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Implications of behavioral change for the resilience of pastoral systems – lessons from an agent-based model

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THE IMPLEMENTATION OF THE ABM IS AVAILABLE TO DOWNLOAD AT COMSES NET:
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Abstract

In many dryland regions, traditional pastoral land use strategies are exposed to various drivers such as demographic or socio-economic change. This may lead to an adjustment of livelihood strategies and behavior of pastoral households, involving a change in attitudes toward livestock, pasture condition and social norms. We use an agent-based model to examine long-term social-ecological consequences and implications for system resilience of such behavioral changes (e.g., giving up a social norm). The model captures feedback between pastures, livestock and household livelihood in a common property grazing system. We systematically compare three stylized household behavioral types (traditional, maximizer and satisficer) that differ in their preferences for livestock, their compliance with social norms on pasture resting and how they are influenced by the behavior of others. Simulation results show that the traditional, norm-abiding household type maintains the pasture condition, provided that overall household numbers do not exceed a critical threshold. In contrast, a switch to a maximizer type that ignores norms may lead to long-term pasture degradation and livestock loss, pushing the system to an undesirable state. A change toward a new satisficing household type that constrains its herd size while diversifying its income sources can lead to improved pasture conditions and higher total livestock numbers, even with increased household numbers. We conclude that changes in household behavior have strong implications for long-term social-ecological system dynamics and have to be considered to assess the resilience of pastoral common property systems.

Keywords: multi-agent simulation; social-ecological model; decision theory; social norms; common property; income diversification

1. Introduction

Approximately 40% of the world's surface is covered by drylands (UNCCD 2010) that provide the livelihood for approximately two billion people. In these resource-scarce regions, pastoralism is a main way of life that allows households to cope with the characteristic environmental variability of dry rangelands (Krätli et al. 2013). Moreover, it is most often the only relevant way of food production in marginal lands (Reid 2014), as it is better adapted to the climate than crop farming is. However, to avoid pasture degradation, appropriate grazing strategies are needed. Pasture resting is one important component of these strategies and has been in place for centuries. It has become a *social norm* in formal or informal regulations, such as the declaration of areas of drought reserves in Namibia (Müller et al. 2007a) or pasture access regimes of the *Agdal* in Morocco (Dominguez et al. 2012). However, in many regions, such traditional norms are at stake as a result of ongoing transition processes in the last decades. Liberalization trends since the 1980s have led to an opening of national economies and markets. This has given rise to the privatization of land and property (Gertel 2015) but also to a change in the economic orientation of many pastoral households. Alongside these economic transformations, many rangeland territories are undergoing serious demographic transitions. A significant population increase in many regions leads to less land being available for pastoralists (Gruschke 2011; Pricope et al. 2013; Wario et al. 2016). Population growth often also comes along with an expansion of agricultural land into former grazing areas, resulting in a growing scarcity of pastures for the herds (McPeak et al. 2015; Dressler et al. 2016). Together, these changes challenge the livelihood of pastoralists and raise the question whether traditional pastoralist strategies are still viable (Robinson et al. 2010, Devereux et al. 2008, Sandford 2007) or how they should be adjusted to cope with the impacts of land use change in a sustainable way.

Pastoralists' strategies traditionally valued livestock as a symbol of wealth and aimed at large herd sizes (Roth 1996; Western 1986). However, in the course of economic liberalization, behavioral attitudes may change, too, causing customary institutions and regulations to lose their influence (Gertel 2015; Ruttan 1999). This affects the dynamics of the social-ecological system (SES) in an unknown way, since the interdependence of household behavior and its impact on land use sustainability is complex and not well understood (cf. Thébaud et al. 2001 for the Sahel region).

From a systems perspective, we can analyze the impact of changes in household behavior taking a *resilience* perspective. Following the definition given by Cumming et al. (2005), resilience is "the ability of the system to maintain its identity in the face of internal change and external shocks and disturbances". Here, the 'identity' of a system is characterized by four aspects: a) the components that the system is made up of, b) the relationships between these components, c) the sources of innovation that allow the system to generate change or novelty, and d) the sources of continuity that enable the system to maintain its identity through space and time (Cumming et al. 2005). By identifying the elements that make up the system's identity and possible alternative future states that indicate a loss of identity, we can assess the resilience of the SES in the future.

To explore the implications of changes in behavioral strategies for the future state of the SES, simulation modeling is a powerful approach. However, in the context of models, especially in land use science, human behavior is often not considered or is considered only in a simplified manner. Crooks et al. (2008) state that the implementation of decision models is often *ad hoc* and rarely grounded in theory. In a recent quantitative review, Groeneveld et al. (2017) underpin this statement: they find that in the majority of models human decision-making is not explicitly based on a theory, and the single most often used theory is the expected utility theory. Thus, agents are assumed to be selfish rational actors who maximize their personal utility based on stable preferences, perfect knowledge and unlimited cognitive abilities (Monroe 2001). Humans, however, rarely act fully rational: they have limited cognitive abilities and often rely on simple heuristics to make decisions (Gigerenzer and Goldstein 1996; Levine 2015). Furthermore, the rational actor approach completely ignores the social dimension of human decision-making such as social learning, imitation or norms (Levine 2015).

Several modeling studies have already addressed the interplay of pastoral land use and environmental dynamics, e.g., the effects of climate change and droughts on pastoralists' livelihood security (Martin et al. 2016, Martin et al. 2014), trade-offs between wealth allocation in a migratory pastoralist system in Kazakhstan (Milner-Gulland et al. 2006), the emergence of cooperation in and resilience of a communal livestock production system (Rasch et al. 2016, Rasch et al. 2017) or on mechanisms of coexistence of wealthy and poor herders in a mobile pastoralist system in Mongolia (Okayasu et al. 2010). However, there is still a lack of knowledge to what degree more refined models of human behavior can adequately capture the observed behavioral changes and how these changes influence SES dynamics. We aim to contribute to these questions by investigating the consequences of behavioral change in pastoral societies, using a social-ecological agent-based model (ABM). The model is designed as a virtual lab (Dibble 2006; Seppelt et al. 2009; Zurell et al. 2010) that emphasizes the dynamics of and feedbacks between household behavior, pastures and livestock. We model a stylized common property grazing system in which households follow a certain behavioral type that specifies how they choose pastures on which they relocate, feed and breed their herds. We consider three household behavioral types that reflect empirically observed trends of behavioral change in different dryland regions (detailed in Section 2) and that are conceptualized in the model using behavioral theories (detailed on Section 3.4). We specifically use the theory of descriptive norms – the influence of perceiving what other people do (Cialdini et al. 1990) – to design three types that differ in their preferences for livestock numbers, how they value social norms and how they are influenced by the behavior of others. Using the model, we assess the social-ecological consequences of scenarios of behavioral and demographic change and address the following research questions:

1) Under which demographic conditions (number of pastoralist households) do differences in decision-making matter, i.e., when do the behavioral types lead to the same or to different social-ecological consequences?
2) When can behavioral types increase the risk for long-term negative effects such as pasture degradation and livestock loss, and under which conditions might such a collapse be prevailed?
3) How does behavioral change affect the resilience of the SES over the long term?

To address these questions, we take a stepwise approach. First, we analyze all three behavioral types separately with respect to demographic change. In a second step, we comparatively assess populations that differ in their composition of household behavioral types to simulate the effects of behavioral change within the pastoralist community.

2. Empirical background and motivation of pastoralist behavioral types

In our model, we implement three behavioral types that reflect – in a simplified representation – livelihood strategies of pastoralist households as they were in the past and the direction in which they are evolving currently. This section provides empirical motivation for these three types and how we conceptualize them in our study.

Traditionally, pastoralists have always valued livestock, as it constitutes the main asset to secure their livelihoods. However, pastoralists are also aware of the importance of pastures as a resource that has to be shared among all. Applying the framework of Cumming et al. (2005), households, livestock and pastures are the integral *components* that define the identity of the system. A substantial loss of any of these components would also imply a loss of resilience. The *relationships* between these components are manifold: grazing of livestock on pastures and the mobility of herds affects both pasture and livestock condition. Different forms of land tenure define how, when and by whom pastures can be accessed. Access to pastures has always been subject to some sort of coordination (Ruttan 1999), and access rules, for example to dry season grazing areas, are often determined consensually and enforced by community sanctions (Galaty 1994). Such rules have often evolved into social norms over time. Herders also do not act just by themselves; they rather employ strategies that consider other herder’s behavior as well, e.g., following grazing decisions of successful individuals in their community (McCabe 1997). Thus, a traditional type of pastoralist can be described as livestock-oriented, norm-following and socially susceptible to other’s behavior. Traditional norms and rules provide one source of *continuity* that enables the system to maintain its identity.

However, traditional pastoral strategies and customary institutions that regulate resource access are disappearing in many regions as people change or are forced to change their values (Goldmann 2013; Galvin 2009). A combination of processes causes these changes: an increasing resource scarcity due to more severe climatic conditions on the one side, and a growing population on the other side, economic change that leads to a liberalization of markets, and technical innovations. Pastoralists on the High Plateau in Eastern Morocco, for example, have traditionally relied on the camel to relocate their herds and tents in response to the current climatic conditions.

The last decades, however, have seen an abandonment of the camel in favor of motorized transport and an increased monetarization of the society (Kreuer 2011). Especially, the increasing importance of money in the life of pastoralists is changing their attitude: monetary considerations now come before cooperation and charity, as money facilitates anonymous relationships and contributes to the breakdown of community relations based on permanent cooperation (Rachik 2000). A significant challenge also stems from population growth. A more than doubled population in Eastern Tibet's Yushu Region since the 1950s, for example, has led to an increase in the total livestock number of the region, and more and more pastoralists are left without pasture and will fail to subsist from their shrinking number of livestock (Gruschke 2011). Furthermore, agricultural expansion into former pastoral grazing grounds has been observed in many regions (McPeak et al. 2015; Brottem et al. 2014; Ruttan et al. 1999). This leads to a fragmentation and loss of pasture areas (Hobbs et al. 2008; Pricope et al. 2013) and pastoralists being forced to use grazing reserves in times of the year when they should be rested and community elders being unable to enforce traditional sanctions (Ruttan et al. 1999).

This has given rise to a devaluation of traditional norms, rules, and changes in economic orientation and the livelihood strategies of the households. On the one hand, households that do not follow traditional grazing rules tend to turn toward a higher profit orientation and commercialization of livestock production (Fratkin 2001), trying to maximize their herd size. On the other hand, a diversification of economic activities is increasingly used to spread the risk of relying on a single income source. In Tibet, for example, many pastoralists have specialized in the collection of caterpillar fungus, which is very profitable (Gruschke 2011). Taking up wage labor outside of pastoralism is another form of income diversification. Calkins (2009), for example, reports in empirical narratives of the Rashâyda pastoralists in Sudan that especially international labor migration plays an important role to support the families' livelihood at home.

Thus, we see two types of pastoralists emerging from the traditional type: one type that is profit-oriented and tries to maximize its herd size without considering traditional rules or other's behavior, and another type that tries to reduce its reliance on livestock and thereby lowers its need for a large herd size by diversifying its income sources. These new behavioral types represent a source of *innovation*. Its effect on the resilience of the SES, however, is not clear.

3. Methods

In the following, we describe the simulation model in a structured form, based on the ODD+D protocol (Müller et al. 2013). A complete protocol including the description of the submodels can be found in the appendix.

3.1. Model background and purpose

We aim to enhance the understanding of whether and how human decision-making is influencing the long-term development of livestock numbers, pasture condition and household livelihood in a stylized semi-arid pastoral system. A special interest is in the impact of behavioral changes on the resilience of the SES, i.e., the extent to which a change in the household's decision-making can drive the system into a degraded state or can counteract such a development. We want to gain a principle mechanistic understanding in a virtual lab approach rather than analyze a specific case study.

3.2. Entities, state variables, and scales

Agents represent pastoralist households H. A population of households consists of N_H households H_i, where i indicates the household number. Each household is characterized by its number of livestock L, its current location and the assigned behavioral type BT.

The modeled landscape is represented as a grid of 10 x 10 = 100 pasture patches P_j. Each patch has a size of 100 ha such that the total landscape has an extent of 10,000 ha. Vegetation on pasture patch P_j is modeled by two functional parts: green biomass G_j and reserve biomass R_j. Green biomass G_j comprises all photosynthetically active parts of the plants and represents the main fodder for the livestock. Reserve biomass R_j summarizes the storage parts of the plants below and above ground, e.g., roots or woody branches.

Green biomass growth is driven by precipitation S. We assume a semi-arid climate where rainfall is low on average but highly variable; therefore, we use a lognormal distribution to simulate rainfall. The model uses discrete time steps, and one time step represents one year. The simulated time horizon T is 100 years. A conceptual diagram of the model entities and their relationships is shown in Fig. 1 (Details of the vegetation model can be found in Müller et al. 2007; Dressler et al. 2012).

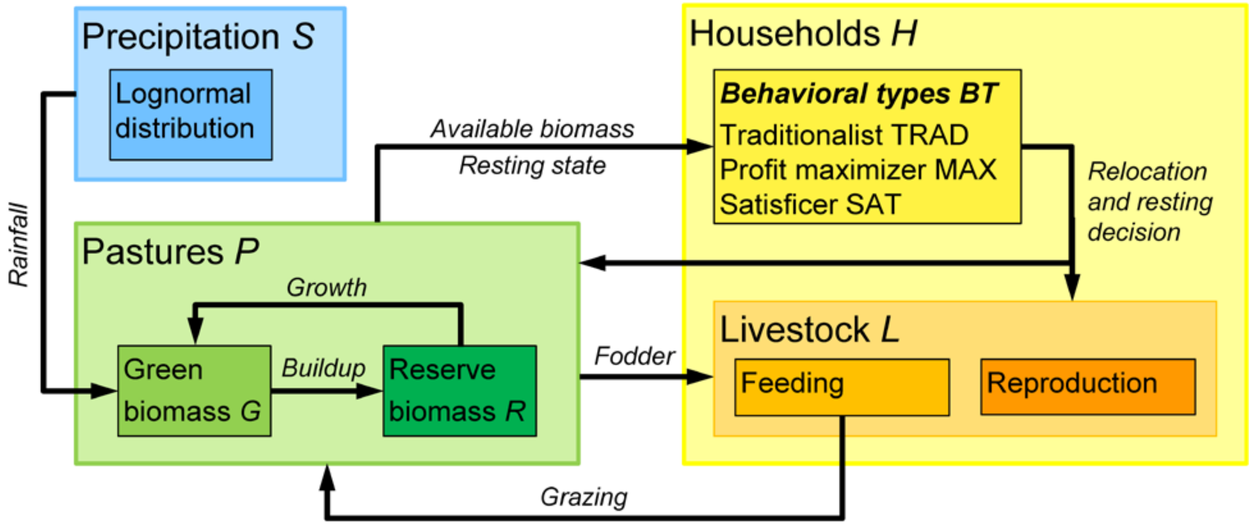

Figure 1: Conceptual diagram of the model showing the entities (households *H*, livestock *L*, pastures *P* and precipitation *S*) and their relationships. The model is implemented in NetLogo and available to download at CoMSES Net: https://www.comses.net/codebases/5721 (last accessed: 2018-06-19).

3.3. Process overview and scheduling

Each year, precipitation and the subsequent growth of green biomass on each pasture occurs first. After that, livestock reproduces with a fixed birth rate followed by the pasture selection of the agents. Each agent acts sequentially, whereby the order is determined randomly in each time step. Households try to find a suitable pasture based on their behavioral type, which considers available biomass and state of the pastures (i.e., rested or not), their current herd size and individual preferences. After a household has selected a suitable pasture, destocking of livestock occurs if necessary (e.g., due to biomass availability on the selected pasture), and livestock will feed immediately. If a household loses all its livestock (i.e., $L_i(t) = 0$), it will exit the system. After that, the next household acts. At the end of the year, the regeneration of reserve biomass occurs.

3.4. Household behavioral types

Each household H_i is assumed to follow a certain behavioral type that is assigned to it at the beginning of the simulation and does not change in the course of the simulation. We implemented three behavioral types BT: a traditionalist (TRAD), a profit maximizer (MAX) and a satisficer (SAT). Their empirical motivation is reflected in Section 2. Here, we conceptualize them using decision-making theories, and operationalize them using the *MoHuB* framework (*Mo*delling *Hu*man *B*ehavior, Schlüter et al. 2017). The framework provides a tool to map, describe, and compare theories of human decision-making and thus, facilitates their implementation within simulation models. This framework decomposes the decision-making process of an individual actor in our model into several interlinked parts, which are displayed in Fig. 2.

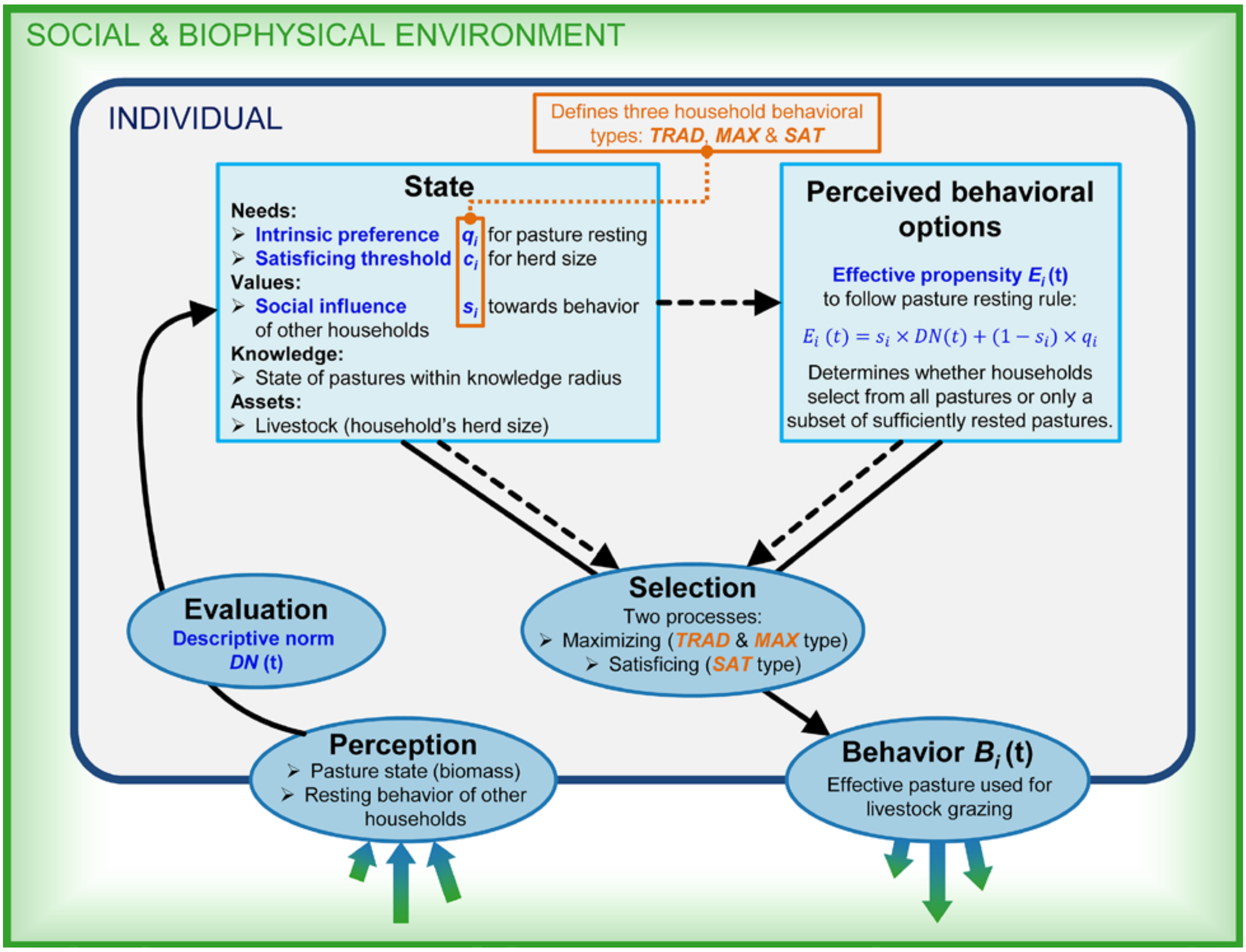

Figure 2: Application of the MoHuB framework (Schlüter et al. 2017) for the behavioral types represented in our model. Solid arrows and corresponding ellipses indicate processes and boxes represent structural elements. The solid arrows coming from State and Perceived behavioral options merge in Selection to form the Behavior. Dashed arrows represent an influence of one element on another, e.g., the state influencing the set of perceived behavioral options. For more details see the main text.

Each household's *state* is characterized by a set of *needs, values, knowledge* and *assets*. The household's needs are characterized by a satisficing threshold for the herd size c_i and an intrinsic preference for pasture resting q_i. In our model, we assume a simple resting rule based on a global resting threshold θ relative to the maximum possible reserve biomass R_{max}: if

$$\mathrm{R_j}(t) < \theta \times R_{max} \quad (1)$$

the pasture R_j is flagged as “resting needed” at time t and when the pasture conditions have improved, this flag will be removed. We assume that households have their own intrinsic preference $q_i \in [0,1]$ for pasture resting but are also influenced by the resting behavior $B_i(t)$ of all households of the previous time step. We define the household’s resting behavior as $B_i(t-1) = 1$ if it abided by the resting rule and only used pastures that were available for grazing or $B_i(t-1) = 0$ if it ignored this rule. Based on this definition, we can express the average behavior of all households by a descriptive norm $DN(t)$ – in contrast to an injunctive norm that states how people should behave (Cialdini et al., 1990). Agents *perceive* the behavior of the other households and the state of the pastures and *evaluate* the descriptive norm $DN(t)$, which is defined in Eq. (2) as follows:

$$DN(t) = \frac{1}{N_H} \sum_{i=1}^{N_H} B_i(t-1) \tag{2}$$

where N_H is the number of households. Agents determine their *perceived behavioral options* by calculating their effective propensity $E_i(t)$ (Eq. (3)) to follow the pasture resting rule:

$$E_i(t) = s_i \times DN(t) + (1 - s_i) \times q_i \tag{3}$$

where $s_i \in [0,1]$ is the social influence weighting their susceptibility toward the resting behavior $DN(t)$ of other households over their own preference q_i for resting. This formulation follows the stylized model of Muldoon et al. (2014) who analyzed the formation of standing ovations based on descriptive norms. Based on the effective propensity $E_i(t)$, each household selects a pasture $P_i(t)$ from either rested pastures or all pastures, according to the *selection* process of the respective behavioral type (either maximizing or satisficing). All agents have the same vision and can *perceive* the state of all surrounding pastures. However, agents may be constrained in their choice of pastures due to different *preferences* for herd size or pasture resting and their selection process. Here, the level of livestock that household H_i aims for is defined as the satisficing threshold c_i. If the household’s preference is to maximize livestock numbers, then c_i is infinite (however, the herd size is limited by the available green biomass on the pasture).

Based on these three parameters – intrinsic preference q_i, social influence s_i and satisficing threshold c_i – we define a three-dimensional behavioral space $BT(q, s, c)$ (see supplement S1 for a graphical representation) in which we differentiate the three types:

1. The traditional behavioral type (TRAD) aims to reach a large herd size while at the same time ensuring the ecological state of the pastures by following traditional resting rules. Thus, TRAD households have a high preference for its herd size ($c_i = \infty$) and for pasture resting ($q_i = 0.95$). However, we assume that this type is also susceptible to the behavior of others, depicted in a high social influence value ($s_i = 0.8$). Depending on the behavior of the other households and the resulting decision to follow or not follow the resting norm, the household either evaluates all pastures or only the subset of sufficiently rested pastures. To *maximize* its herd size ($c_i = \infty$), this type then selects the available pasture $P_j(t)$ with the highest amount of biomass.
2. The short-term profit maximizer (MAX) is conceptualized as a selfish, rational actor that aims to maximize its personal utility. Its goal is to maximize its herd size ($c_i = \infty$), so it always selects the pasture $P_j(t)$ with the highest available amount of biomass among all pastures P. It is not influenced by the behavior of others ($s_i = 0$) and ignores all resting rules ($q_i = 0$), as this guarantees it the highest current profit.

3. The satisficer (SAT) is conceptualized as a household type that covers part of its income from other sources. Therefore, its goal is to reach a satisfactory level of livestock $c_i \in [c_{min}, c_{max}]$ instead of the maximum possible herd size. In addition to constraining its herd size aspiration level, we assume that the SAT type is constrained in the amount of labor it allocates to pasture selection. Thus, it follows a simple satisficing heuristic to select a suitable pasture: it will select the first pasture $P_j(t)$ with sufficient available biomass that matches its satisficing threshold c_i. It will stop searching after a limited number of trials p_i and if it did not find a suitable pasture until then, will select the best pasture that it evaluated so far and destock its herd. Likewise, if it finds a pasture that would allow for more livestock than its satisficing threshold c_i, it will not keep more animals and potentially destock any surplus animals. As with the MAX type, we assume that this type is not influenced by others in its behavior ($s_i = 0$) and does not abide by resting rules ($q_i = 0$).

These three types are stylized representations of the empirical trends of behavioral change outlined in Section 2. Whereas the MAX type represents a rational "homo economicus" type of actor, the traditionalist TRAD and the satisficer SAT both represent bounded rational actors, as their behavior is guided by social norms or follows a decision heuristic, respectively (cf. Gigerenzer, 2001).

3.5. Individual sensing, interaction and heterogeneity

Households perceive the vegetation state (amount of green and reserve biomass available) of all pastures. Because households make their decisions one after the other in a random order, they sense the actions of other households indirectly by perceiving the grazing state of each pasture when they make their decision. The sensing is not erroneous, i.e., households always perceive the true biomass amounts. Interactions between households are indirect via the perception of the pasture state and the social norm. When running scenarios with household populations composed of mixed behavioral types, households differ in their behavior. However, within a single behavioral type, all households behave in the same way.

3.6. Analyzed scenarios and outcome measures

Our analysis is structured into two parts: In a first step, we consider populations of households that are all of the same behavioral type and analyze how the behavioral types perform with respect to ecological, economic and social output variables. Here, we specifically focus on the influence of demographic change (i.e., increasing the number of households N_H). In the second step, we simulate populations of households composed of mixed behavioral types. By varying the composition of the agent population (holding N_H constant), we can map the conditions of behavioral change. Because we are interested in the long-term sustainability of the system and the impact of demographic and behavioral change on resilience, we run each simulation over a time span of 100 years and then evaluate the final state of the system.
To measure resilience, Bennett et al. (2005) suggest monitoring attributes of the system that are measurable and related to resilience to select *resilience surrogates*. To evaluate the behavioral types in our model, we have selected indicators across three dimensions of outcomes: As a *social* indicator, we measure the number of households able to stay (i.e., "survive") in the system $N_{H,surviving}$, i.e., households with livestock numbers > 0 at the end of the simulation. The *economic* indicator is the cumulative herd size across all households L_Σ. As an indicator for the ecological state of the system, we measure the average reserve biomass of all pastures R_μ. Evaluating the

state of these variables with respect to demographic and behavioral change provides us conclusions regarding the resilience of the SES.

An overview of the analyzed model parameters and their values is presented in Table 1. For each parameter combination, we have carried out 100 simulation runs for the individual analysis of the three behavioral types (Section 4.1 and 4.2); 10 simulation runs have been carried out for the populations of all three behavioral types (Section 4.3), as here, the number of possible behavioral combinations for a given number of households is very large (e.g., 5151 combinations for 100 households).

Table 1: Overview of the analyzed behavioral parameters and their values or ranges. A table of all model parameters can be found in the appendix. R_{max} refers to the maximum reserve biomass per pasture, which is set to 1500 kg/ha.

Parameter	Value / range		
Number of time steps T	100 years		
Number of households N_H	[20,100]		
Resting threshold θ	{0.2, 0.4, 0.6}		
Mix of TRAD, MAX and SAT strategies Δ	all combinations of $\{N_{TRAD}, N_{MAX}, N_{SAT}\}$ with $N_{TRAD} + N_{MAX} + N_{SAT} = N_H$		
Behavioral types BT	TRAD	MAX	SAT
Intrinsic preference q_i	0.95	0.0	0.0
Social influence s_i	0.8	0.0	0.0
Satisficing threshold c_i	∞	∞	{50,80}
Satisficing trials p_i	-	-	10

4. Results

4.1. System dynamics over time

First, we present one exemplary simulation run for populations of households of the same behavioral type over 100 years to illustrate the general model dynamics (Fig. 3). The system starts in a completely non-grazed state with 10 animals per household. Livestock accumulates at the beginning of the simulation up to a maximum, where the carrying capacity in terms of biomass is reached. The cumulative livestock L_Σ in a population of MAX, respectively TRAD households, reaches a higher peak (~ 8500 animals) than in a population of the SAT households, as they maximize their herd size, whereas the SAT actors do not stock more animals than their satisficing threshold $c_i = 80$.

After this point, the cumulative livestock numbers L_Σ decrease for all three behavioral types, as biomass availability is now a limiting factor. When reserve biomass falls below the resting threshold $\theta = 0.4$, and the pastures are closed off for resting, some households in a TRAD type population have to leave the system, as they are unable to find a suitable pasture, and only 75% of the initial households survive. As the households in a MAX type population do not abide by resting rules, all households are able to survive. However, failure to rest the pastures leads to a breakdown of reserve biomass and, consequently, of livestock. In the TRAD type population, by contrast, the households achieve a moderate but stable level of reserve biomass and livestock. The SAT type does not actively abide by resting rules. However, because of its conservative satisficing threshold of $c_i = 80$ animals, it indirectly gives the pasture the ability to regenerate.

Even though reserve biomass and livestock levels drop below the levels of the TRAD type, they do not collapse but level off after 40 years and even slightly increase afterwards.

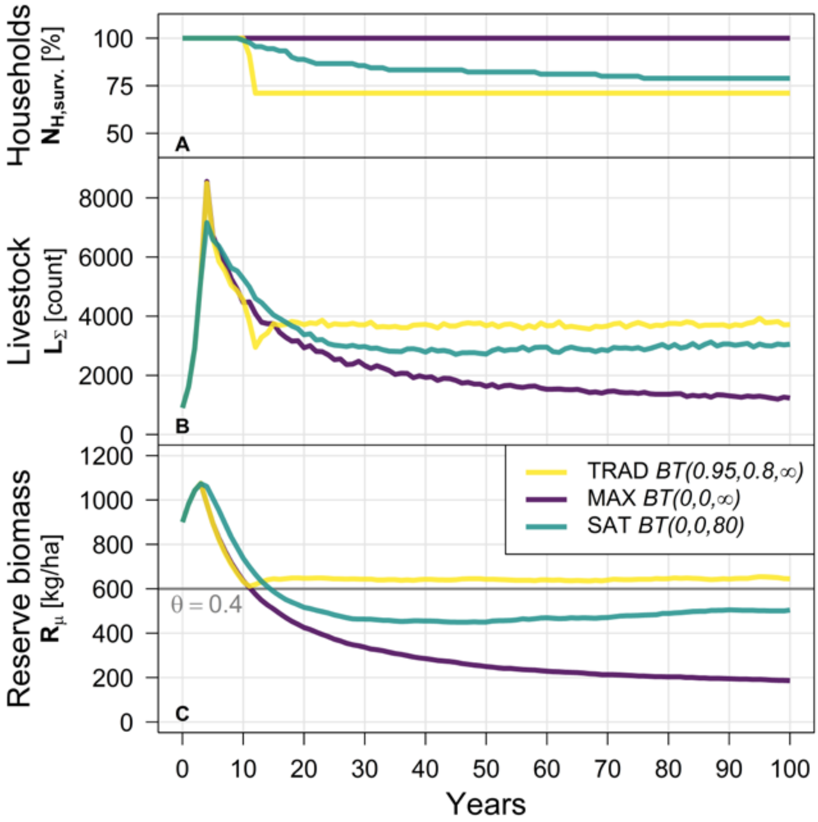

Figure 3: Exemplary simulation run over 100 years for the three behavioral types BT. Panels show: A) the percentage of surviving households $N_{H,surviving}$, B) the livestock sum L_{Σ}, and C) the average reserve biomass R_{μ}. The simulation started with $N_H = 90$ initial households, the SAT type had a satisficing threshold of $c_i = 80$ animals and the TRAD type an intrinsic preference $q_i = 0.95$ and social influence $s_i = 0.8$. The resting threshold $\theta = 0.4$ is superimposed in panel C.

4.2. The effect of demographic change

To investigate the effect of demographic change, we systematically assessed the effect of increasing the household numbers N_H, separately, for the three behavioral types: TRAD $BT(0.95,0.8,\infty)$, MAX $BT(0,0,\infty)$, and SAT $BT(0,0,\{50,80\})$.

We first looked at the number of surviving households $N_{H,surviving}$: As the number of households increases, competition over pasture biomass intensifies, which then leads to different outcomes for each household behavioral type. For the TRAD type (Fig. 4A), we see that the resting threshold θ has a strong effect. The intrinsic preference of all TRAD households is high, and the resting threshold forbids certain pastures to be used, so some households cannot find a pasture to graze. The higher the resting threshold θ and the number of households N_H, the stronger is the competition for accessible pastures, which forces more households to leave the system. By contrast, for populations of MAX type households, $N_{H,surviving}$ is always 100% (Fig. 4D), as they use all pastures irrespective of their state. The population of SAT type households (Fig. 4G), although not abiding by resting rules, shows a different behavior depending on its satisficing threshold: for $c_i = 50$, all households are able to survive since small herds do not overuse pastures. For a higher satisficing threshold $c_i = 80$, $N_{H,surviving}$ decreases for initial household numbers larger than $N_H = 60$. As populations of SAT type households only carry out a limited number of trials p_i to find a suitable pasture, the chance of not finding such a pasture and therefore leaving the system increases with an increasing number of households N_H (for an analysis of the effect of p_i, see supplement S2).

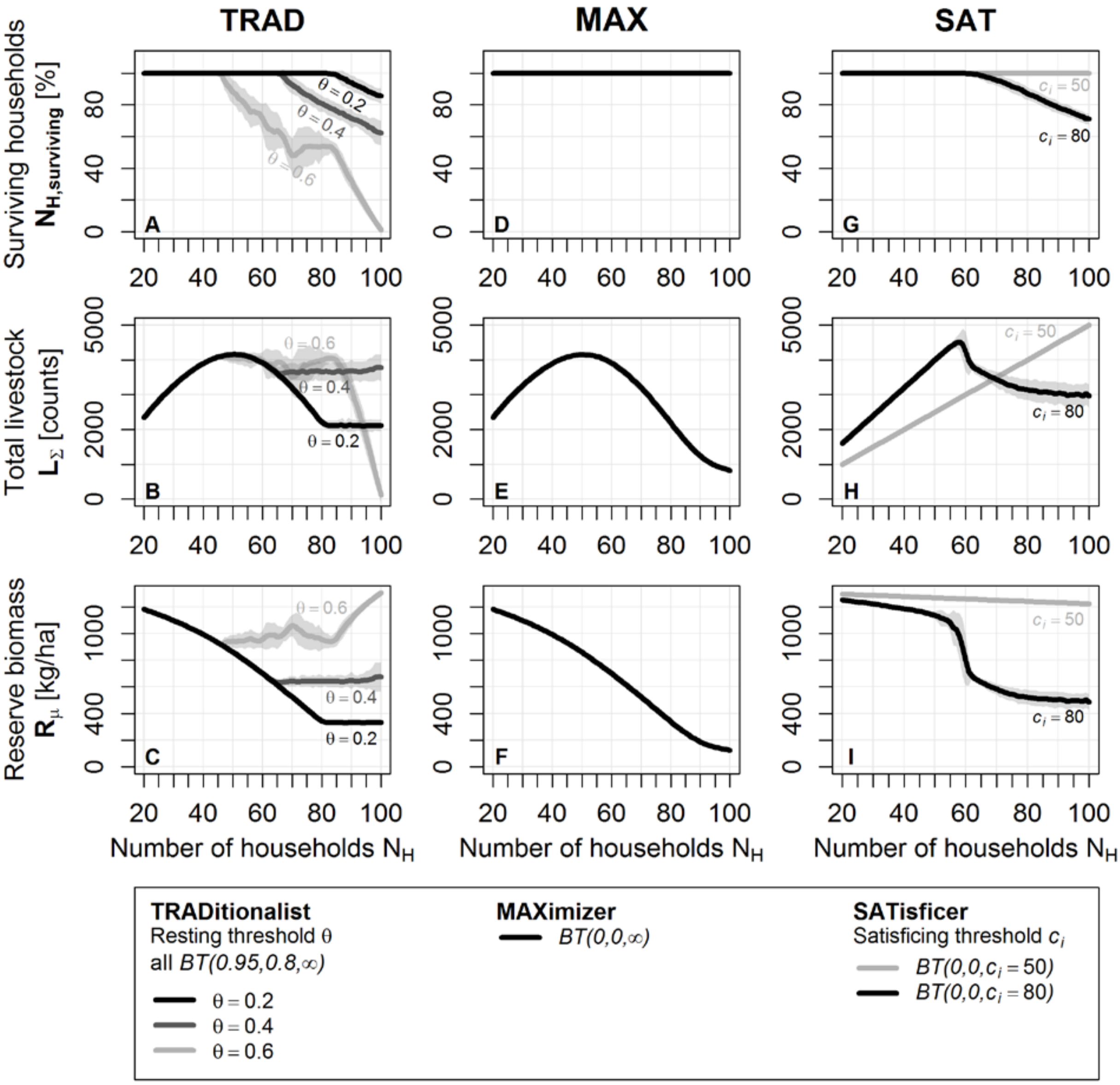

Figure 4: Results for the TRAD, MAX and SAT type households depending on the initial number of households N_H. The lines depict averages across households/patches at the end of the simulation ($t = 100$) over 100 simulation runs. The shaded area represents two times the standard deviation of the results.

Looking at the cumulative livestock numbers L_Σ (the sum of livestock across all households), we see that the TRAD and MAX type populations show a maximum number of animals at $N_H = 50$. While the cumulative livestock L_Σ in the MAX type population tends to zero (Fig. 4E) for N_H approaching 100, the TRAD type population keeps livestock at a stable level, depending on the resting threshold θ (Fig. 4B). As the MAX type does not abide by resting rules, it overexploits the pastures, which is apparent from the declining levels of the reserve biomass (Fig. 4F). The TRAD type avoids this degradation of the ecological system, and a higher resting threshold leads to improved pasture conditions.

For the SAT type population, the cumulative livestock curves exhibit a different shape: for $N_H \leq 60$, both curves increase linearly, indicating that the households are always able to achieve their satisficing threshold. At $N_H = 60$, the $BT\ (0,0,80)$ type population reaches a peak livestock sum of 4800 head, after which it decreases. Furthermore, beyond an initial number of 70 households, the $BT(0,0,50)$ type population achieves the highest cumulative livestock L_Σ compared to all other strategies. Populations of SAT type households reach a higher peak livestock level than those of MAX or TRAD type households due to their conservative stocking that allows pasture regeneration. At the same time, herd sizes remain at a stable level over the long term. The difference between both SAT types is also reflected in the state of the reserve biomass R_μ (Fig. 4I): for a low satisficing threshold $c_i = 50$, the reserve biomass hardly decreases. For $c_i = 80$, however, the satisfaction need of households exceeds the regeneration capacity of the pastures for household numbers $N_H > 60$, which leads to a sharp drop of the reserve biomass levels.
From this analysis, we see that under low to medium household numbers, pasture resources are in a sufficiently good state, so that populations of all three behavioral types achieve similar outcomes. For high household numbers, however, all three behavioral types exhibit a very different behavior across the social, economic and ecological analysis dimension.

4.3. The impact of changes in the distribution of behavioral types in the population

We now explore populations that are composed of all three household behavioral types. This reflects the outcomes of social transitions that can be observed in several pastoral systems. Each population can be described by a share of household types $\Delta = \{N_{TRAD}, N_{MAX}, N_{SAT}\}$ with $N_{TRAD} + N_{MAX} + N_{SAT} = N_H$ for a given number of initial households N_H. Here, we examine the case of a very dense system with $N_H = 100$ initial households and focus on two values of the resting threshold, $\theta = 0.2$ and $\theta = 0.6$ (Fig. 5 left and right panel, respectively). We present the results for the social, economic and ecological outcome measures in the form of ternary plots, where each axis defines the share of one behavioral type BT. Each point k of the graph, therefore, corresponds to one specific share of behavioral types Δ_k. The outcome measures have been classified along equally spaced intervals (see Fig. 5).
As a starting point, we chose a population that is close to a pure TRAD type population with only a few MAX and SAT type households integrated, which we mark as Δ_A in the plot (the origin of both red arrows). We believe that this distribution reflects the population "how it was" – a stylized case in traditional pastoral communities, i.e., before the onset of the change. We can now interpret moving across the space of combinations of behavioral types toward Δ_B and Δ_C as potential trajectories of behavioral change.
For a low resting threshold $\theta = 0.2$, no strong qualitative changes occur in a wide area around Δ_A. Following the trajectory from Δ_A toward Δ_B reflects the shift from a TRAD type to a MAX type "monoculture" population (for a detailed analysis of the shift from a pure TRAD to a MAX population, see supplement S3). Here, we see that for cumulative livestock L_Σ (Fig. 5 B1), only an increase in N_{MAX} to more than 75 ($N_{TRAD} < 20$) will lead to a noticeable drop in L_Σ below 2000 animals. The same decline is apparent for the reserve biomass R_μ with a biomass in a very low quasi-degraded state.
Assuming an increase in the share N_{SAT} of the SAT type households (moving toward Δ_C), cumulative livestock numbers remain in a range of 2000-2500 animals until a share N_{SAT} of at least 40 households is reached. Above $N_{SAT} \approx 30$, the class breaks run parallel to the isolines of

N_{SAT}. This indicates that above a certain share of the SAT type households, the explicit shares of the MAX and TRAD type households have no effect on livestock.

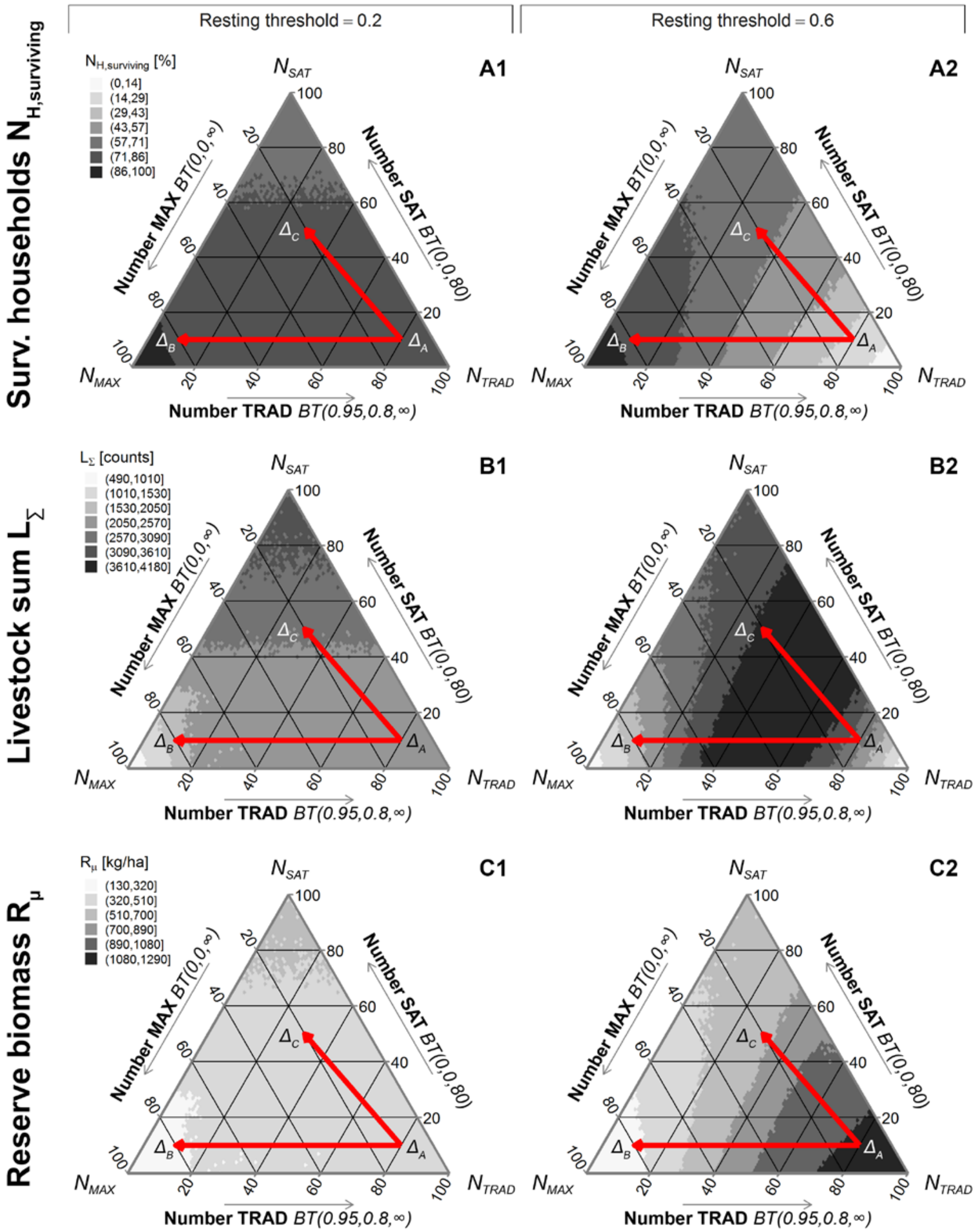

Figure 5: Comparison of the three behavioral types TRAD, MAX and SAT. Each axis defines the share of one behavioral type. The results are shown for two values of the resting threshold, θ = 0.2 and θ = 0.6 (left and right panel, respectively). Outcome measures have been classified along equally spaced intervals $\zeta(x)$: for surviving households (A1, A2) $\zeta(N_{H,surviving})$ = 14%; for livestock (B1, B2) $\zeta(L_{\Sigma})$ = 520 counts; and for reserve biomass (C1, C2) $\zeta(R_{\mu})$ = 190 kg/ha.

When we turn to the results for a high resting threshold $\theta = 0.6$, we see that the qualitative pattern changes: In a large range of mixing ratios of household behavioral types (all shares with $N_{TRAD} > 30$), the borders between the classes of the outcome measures now run parallel to the isolines of the share N_{TRAD} of the TRAD type households. At Δ_A, a TRAD type monoculture population keeps the ecological state in a very good condition (Fig. 5 C2). However, such a high level of reserve biomass can only be achieved at the expense of livestock and surviving households, which are both at a very low level (Fig. 5 A2 & 5 B2). Already, a slight decrease in the share of the TRAD type households to approximately 65 leads to a sharp increase in cumulative livestock and an increase in the percentage of surviving households. This, of course, leads to a decrease in reserve biomass, as households that do not abide by resting rules (MAX or SAT types) use pastures not accessed by traditionalist households.
A striking result is the large range of combinations of the three household behavioral types that are economically most productive (in terms of the cumulative livestock L_{Σ}) among all behavioral combinations. For the shares of the TRAD type households between 70 and 35, the results are also independent of the shares of the MAX and SAT type households in the population. However, as N_{TRAD} decreases further, breaks between classes are not parallel to isolines of N_{TRAD} but are shifted. In fact, the lower the share of the TRAD type households, the higher is the difference between the MAX-TRAD and SAT-TRAD populations (see supplement S4 for details). Thus, an increase in the share of the SAT over MAX type households can effectively increase the herd size when the number of the TRAD type households decreases.

5. Discussion

5.1. The value of traditional strategies in a changing world

With this study, we investigated the influence of human behavior on the resilience of a semi-arid pastoralist system. We implemented three household behavioral types that reflect – in a simplified representation – livelihood strategies of pastoralist households as they were in the past (TRAD) and the direction in which they are evolving currently (MAX, SAT). We have seen that these behavioral types represent integral aspects of the identity of the system and that a change from one type to another can have a strong impact on the ecological, economic and social dimensions of the system. A change toward a more conservative stocking approach, as applied by the bounded rational satisficer (SAT), can tolerate larger household numbers and thus increases resilience toward demographic change. A lower stocking level, though, is only realizable if households have some other source of income to satisfy their needs and secure their livelihood. In the following, we will discuss the effect of change on the identity of the system and its implications for resilience (see Table 2) and highlight empirical evidence from several regions.
Traditionally, the use of common property pastures has always been subject to norms and sanctions that are determined at the community level (Galaty 1994; Ruttan 1999). However, traditional pastoral strategies are increasingly under pressure. López-i-Gelats et al. (2016), for example, reported that livelihood options of pastoralists are becoming narrower, as pastoralists face a decreased access to rangelands and difficulties in conducting customary management practices. This increases the likelihood that households may adopt different behavioral strategies. In addition, many pastoralist regions are facing demographic change. In many East-African countries, for example, population growth is high, leading to a higher competition over already scarce resources while at the same time contributing to declining vegetation conditions (Pricope et al. 2013). In addition, people who newly enter the system might challenge traditional strategies:

in Mongolia, new herders who settled in the region only after the privatization of the herding collectives in the 1990s were more likely to violate rights to pasture and to graze reserve pastures out of the season (Fernandez-Gimenez 1997).

In our model, the traditional household type reflects a strategy that values both herd size and the ecological state of the pastures. However, as it is socially susceptible to the behavior of others, it also reflects that herders most often act in consensus with other herders of their community. The traditional strategy represents a source of continuity (see Table 2) to maintain livestock and pasture conditions and is thus an integral part of system identity. A loss of the traditionalist household type will therefore also lead to a loss of system identity and resilience. However, the changes in households' behavioral strategies will determine whether the system moves toward a desirable or undesirable state.

When people gradually adjust their preferences for resting in favor of increasing their own wealth, other pastoralists might follow suit, leading to the following: a) a marginalization of those who try to stick to the rules and b) a long-term breakdown of the system, as piece by piece resources are overexploited. We observed this behavior in our model when we simulated household populations with a gradually increasing share of the MAX household type in relation to the TRAD household type: already, a small percentage of the MAX type households that do not abide by the resting rule could lead to the TRAD type households either changing their behavior (not resting anymore) or losing their herd and exiting the system, as they were unable to find suitably rested pastures. Thus, if household numbers increase and households are less likely to follow traditional norms, the system is prone to lose its identity. Here, the loss of system identity and resilience will cause a transition toward an undesirable system state. In most communities, however, such 'free-riding' behavior would be subject to sanctions, which we have not included in the current model. Rasch et al. (2016), for example, showed that sanctioning norm-violating behavior decreases the probability of a collapse of the SES. Similarly, Wang et al. 2013 demonstrated the effectiveness of punishment of free-riders to maintain cooperation among the pastoralists.

This emphasizes the role of social norms as a source of continuity to enhance the resilience of the SES. Therefore, governmental interventions or measures aiming at enhancing pastoralists' livelihood should be designed in such a way that they strengthen traditional institutions and norms rather than undermining them. Not without reason, it has been argued that environmental regulations based on traditional customs and sanctioned by community institutions are more likely to be respected than those imposed by external authorities (Ruttan 1999).

So far, we have reflected on factors that might challenge the traditional values and livelihood strategies of pastoralists. However, there also exist strategies that can avoid negative effects, as the satisficer household type (SAT) has shown in our model. The main idea behind the SAT household type is that households might reduce the level of livestock that they need to keep by diversifying their income sources. Households with a (reasonably) low satisficing threshold in terms of herd size ensure that pastures are rested, as they reduce the pressure on the pasture. Our simulation results have shown that this strategy can be long-term sustainable, even though households do not directly abide by resting rules. Moreover, from the viewpoint of the whole population of households, the SAT household type could tolerate the highest total number of livestock in the system. Therefore, the satisficer household type represents a *source of innovation* (see Table 2). Although a change to the satisficer household type also changes the identity of the system, it can drive the system toward a new desirable state with improved household livelihoods that may be more resilient under change. Here, the indirect resting of pastures is an important mechanism to ensure pasture productivity and enhance SES resilience.

As mentioned in the introduction, there exist several options for pastoralist households to spread their risk of relying on livestock production and diversify their income sources. Especially, international labor migration plays an important role currently. However, diversification does not always constitute a voluntary adaptation strategy: in the Borena zone in Southern Ethiopia, the pastoralists are increasingly engaging in crop cultivation, but their motivation to do so varies by wealth; for the poorest households – those who have lost enough livestock to survive on pastoralism alone – farming is a matter of necessity; and only for wealthier households, farming is a diversification and risk mitigation strategy (Dressler et al. 2016; Solomon et al. 2007; Tache and Oba 2010). This indicates that income diversification is a strategy that is only feasible for pastoralists with the necessary means to do so. In addition, a similar diversification from pastoralism to agro-pastoralism that relies mostly on high-risk rain-fed cultivation has been observed in Kenya (Boone et al. 2011).

Table 2: Impact of change on the different aspects of system identity. The impact of change is compiled from empirical literature and linked to the modeling results to draw implications for system identity and resilience.

Aspect of identity		Impact of change	Implication for system identity and resilience
Components	Households	Population growth (Gruschke 2011, Robinson et al. 2010, Ganya et al. 2004)	Increasing pressure on the current state of the SES and system identity may lead to loss of resilience.
	Livestock	Increasing herd sizes (Robinson et al 2010)	
	Pastures	Less land available (Wario et al., 2016; Pricope et al. 2013; Gruschke 2011, Ganya et al. 2004)	
	Livestock-based livelihood	Declining livelihood options (López-i-Gelats et al. 2016, Robinson et al. 2010)	
Relationships	Pasture use	Increased grazing pressure (Alemu et al. 2015; Robinson et al. 2010)	Increasing pressure on the current state of the SES and system identity may lead to loss of resilience.
	Land tenure	Privatization of land and property (Gertel 2015) Expansion of agricultural land into former grazing areas (McPeak et al. 2015, Tache and Oba 2010)	
Innovation	New behavioral types	Higher profit orientation, commercialization of livestock production (Fratkin 2001, Zaal et al. 1999) Income diversification (Boone et al. 2011; Gruschke 2011; Calkins 2009; Solomon et al. 2007)	Transition toward new behavioral types leads to *loss of system identity and resilience.* Maximizer causes breakdown of herd sizes and pasture condition → transition to *undesirable system state*. Satisficer is less dependent on livestock, reduced grazing pressure provides indirect pasture resting → transition toward *desirable system state* possible.
Continuity	Traditional norms and rules	Customary institutions and regulations losing influence (Gertel 2015; Ruttan 1999) Traditional rules no longer carried out (Fernandez-Gimenez 1997) People changing their values (Goldmann 2013; Galvin 2009)	Traditional household types efficiently manage pastures and livestock → *social norms can preserve system identity and thus be a generating mechanism for resilience.* Increase in household numbers above critical threshold challenges traditional type → demographic change can lead to *loss of resilience.*
	Pasture regeneration capacity	Increased grazing pressure leads to reduced pasture regrowth (Hein 2006; O'Connor 1994; O'Connor & Pickett 1992)	Pasture resting (direct or indirect) is necessary to ensure long-term pasture productivity → maintain system identity.

5.2. The mode of human decision-making matters

Humans and their behavior represent a key uncertainty for sustainable management. The rising popularity of ABMs that allow the flexible integration of individual decision-making has produced a number of studies that represent human decision-making explicitly (Groeneveld et al. 2017, for the field of land-use ABMs). However, many implementations of the decision-making process are based rather on ad hoc assumptions and only seldom on behavioral theories of economics, psychology or sociology (Crooks et al. 2008; Groeneveld et al. 2017). In recent years, a rethinking has taken place that argues for an explicit integration of more sophisticated models of human decision-making into formal models of natural resource use and ABMs in particular (Schlüter et al. 2017; Crooks et al. 2008; Parker et al. 2003). In this study, we have explicitly posed the question of how the composition of households representing different behavioral types affects the long-term dynamics and resilience of a pastoralist grazing system. We represented the decision-making of pastoralist households according to economic and psychological theories and have especially considered the role of social norms, which are known to be a key element that influences human decision-making. Social norms have been widely studied in the social sciences (e.g., Berkowitz 1972; Bandura 1977; Kallgren et al. 2000; Borsari et al. 2003; Goldstein et al. 2008). Descriptive norms (that describe how people behave) have been studied, in particular, for environmentally related problems, e.g., by Schultz et al. (2007) in the context of energy-saving behavior, or by Cialdini et al. (2003) on pro-environmental behavior. However, in the context of the SES, descriptive norms have only rarely been considered (one example being the work of Feola and Binder 2010). Using agent-based modeling, we demonstrated the following: a) the importance of considering human decision-making for the analysis of SES-dynamics and b) the role of social norms as mechanisms to maintain the resilience of the pastoral system. Especially, the modeling of heterogeneous agent populations has already shown that small changes in household's values, i.e., their preference toward pasture resting, can lead to drastic changes in the long-term dynamics of the SES. Modeling a descriptive norm on pasture resting has shown that abiding by common resting rules can sustain herd sizes and pasture conditions, provided that overall household numbers keep below a critical threshold. Although we have not included a sanctioning of norm violation in our model, the combination of a social norm and effective sanctioning is a likely mechanism to generate SES resilience.

Another reason for the limited use of social science theories in models of SESs can be attributed to the difficulty of implementing a theory such as descriptive norms within a dynamic modeling context. Theories often face ambiguities when they are translated into formal equations and model code, and modelers need to make assumptions to achieve a functional implementation (Schlüter et al. 2017). Here, using the *MoHuB* framework (*Mo*delling *Hu*man *B*ehavior, Schlüter et al. 2017) has helped to conceptualize the behavioral types (TRAD, MAX and SAT) in the model. One step in which the framework has been especially useful was to uncover missing elements within a theory that need to be specified or filled with elements from another theory. Descriptive norms, for instance, do not specify how the selection process occurs; therefore, we integrated two processes, maximizing and satisficing, to fill this gap. Still, implementing a behavioral theory is not a straightforward task but rather an iterative process, even for such rather simple behavioral theories. Implementing more complex models of human decision-making, therefore, requires a stronger involvement of social scientists into the modeling process.

5.3. Conclusion

In our study, we have shown that pastoralist households might increasingly be under pressure when social and demographic change renders their traditional livelihood strategies as no longer viable. As households adjust their strategies, policies that aim at enhancing their livelihood should consider the inherent variability of dryland areas that makes some strategies less likely to be successful (e.g., intensification of production). One option that can help to secure household's livelihood and maintain the resilience of the SES lies in income diversification. This gives households the chance to spread their income risk and can reduce the pressure on the ecosystem because households do not need to rely completely on raising livestock and can lower their stocking rates. However, social norms also provide a mechanism to maintain resilience if the number of households does not exceed a critical threshold.

In a stylized ABM of a common property grazing system, we have implemented three different behavioral types based on social theory and empirical observations. Here, the comparison of heterogeneous agent populations with mixed behavioral types enabled us to draw conclusions about the system's resilience: whereas a displacement of the traditional household type by a short-term profit maximizer can move the system into an undesirable state, such negative ecological and economic consequences can be prevented by a satisficer household type that tries to diversify its income sources. This proves that the way human decision-making is represented in ABMs matters and simply assuming household's decision-making to be homogeneous and rational (as many social-ecological models still do) will leave out important details. Thus, we need more social science research in conjunction with ecological research (Ruttan 1999). Researchers who aim to analyze SES and their resilience should give greater attention to the impact of human decision-making.

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