degradation in highly resilient South African "sweetvelds" (Harrison and Shackleton 1999): grazing pressure and basal cover.

Grazing pressure on rangelands is a main driver for the functioning of grasslands and can cause degradation if it is above the system-specific grazing capacity for a sustained time span (Harrison and Shackleton 1999, p.233; Ebrahimi et al. 2010). Consequently, grazing pressure may serve as an indicator for upcoming degradation. We propose to complement this surrogate with the basal cover to identify if resource degradation is the cause of a decline in grazing pressure. Basal cover is the area covered by plants at ground level and is directly related to the amount of photosynthetic biomass responsible for future growth and recovery. Basal cover is commonly used as an indicator for rangeland qualities of semi-arid grassland ecosystems of South Africa (Wiegand et al. 2004, p.245; Snyman 2005). Those qualities resemble different grazing histories in terms of grazing pressure. Snyman found 8.3%, 6.4% and 2.9% basal cover for good, moderate and poor rangeland respectively (2005). Basal cover as a dynamic surrogate can be used to measure the change of rangeland condition and degradation over time.

4.2.2 *Household resilience*

In the social realm, individuals form the social construct of a household (HH). An example for the attempt to assess resilience on HH level can be found in the discourse on vulnerability which is closely related to resilience thinking. Berzborn et al. define resilience from the vulnerability perspective as:

> “[...] the ability to cope with hazards and includes strategies to reduce the vulnerability of households and individuals.” (2007, p.673)

Similar lines of reasoning can also be found in Kelly and Adger (2000) and Smit and Wandel (2006). According to Adger, the integration of vulnerability with resilience research offers a great potential for arriving at quantifiable measurements of SES dynamics (2006). In the context of communal livestock production systems, livestock husbandry constitutes a HH strategy which increases income diversity, buffer capacity and adaptability to unfavourable circumstances as it can be quickly liquidized (Giannecchini et al. 2007, p.37). In addition, livestock serves non-monetary purposes in the cultural context of communities (Shackleton et al. 2001).

We propose to measure the degree of HH resilience stemming from livestock husbandry on two levels of increasing rigor. These are (1) realization of access to the resource and (2) asset poverty. The realization of resource access is measured as the total number of HH owning livestock within a community and represents the potential to build HH resilience. Asset poverty measures the number of HH whose assets are not sufficient to sustain an income above the national poverty line for a defined time span by liquidizing their wealth. That is, HH are asset poor if the value of assets (livestock) is lower than a certain fraction of the annual national poverty line. The latter determines the time span in months in which poverty is avoided by selling assets (Brandolini et al. 2010, p.11). HH resilience must then be analysed in the light of resource degradation as HH resilience involves sustaining the resource base.

4.2.3 *Social resilience on the community scale*

Following Giannecchini et al., we differentiate resilience on the HH level from social resilience on the community level (2007, p.39). For Adger, social resilience is equivalent to the resilience of institutions and the degree of trust in communities (2000, p.351). We propose to investigate the emergent phenomena on the social level which are hypothesized to impact institutions and trust, i.e. a surrogate for social resilience.

According to Ostrom, institutional arrangements are derived in a so-called 'action arena' representing the social space of interaction (2005, p.13). Action arenas are by themselves influenced by the attributes of the community determining the costs for implementation and maintenance of rules. One such attribute is the "extent of inequality of basic assets [...]" (Ostrom 2005, p.27) which is an emergent property of HH interaction as they compete in terms of resource appropriation and regulate each other during social interactions. Costs are associated with the enforcement of rules if those have not been normatively internalized. Normative sanctioning is cheaper.

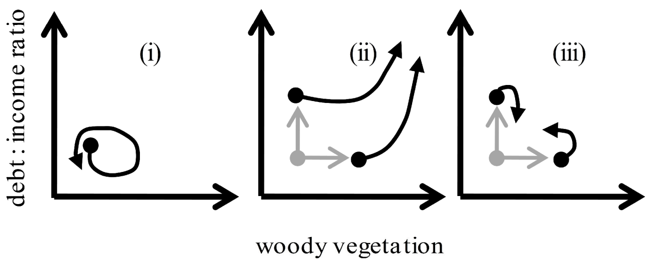
Bounded rational decision makers are highly inequality averse (Tyran and Sausgruber 2006). They punish those raising inequality (Fehr and Gachter 2002, p.139). Thus, persistent high inequality indicates a loss in the receptiveness of participants towards social pressure arising from normative sanctioning which makes formal sanctioning necessary to enforce rules. The latter might be too costly for implementation such that institutions collapse or do not emerge. As a surrogate for social resilience, we apply the Gini coefficient to the herd sizes of HH in our communal livestock production system as a measure for inequality.

4.2.4 *Socio-ecological resilience*

Referring to our example SES, the interaction between the social and the ecological dimension of rangelands "can introduce thresholds in addition to those introduced by ecological processes alone" (Gross et al. 2006, p.1265). We furthermore assume that this accounts for social processes as well. Irrespective of the specific SES, a variable being able to assess the resilience of a coupled system should be focused on the intertwined dynamics of emergent phenomena on the social and ecological scale. Walker et al. propose the mapping of ecological with social variables to tackle the operationalization of SES resilience (2002).

They focus on the dynamic patterns of such a combined measure. In their example of a rangeland SES, the authors use debt-income ratio and woody vegetation as social and ecological variables, respectively. The system can be characterized by the type of its dynamic patterns which is a function of the size of the basin of attraction as well as of the position of the basin in the configuration space. In their example (Figure 4.2), a system configuration characterized by low debt-income ratio and low degree of woody vegetation (i) is pushed into one exhibiting high values for both variables (ii). The disturbance can either stem from the ecological or social realm.

Figure 4.2 SES resilience measured as dynamic patterns of social and ecological surrogates



Source: adapted from Walker et al. (2002)

An increase of the size of the basin of attraction (iii) might prevent such shifts and means an increase in the resilience of the first (i) configuration. According to system theory, the first pattern (i) can be characterized as a limit cycle whereas the second (ii) represents a lock-in pattern. The increase of the basin of attraction (iii) prevents the transition from limit cycling to lock-in. The sustained identity of the dynamic pattern in the face of external disturbances constitutes SES resilience. Janssen et al. applied this approach for mapping dynamic resilience surrogates to ecological scales in their rangeland model (2001). However, we are not aware of any application of the concept to socio-ecological scales.

We use the ecological and social resilience surrogates of grazing pressure and inequality of herd sizes to map the dynamic patterns constituting SES resilience in order to identify systemic change due to external disturbances.

4.3 **Case study**

The following section delineates the SES case, presents field data collection methods and outlines the main findings. A condensed case study description can be found in Rasch et al. (2014).

4.3.1 *Delineation*

The empirical case informing our SES model is constituted by the village community of Sediba. Sediba is one out of 37 communities spread over the rural area of Thaba Nchu in South Africa. During Apartheid, the Thaba Nchu district was a target area for massive betterment and resettlement program. In 1972, the district became part of the Bophuthatswana Homeland, which was declared "independent" in 1977. The agricultural policy of Bophuthatswana aimed at the increase of the agricultural production to achieve self-sufficiency in food production and the improvement of the livelihoods of the people living in the rural areas. A parastatal organization called Agricultural Development Corporation of Bophuthatswana (Agricor) was established in 1978 in order to plan agricultural projects and rendering assistance to local farmers (Erasmus and Krige 1998; Drummond 1990). Agricor implemented projects in which participants hired the organization to conduct all the agricultural operations. At the seasons end the organization paid them after deducting the costs for the services. This procedure created a high dependency of the rural farmers from governmental aid. Agricor's support discontinued in the early 1990s (Murray 1996). Agricultural subsidization ended but the inflow of capital remained after the fall of Apartheid. That is, post-apartheid government substantially increased large-scale social assistance payment schemes which changed the determinants of livestock ownership structure and management.

4.3.2 *Data*

A living standard and measurement survey (Worldbank) was administered to 230 livestock producing HH in several villages of the rural Thaba Nchu region. The questionnaire entailed modules on HH structure, livestock production and management, income, assets, expenditures, credit, savings and institutional issues. Additionally, a survey encompassing 120 HH who are not engaged in livestock production contributed to the data base on social determinants of the SES. Moreover, nine months of anthropological field research assessed cultural aspects and ecosystem perception. The assessment of rangeland condition and productive capacity was conducted by rangeland and soil scientists by sampling vegetation (cover, biomass, species composition) and soil (composition, bulk density) along a degradation transect, and at random plots throughout the community's rangelands. Links to survey templates and data files can be found in the appendix (A).

4.3.3 *The Sediba SES*

Among the respondents of the HH survey was the full population (80) of livestock producers out of the total population of 160 HH residing in Sediba. A 2500 ha rangeland constitutes the natural resource base for the village community. The region is categorized as a semi-arid grassland biome (Rutherford and Westfall 1994). The mean precipitation is 537 mm per annum (Swemmer et al. 2007; Woyessa et al. 2006). Forage is the main ecosystem service of the rangeland.

Dominant species of the "Moist Cool Highveld Grassland Type" (Bredenkamp and van Rooyen 1996) are perennial C4 bunchgrasses (Themeda triandra, Eragrostis lehmanniana and Digitaria eriantha). The South African term "sweet veld" refers to the good palatability of the dominant species on those rangelands (Palmer and Ainslie 2005). Cattle are the predominant grazer. Villagers have common access to the rangeland such that the regime is characterized as a common-pool resource (CPR) (Ostrom 2005, p.24). Ownership in Sediba is fluctuating due to entries and exits of HH into and from livestock production. Herds belonging to HH are small with 25 cattle in the largest herd. Livestock is not viewed to be a main income source (Berzborn 2007, p.679). Instead, livestock ownership reduces HH vulnerability, is seen as a saving account or is slaughtered during funerals and other cultural events. Livestock production is a phenomenon of a middle class as the probability to own livestock is lower for poor and richer HH compared to those with a moderate income. Villagers either sell cattle according to simple rules of thumb or because of liquidity constraints. The latter does not occur if HH have income and monetary savings giving them a “superior coping capacity” (Barrett et al. 2001, p.326). Cash income also increases the probability to sustain herds in times of drought allowing to buy agricultural inputs (Berzborn 2007, p.683). From the standpoint of the poor we might say: “the poor are poor not only because they have few assets, but also because they are constrained in their ability to utilize effectively the assets they do have” (Carter and May 1999, p.15). Carter and May specifically mention transfer income in this context. In Sediba, off-farm income itself is dominated by state transfers. Figure 4.3 shows the sources of HH income along the income quintiles.

Figure 4.3 Income quintiles with sources for livestock producing HH in Sediba

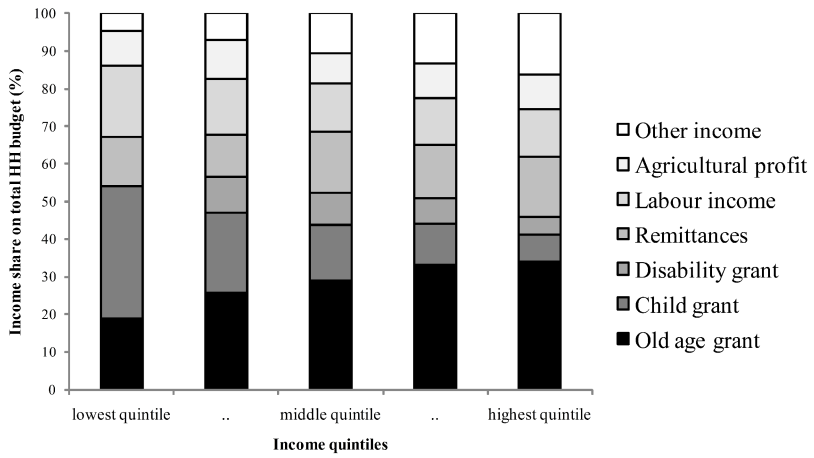


Figure 4.3 emphasizes the importance of state grants per se (old age, child, and disability grant) as well as the effect of the demographic structure of HH. That is, the most important state grants are coupled to age: child grant (<18 years) and old age grant (>60 years). Low-income HH receive a larger share of income from child grant (270 Rand per child) whereas old age grant (1140-1160 Rand per eligible person) constitutes the main income source for richer HH.

Next to off-farm-income-driven selling practices, HH pursue a minimal input strategy. New livestock is only bought for entering livestock production and inputs as supplementary fodder or veterinary items are only supplied with low intensity. Input intensity is low because of risk aversion towards potential losses of investments and is additionally constrained by HH income.

During interviews with stakeholders, it became evident that no formal rules of resource governance have emerged after the dismantling of Agricor as a top-down service provider. However, many respondents stated that a significant increase in their herd size would result in a form of normative sanctioning. That is, others would “become envious and make problems”. The simple norm is not driven by ecosystem constraints rather than by inequality aversion which is one of the main drivers of social interaction within the SES. However, several HH were identified who did not produce their own livestock but livestock owned by non-residents. Consequently, those HH manage such herds in accordance with the instructions of owners who are located outside the border of the SES.

To summarize, formal institutions collapsed in the post-apartheid era as they were externally imposed and no formal institutions of resource use emerged thereafter. The probability to be in or to enter into livestock production is greatest for middle income HH. Selling practices, input strategies and entries into livestock production are driven by HH liquidity with age coupled state grants as their main income source. Inequality of herd sizes is sanctioned in a normative manner. The prohibitive norm prescribes not to raise inequality in terms of herd size. However, the norm is only applicable to those HH who manage their own herds. The next section outlines the principle model structure which was designed in order to reflect the structurally relevant elements described above.

4.4 Model description

The SES model is constituted by the integration of a social agent based model (ABM) and an ecological rangeland model. The model is an adapted version of Rasch et al. (2014). The following section introduces an overview of the model but restricts sub-model descriptions to changes to the references model. A full ODD+D protocol, including details on sub-models, can be found in the online appendix (http://www.ilr.uni-bonn.de/agpo/publ/techpap/Techpap15-01.pdf).

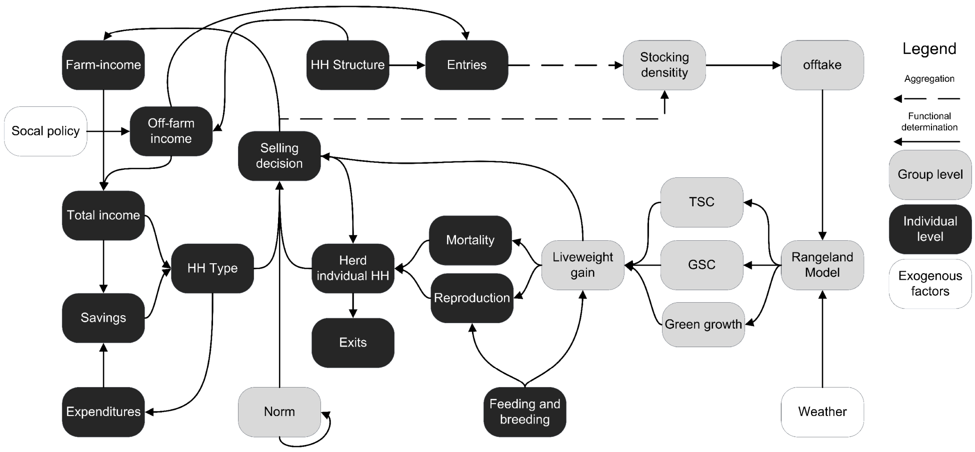
The motivation for changes to the model structure is the construction of HH and social resilience measures which commanded a more fine grained resolution with respect to agent heterogeneity. All changes are based on empirical findings from case study data. Allowing for empirically motivated agent heterogeneity follows findings from earlier model analysis which underpins the importance of heterogeneity in agent attributes for model outcomes (Rasch et al. 2014).

Changes or additions to the reference model were made with respect to (1) fertility management, (2) livestock reproduction, (3) timing of the selling decision, (4) HH heterogeneity regarding expenditures and selling behaviour, (5) learning of selling rules and (6) cooperation in the context of a social norm.

4.4.1 *Overview*

A condensed overview of the functional relationships between model elements is given in figure 4.4.

Figure 4.4 Model flow - overview



Starting with the exogenous impact of weather on resource biomass production, the rangeland model calculates the available total standing biomass (TSC), green standing biomass (GSC) and green growth of the last month while taking past forage consumption into account. The three biomass variables result in a monthly value for live-weight gain from ecosystem service provision. Annual live-weight gain is additionally increased by supplementary feeding and determines adult mortality and maximum net-reproduction. Reproduction is additionally influenced by fertility management. HH exit livestock production in case cattle mortality resulted in an extinction of the reproductive capital of herds. Depending on the respective HH selling practice, agents sell livestock relying on animal characteristics or the size of the herd. Livestock can also be sold as a result of rule obedience in terms of social interaction as a self-enforcing process. Here, mutual cooperation or defection is an emergent phenomenon produced by agents who are heterogeneous in terms of cooperativeness and reciprocity. The type of HH, determining selling practices, is a function of total income and savings per HH member. After initialization, the HH type also determines expenditures which are deducted from total income to calculate savings. Total income is the sum of profit from livestock sales and off-farm income. The latter is exogenously defined by four social grants, wages, HH businesses, and remittances. Social grants depend on the HH structure and social policy measures targeted at certain attributes of HH members. The probability of new entries depends on off-farm income and HH attributes. The total herd size plus additional cattle of entry-HH accumulate to the total stocking rate which results in an aggregate consumption of resource biomass during each month.

The following sub-sections describes additions and changes to the reference model in Rasch et al. (2014).

4.4.2 *Fertility management*

HH data from the Sediba survey showed that calving intervals are heterogeneous between herds. They were estimated by the respondents to be 12, 18 or 24 months long. We implemented calving intervals specific for females of distinctive herds by means of an ordered probit model. We hypothesize that experience, practices increasing animal health and breeding strategies increase the probability for a shorter calving interval.

4.4.3 *Net-reproduction*

The model allows for births in every month in order to account for the findings of heterogeneous calving intervals. In the reference model, net reproduction was based on the assumption of yearly calving intervals directly derived from the branding rate[14] as in Gross et al. (2006). However, cows in Sediba can have considerable longer calving intervals compared to commercial settings. Longer calving intervals lead to a lower net reproduction. In the current model, the branding rate represents an upper constraint on net reproduction. Maximum net reproduction is modelled as explicit births. Calves don't survive the first year if births exceed an upper bound of net-reproduction as determined by the branding rate for that year. This approach allows accounting for lower reproduction due to unsound management and for an upper limit on reproduction only restricted by forage availability expressed by the branding rate[15].

4.4.4 *Timing of selling*

Survey data revealed that HH differ with respect to the timing of livestock sales during the year. Data analysis showed that HH who use less supplementary feed are more likely to sell during winter. This is a time of forage shortage on the rangelands with an increasing risk of livestock losses. HH who provide more supplementary feeding are able to sustain their herds during winter and can sell livestock during the growing season which results in higher live-weight and thus in higher selling prices.

4.4.5 *HH typology regarding expenditures and selling behaviour*

HH differ in their expenditure pattern, income and resulting liquidity. This heterogeneity results in differences in the need to sell livestock in order to balance expenditures with agricultural income. The HH typology differentiates between HH above and below the upper poverty line. A cluster analysis of HH below the poverty line revealed three homogenous sub-groups differing with respect to income, savings and livestock selling rates (% herd sold). The model accounts for this type of agent heterogeneity by allowing for differences in selling behaviour

[14] Branding rate is the percentage of calves which survived the first year. Gross et al.'s calculation assumes that all cows calve in each year.

[15] banding rate is a linear function of yearly live-weight gain

and expenditure patterns among four HH types. HH types can dynamically change depending on changes in income and savings.

4.4.6 *Learning of selling rules*

The current model integrates a more fine-grained learning process with respect to environmental conditions by utilizing the genetic algorithm in the selling decision in the framework of a learning classifier system (Hufschlag 2010). A learning classifier system classifies the environment of the decision maker. Each potential action of the agent is coupled with an external condition. The model accounts for two different conditions; drought periods and times of forage abundance. The agent observes the environment indirectly by monitoring the live-weight gain of the herd. A bad period triggers one of the two sets of solution candidates with respect to selling rules. Thus, the adaptive learning of agents is directly coupled to environmental states which induce a parallel evolution of solution chromosomes.

4.4.7 *Norm*

Agents are conditional co-operators wavering between cooperation and defection with respect to a social norm (Ostrom 2003; Ebenhöh and Pahl-Wostl 2008). The norm “not to have much more cattle than others” is enforced by normative sanctioning. The likelihood of conditional co-operators engaging in mutual cooperation increases with rising inequality and the share of co-operators. Contrary, the probability for cooperation decreases with the severity of norm violations. Cooperation leads to additional sales of livestock in case HH have larger herds. Agents are heterogeneous in their initial value for conditional cooperation based on four agent attributes. Please find a detailed description of the theoretical framework, modelled processes and implementation details in Rasch et al. (2014) or in the ODD+D protocol (http://www.ilr.uni-bonn.de/agpo/publ/techpap/Techpap15-01.pdf).

The model was adapted to allow agents to be permanent defectors. Defectors will never adhere to the norm. Thus, the model introduces additional heterogeneity by differentiating between those agents being conditional co-operators and those who always defect.

4.5 Scenarios and results

Next, we present three different disturbance scenarios and corresponding results, which are compared to a baseline scenario in terms of the earlier defined resilience surrogates.

4.5.1 *Scenarios*

In order to assess the system reaction towards social and ecological impacts, we ran three different scenarios and compared resulting resilience surrogates with those from a baseline scenario. All runs span 100 years and we present results following an initial warm-up phase (120 months). Underlying assumptions are that the demographic structure in terms of HH composition and size of the population persists and that the relation of income and prices is stable over time. The baseline scenario uses randomized weather data collected over 12 years in the region and assumes that all agents are conditional co-operators. We compare the baseline system configuration measured at ecological, HH and SES resilience with a system (1) shocked by droughts, (2) loss of social embededdness and with (3) a system where severe poverty is reduced due to anti-poverty policies. In order to account for stochasticity, we conducted repeated experiments (n=300) for each scenario.

(1) The drought scenario assumes a twelve year period with ~50% of average rain from year 40 on.

(2) A second scenario mimicking the loss of social embededdness (e.g. due to an increasing share of HH producing livestock for non-residents) assumes a share of 50% defectors in the population.

(3) A third experiment reduces poverty by means of policy measures. A Basic Income Grant (BIG) is implemented which is a widely discussed policy instrument in South Africa (Barchiesi 2007; Standing and Samson 2003; Standing 2008)(http://binews.org/2012/07/south-africa-protesters-demand-basic-income-grant/). The aim of BIG is to decrease severe poverty by reaching the unemployed labour force currently not receiving any (age-coupled) social grants. BIG guarantees a low and unconditional grant for all citizens of South Africa. No person should be worse off after

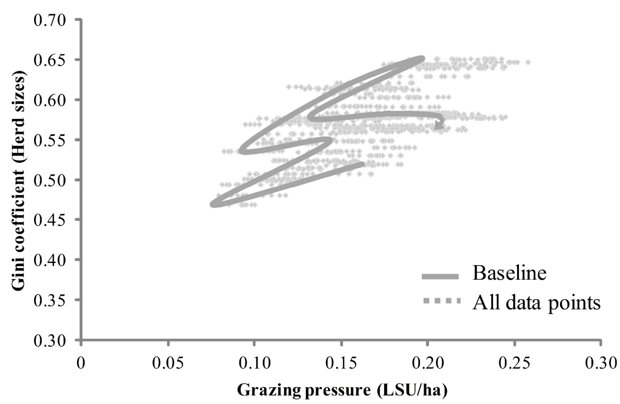
the implementation. We implement BIG as an unconditional grant of 200 Rand per month and person. We additionally increase the child grant by 50% in order reach the poorest HH (Triegaardt 2005). To reflect current discussion on consequences for the state budget, the old age grant (1140-1160 Rand) is reduced by the BIG amount.

As we are interested in general long-term patterns of the system, we use the data points of every 10th year with an indication of the temporal direction. Ten-yearly measurements are taken for one month (September) during the dry season when winter forage shortage limits live-weight gain and the probability for degradation is highest.

4.5.2 *Baseline*

The pattern of SES resilience measured at the *gini coefficient* of herd sizes and *grazing pressure* as ha per large stock unit (400kg) (Figure 4.5) for the time span of analysis indicates that the system configuration exhibits the dynamic pattern of a limit cycle. That is, the SES resides in the basin of a system inherent attractor and is not crossing the border of the basin.

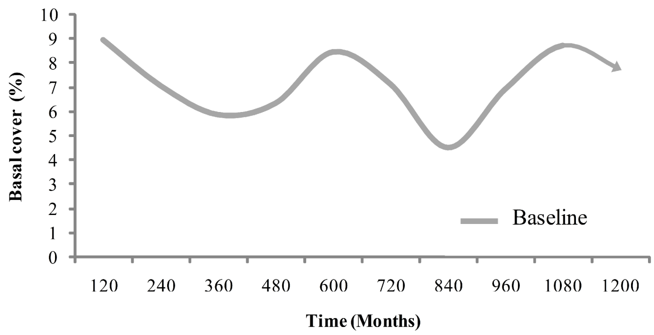
Figure 4.5 SES resilience – baseline scenario



Note: Grey dots represent data points for all months simulated (without warm up phase). We omit the presentation of all data points in the forthcoming graphs for the sake of visual clarity.

The percentage of basal cover is oscillating around the value measured for a moderate veld (6.4%) (Figure 4.6).

Figure 4.6 Basal cover – baseline scenario

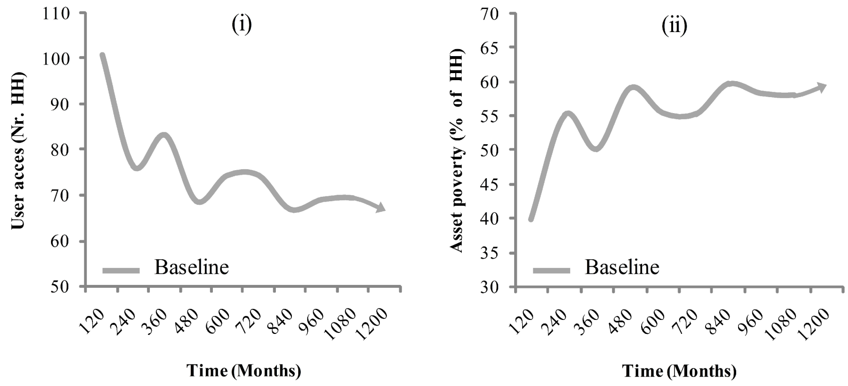


Underlying processes explaining this pattern are twofold. First, higher stocking density increases appropriation and decreases the productive capacity of the resource leading to lower livestock reproduction and more cattle losses which in turn reduce herd sizes as well as inequality among those. Second, high inequality increases the vividness of the situation (perceived inequality) and inequality averse agents increase normative sanctioning. Norm obedience then results in additional sales reducing herd sizes of larger herds. The latter decreases both: inequality and grazing pressure.

These patterns constitute a stable system configuration. Thus, the baseline SES does not exhibit the system characteristics, which would result in a "tragedy of the commons" as predicted by classical economic theory (Hardin 1968). The social system (including livestock) buffers resource limitations by adaption of herd sizes, constituting a central resilience mechanism of the SES.

However, time series data on HH resilience surrogates user access and asset poverty reveal dynamic patterns on another resilience scale. Figure 4.7(i) shows that user access in terms of HH being able to sustain production shows a downward trend. Moreover, the share of asset poor HH is increasing over the analyzed period (Figure 4.7(ii)).

Figure 4.7 User access and asset poverty – baseline scenario

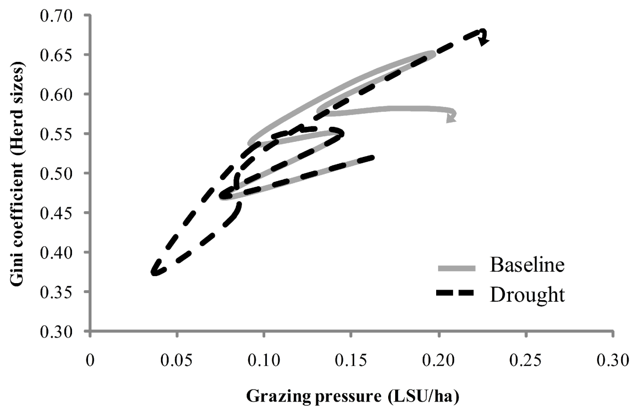


There is a discrepancy between SES and HH resilience as the stability of the SES is accompanied by a decreasing user base over time. Poor HH are slowly exiting production and richer HH fill the gap by increasing herd sizes within the boundaries allowed by the norm. However, they do so collectively such that inequality (within the group of livestock owners) is not affected and grazing pressure remains stable.

4.5.3 *Drought*

Figure 4.8 shows the dynamic pattern of SES resilience for the system subject to the drought scenario.

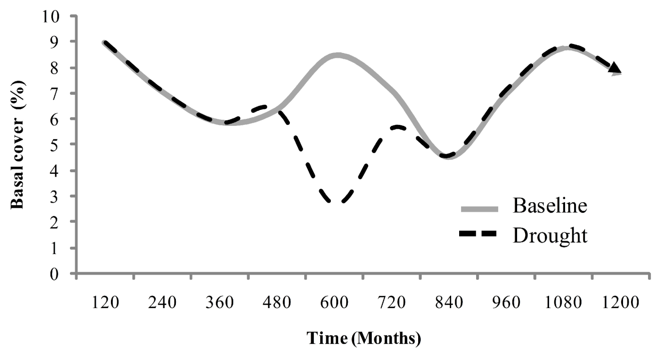
Figure 4.8 SES resilience – drought vs. baseline scenario



The drought shock pushed the system towards the boundary of the basin of attraction but it returned to the limit cycle pattern thereafter with a temporal delay. The SES was resilient towards the shock but needed several decades to recover.

Due to the dry years, resource biomass production is limited and further reduced by animal intake. This short time degradation effect is also reflected in a downward shift in basal cover following the drought disturbance (Figure 4.9).

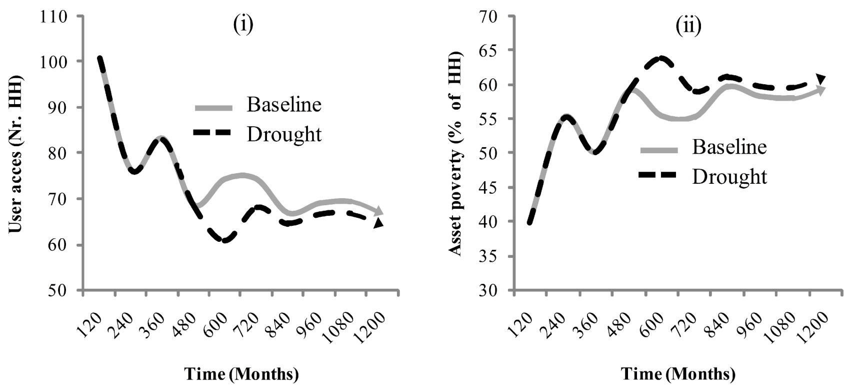
Figure 4.9 Basal cover – drought vs. baseline scenario



The grassland ecosystem was able to recover due to the fact that HH in Sediba usually don't restock their herds. Livestock and thus the social system buffered the shock originating in the ecological system and the coupled system recovered afterwards. This is in line with Campbell et al., who state that “under typical semi-arid conditions, severe degradation may be partially forestalled because cattle die off during dry stressful years, thus allowing the vegetation to recover during subsequent years" (2000, p.429).

HH resilience surrogates also return to the baseline pattern after the eco-system shock. The pattern of user access over time has the same statistical signature in terms of seasonal and long-term trends as in the baseline scenario but its magnitude slightly shifted (Figure 4.10(i)). The number of HH realizing resource access is less and the difference to the baseline level persists. The phenomenon, although with positive long-term trend, shows in asset poverty as well (Figure 4.10(ii)).

Figure 4.10 User access and asset poverty – drought vs. baseline scenario



A multi-annual drought period does not overstrain SES resilience but accelerates the process of structural change in Sediba and reduces HH resilience.

4.5.4 *Erosion of social embededdness*

A second scenario assumes a high share of defectors in the systems. Defecting agents are not socially embedded with respect to the normative process and will thus not obey the norm nor will they participate by sanctioning norm violators. The scenario assumes a share of 50% defectors which results in a collapse of the SES in 20% of the simulation runs. Here, we define SES collapse as a major breakdown of livestock production due to resource depletion. Specifically as a moment in time in which the ecosystem service of forage production declines such that utilization by livestock is zero and herds cannot survive.

Figure 4.11 SES resilience – collapse at 50% defectors (example run)

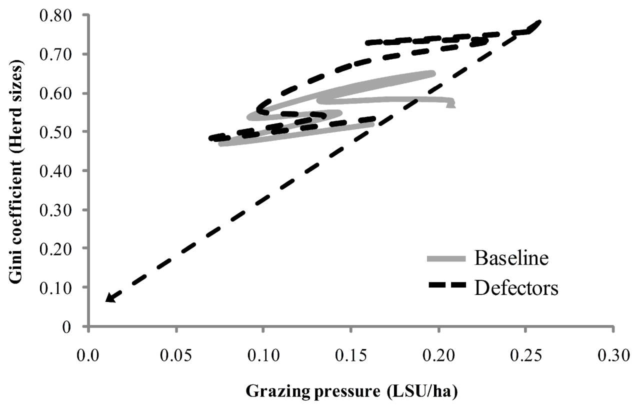
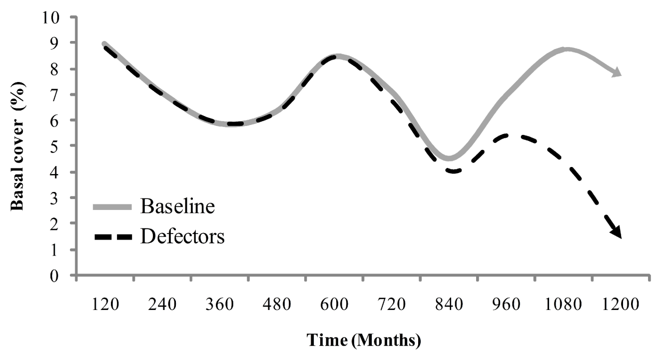


Figure 4.11 shows the simultaneous increase of inequality and grazing pressure over time and exemplifies such a breakdown where long-term overgrazing resulted in grassland-degradation characterized by a low productivity. The total stocking density in later years is above the (dynamic) grazing capacity of the rangeland rendering it sensitive to years with unfavorable weather and eventually leads to a collapse. The effect of resource degradation over time also shows in the trend of basal cover pushed down well below a level indicating a bad veld (2.9%) (Figure 4.12).

Figure 4.12 Basal cover – collapse at 50% defectors (example run)

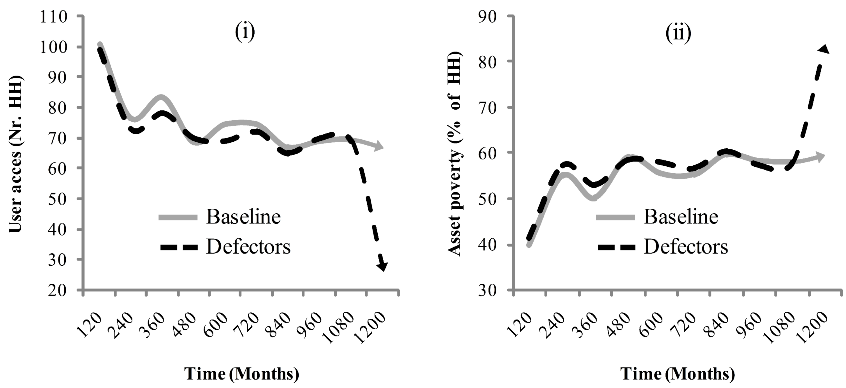


The reversed trend of basal cover in the last phase indicates hysteresis. Here, grazing pressure pushed the ecosystem over an ecological threshold. Cattle losses over the last decade of the run were not sufficient for the ecosystem to return to a state of productivity to be sustainable for the remaining herds. This is not an irreversible flip into another domain of attraction but it highlights the mechanism of hysteresis: a reduction of resource appropriation to a level that was sustainable in the baseline did not suffice for recovery (Janssen et al. 2004, p.141; Bodin and Norberg 2005, p.178).

Rising inequality constitutes a symptom indicating the loss of SES resilience (Figure 4.11). The high share of defectors inhibited collective action in two ways: by (1) decreasing the cooperativeness of conditional cooperators due to increased severity of norm violations and by (2) decreasing reciprocity due to a loss in the trust that others will be reciprocators. The combined effect on conditional cooperativeness was stronger than high inequality lowering the threshold for normative sanctioning. Or termed differently, the "just anger" of participants was replaced by "hopelessness" in the light of collective action being a dead loss.

Figures 4.13 reveal the dramatic and sudden loss of HH resilience in terms of the user access (i) and asset poverty (ii) following ecological collapse.

Figure 4.13 User access and asset poverty – collapse at 50% defectors (example run)



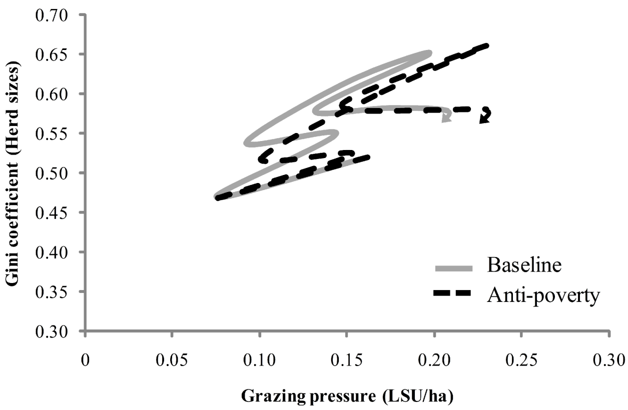
It is, however, notable that the dynamic patterns prior to collapse are close to those for the baseline scenario (Figure 4.13). This fact underpins that the SES configuration crossed a socio-ecological tipping point which induced sudden change. Such a process of resource degradation due to overgrazing with a socially sub-optimal outcome appears to resemble the classic tragedy of the commons. This result mirrors Boding and Norberg's findings of an "inevitability of the tragedy of the commons if no mechanisms are present to provide capacity for mutual agreements" (2005, p.185). Institutional failure, as a result of the loss of social embededdness, eroded the constraints for individual action which led to a loss of SES resilience and collapse. Our results confirm earlier findings that “brittle” social structures can lead to collapse and systemic change (Kobti et al. 2003, p.1988).

4.5.5 *Anti-poverty policy*

A last simulation scenario introduces policy measures aiming at the reduction of severe poverty; namely, a basic income grant to all participants (200 Rand) and an increase in the payment for child support (+50%). Old age grant is adjusted such it remains on the initial level (1140-1160 Rand).

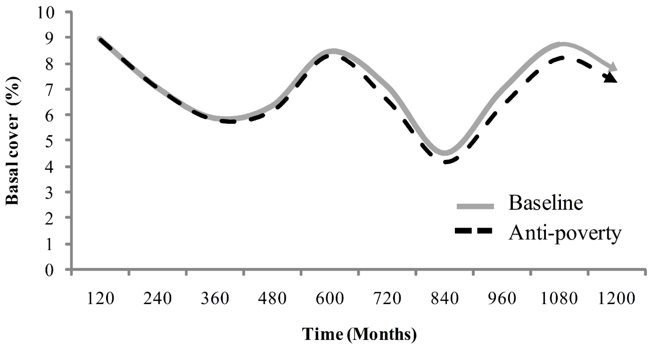
SES resilience patterns exhibit two notable facts: (1) the cyclic pattern shifts to the right indicating a slightly increased grazing pressure (2) but the dynamic pattern remains within the boundary of the initial basin of attraction and patterns match (Figure 4.14). No sudden change occurs.

Figure 4.14 SES resilience - anti-poverty policy



The ecosystem is sufficiently resilient to cope with the increased grazing pressure generated by the social system as indicated by the trends of basal cover in figure 4.15. No change in patterns in terms of trend reversion takes place. Increased degradation is only marginal and does not indicate a systemic change.

Figure 4.15 Basal cover - anti-poverty policy



However, we observe a systemic change on the level of HH resilience (Figures 4.16). The patterns for both surrogates change insofar as they constitute oscillating but stable dynamics over the time span of analysis. Asset poverty (ii) and resource access (i) converge towards a stable attractor.

Figure 4.16 User access and asset poverty - anti-poverty policy

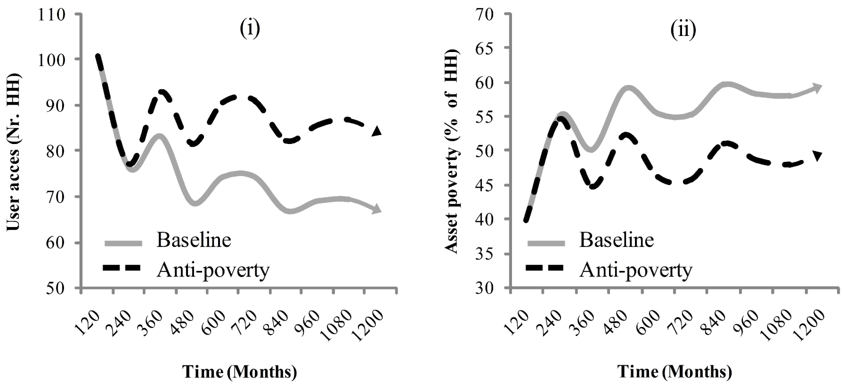
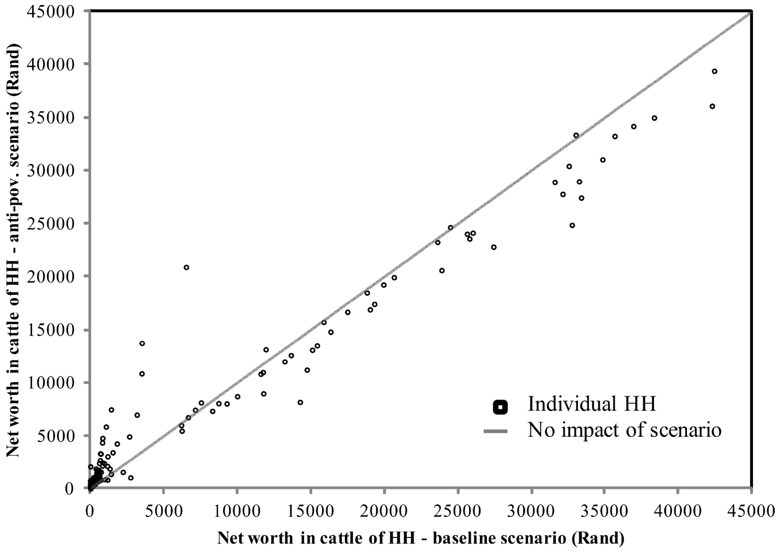


Figure 4.17 depicts individual HH resilience comparing the scenario to the baseline. Data points represent the net wealth of HH in terms of the monetary value of livestock at the end of simulation runs. The x-axis denotes wealth for the baseline and y-axis for the anti-poverty policy scenario. Data points on the 90° line represent HH which have not been affected by the alternative scenario compared to the baseline. Those HH below that line exhibit a lower level of wealth and those above the line a higher level of wealth due to the intervention.

Figure 4.17 Net worth in cattle of individual HH at the end of simulation - baseline vs. anti-poverty policy scenario



Note: we are not measuring the direct effect of increased income on HH resilience. The HH resilience surrogates emerge due to agent interaction and are influenced by the level of off-farm income.

Figure 4.17 shows that those HH who were better off in the baseline scenario exhibit lower values for accumulated wealth whereas the majority of HH with very small or no herds could gain in wealth due to increased off-farm income.

To summarize, the implementation of BIG and child grant increase drastically reduce the negative effects of structural change on HH resilience by increasing the chances for poor HH to successfully compete with richer HH. As a result grazing pressure increases as less HH are forced out of production. This effect is partially compensated by a reduction in herd sizes of richer HH. The ecosystem reaction in terms of increased degradation towards the net increase is moderate. The coupled SES was able to cope with and to internalize the change in exogenous subsidization.

4.6 **Discussion**

In this section, we discuss general insights from our modelling endeavour. We found that the SES is resilient towards droughts but that droughts accelerate structural change in the village. A loss of social embededdness du to an increased share of absentee herders leads to the disintegration of resilience on all scales. Finally, the introduction of a basic income grant alongside with other anti-poverty measures does not jeopardize SES resilience but ends the erosion of HH resilience. Next to the directly derived results from our experiments we want to discuss the lessons learned during our modelling exercise.

The presented modelling approach made an attempt to address three major challenges for the fairly new interdisciplinary field of SES modelling: (1) to get the context right, (2) to arrive at quantifiable measures of resilience on multiple scales and to (3) account for endogenous institutional processes.

The first objective was achieved by combining empirical agent based with bio-physical modelling. Here, empirical case study data from surveys, anthropologic field observation, soil and vegetation samples was used. We found that interdisciplinary research is an unavoidable pre-requisite for building structurally realistic SES models with the aim to reflect the fundamental processes and contexts of a specific case. In our view, a single discipline is simply not able to sufficiently cover, or even understand, the social and the ecological dimensions of the coupled system.

A key finding resulting from quantifying multi-scale resilience is the insight that resiliencies within the same SES can diverge or converge over different scales. This perspective underpins the importance to avoid the trap of utilizing the resilience concept in a strictly normative way. That is, to include the scale perspective within the boundaries of the SES constitutes a meta-normative approach. Here, resilience is not an isolated end-result which has to be achieved by all means but must be treated as an endogenous process cascading over multiple scales of the system. Desirability is relative. The impact of three different shocks on the SES results in contrasting dynamics on the ecosystem, HH, social and SES scale. However, a severe loss of resilience on all scales is only observed in a scenario mimicking the loss of social embededdness resulting in institutional collapse. The latter observation stresses the important role of endogenous institutions in SES modelling which has not seen much attention in the literature so far. Here, the strand of computational studies of norms is a promising field to be considered for SES modelling.

Accordingly, limitations for structurally realistic SES modelling with a resilience focus are:

1. *costs* - associated with interdisciplinary research as well as extensive data requirements
2. *complexity* - necessity to identify relevant scales and to analyze parallel resilience dynamics
3. *innovation* - needed to further develop a methodology for representing endogenous institutional processes

Looking forward, there is the need to deal with a principle dilemma associated with the modelling approach presented in this chapter: the identification of clear causal relationships between individual model components and system outcomes. Model parameters increase with complexity in a non-linear fashion prohibiting a comprehensive sensitivity analysis. The inherent trade-off between accounting for socio-ecological complexity and full understanding of model behaviour constitutes a limitation. While our model gained from acknowledging socio-ecological complexity in terms of structural realism needed to measure multi-scale resilience, it also lacks transparency due to its increased parameter space. It might be worth, at least in our view, to aim at an intermediate level of complexity in order to advance the field of SES modelling.

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4.8 Appendix

Appendix A: 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