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Mobility – a panacea for pastoralism? An ecological-economic modelling approach.

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Abstract: Nomadic systems around the world are subject to changes in economic, social and climatic conditions. Often traditional tenure regimes based on ethno-lineages have been transformed to privatized pastoral systems with individual access regimes. Mobility, a basic principle of nomadic life, is undergoing fundamental changes: On the one hand side the loss of mobility and increased sedentarisation is widely discussed topic, but on the other hand, the introduction of new transportation technologies like trucks or new forms of communication and the availability of weather forecasts have led to an almost instantaneous availability of knowledge for the pastoralists and the possibility to rapidly move between pastures. The increased mobility is often attributed with a benefit in terms of herd size and condition, however, sustainable resource use especially in resource-scarce regions always faces trade-offs: Resting pastures and maintaining livestock at the same time is not easy. In an agent-based ecological-economic simulation model we explore mobility as one mechanism to enhance sustainability on a nomadic grazing system as well as possible negative effects of increased mobility on the long-term pasture quality and herd condition. We analyse the influence of agent density and movement costs on overall biomass and livestock numbers and identify thresholds above which mobility leads to degradation of the pastures and decline of livestock numbers for the pastoralist. These insights can be crucial for developing future policies and access regimes in pastoral communities.

Keywords: agent-based model, livestock, natural resource use, risk management, sustainability

1 INTRODUCTION

Nomadic systems around the world have been undergoing a wide range of transitions in the last century, including economic, social, political and climatic conditions. Sustainable and adapted natural resource use is a central topic in these regions that can be characterized as drylands, since resources are scarce and highly fluctuating. Drylands take up about 35% of the land surface (UNCCD [2010]) and pastoralism is the main way of life. Nomadic lifestyle that has evolved over the course of centuries is in decline and the loss of mobility and increased sedentarisation is widely discussed (Fernandez-Gimenez et al. [2006]). Contrary to that, new transportation technologies like trucks, cell phones as new forms of communication or the availability of weather forecasts have led to an almost instantaneous and omniscient knowledge of the agents in the system and the possibility to rapidly move between pastures. The increased mobility is often attributed with a benefit in terms of herd size and condition, but so far the downsides have rarely been addressed. Okayasu et al. [2010] investigate for instance under which level of costs for movement small and large flock herders coexist, but they do not incorporate feedback of feeding on pasture conditions, so that no information on long-term pasture degradation or sustainability could be
given. Using an agent-based simulation model, we address the question how mobility affects the long-term condition of the pasture and the livestock, if we can identify positive and negative effects of mobility and compare the influence of movement costs and agent density on the mobility pattern of the agents and the condition of pastures and livestock.

2 METHODS

2.1 Model description

We developed an agent-based simulation model that includes patches, agents and livestock as basic entities. The model is spatially implicit and patches resemble points in space. The area of a patch is assumed to be 100 ha. A number of \( n_p \) uniform patches is created at the beginning of the simulation and arranged in a regular, grid-like pattern on the landscape (illustrated in Figure 1 for \( n_p = 8 \)). The minimum distance between two neighbouring patches (\( d_{\text{min}} \)) is fixed, distances between arbitrary patches are calculated as Euclidian distances based on \( d_{\text{min}} \) and are then scaled with the movement costs \( cM \).

Biomass on each patch is modelled by two functional parts: green biomass \( G \), which comprises all photosynthetic active parts of the biomass and serves as the main fodder for the livestock, and reserve biomass \( R \), which summarizes the storage parts of the plant below and above ground. The vegetation model is based on the model in Mueller et al. [2007] and similar to Schulze [2011]. Though the vegetation model is very simplistic and does not consider topography or soil conditions, it is adequate for the scope of our analysis and has proven to be useful so far (cf. Mueller et al. [2007] and Schulze [2011]). A main driver of vegetation growth is the annual precipitation \( P \). Rainfall is modelled by a lognormal random distribution with a given mean and standard deviation and drawn individually from this distribution for each patch, i.e. we assume stochastically uncorrelated rainfall for each patch. In case green biomass is not sufficient to feed the herd, part of the reserve biomass can be consumed as well. Green biomass growth is mainly influenced by the amount of rain that has fallen onto a patch in the current year and the amount of reserve biomass from the previous year. Reserve biomass represents the backbone of the vegetation model. Its build-up depends on green biomass. Green biomass that is not consumed, termed green biomass over \( G_{\text{resm}} \), contributes to a faster growth of reserve biomass. Therefore reserve biomass is an indicator for the grazing and rainfall history of the system. For a detailed description of the vegetation model including the time-discrete difference equations, refer to Mueller et al. [2007] and Schulze [2011].

![Figure 1. Patch layout for \( n_p = 8 \).](image)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of patches</td>
<td>( n_p )</td>
</tr>
<tr>
<td>Number of agents</td>
<td>( n_a )</td>
</tr>
<tr>
<td>Area</td>
<td>( \text{area} )</td>
</tr>
<tr>
<td>Number of time steps</td>
<td>( T )</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>( \text{sim} )</td>
</tr>
<tr>
<td>Mean annual rainfall</td>
<td>( \rho_{\text{mean}} )</td>
</tr>
<tr>
<td>Standard deviation of rainfall</td>
<td>( \rho_{\text{SD}} )</td>
</tr>
<tr>
<td>Conversion factor of green in reserve biomass</td>
<td>( w )</td>
</tr>
<tr>
<td>Rain use efficiency</td>
<td>( \text{rue} )</td>
</tr>
<tr>
<td>Decomposition rate of reserve biomass</td>
<td>( m )</td>
</tr>
<tr>
<td>Limit of green biomass growth</td>
<td>( \lambda )</td>
</tr>
<tr>
<td>Maximal reserve biomass</td>
<td>( R_{\text{max}} )</td>
</tr>
<tr>
<td>Initial reserve biomass</td>
<td>( R_0 )</td>
</tr>
<tr>
<td>Reduced growth of reserve biomass due to grazing</td>
<td>( gr_2 )</td>
</tr>
<tr>
<td>Birth rate of sheep</td>
<td>( b )</td>
</tr>
<tr>
<td>Fodder intake per sheep</td>
<td>( \text{intake} )</td>
</tr>
<tr>
<td>Sheep price</td>
<td>( c )</td>
</tr>
<tr>
<td>Costs for moving</td>
<td>( cM )</td>
</tr>
<tr>
<td>Value of sheep on pasture</td>
<td>( cVP )</td>
</tr>
</tbody>
</table>
A number of $n_a$ agents, $n_a \leq n_p$, is placed on the patches, with every agent on a separate patch at the beginning. Every agent owns livestock $L$ (sheep) whose size is calculated in the first time step based on the available green biomass on the patch. Also, each agent starts with the same amount of monetary resources. Agents can move between patches in each time step, based on an optimisation criterion. The main goal of the agent is to maximize his monetary assets in each time step, which are calculated by stock size plus earnings from selling livestock and reduced by costs for movement $cM$. The costs for movement are normalized to the constant price of one sheep. The static optimisation criterion is very simplistic and does not involve optimisation over time. It does, however, include a factor $cVP$ that describes the long-term value of keeping a sheep instead of selling it. This is done to reflect the need of an agent to keep a minimal viable herd size that will ensure future income. To select the best patch for the next time step, for each patch the agent determines the number of sheep that he could keep there, $L_{\text{keep}}$, and how many sheep he would need to sell, $L_{\text{sell}}$, and how much he would need to pay to relocate his herd to the patch. Movement costs are calculated relative to the distance of the patches. Figure 2 shows a flow chart of the temporal sequence of all model processes. In each time step, precipitation and consequent growth of green biomass is first calculated for each patch, then livestock reproduction takes place.

**Figure 2.** Simplified flowchart of the main model processes. All round-cornered rectangles represent processes, rhombuses are conditionals.
The main part of the model is the patch selection process of the agents. In each time step the order in which agents act is randomized. Every agent checks first whether there is enough biomass to feed his livestock on his current patch. If so, he will not move but stay on the current patch and the livestock will feed on the biomass. If biomass is not enough, the agent will determine the best patch according to the cost benefit ratio as described before, including his current patch, which could still be the best patch but he needs to destock. If he found a new best patch different from his current patch, he will check if he can sustain his full herd on the new patch or if he still needs to destock part of his herd. Finally, he will adjust his monetary assets according to the distance he moved and the number of sheep he sold, if applicable, and the livestock will feed on the biomass of the new patch. After all agents have made their decisions, reserve biomass grows on all patches. The simulation is run with a time horizon $T$ of 100 time steps $t$. We consider yearly time steps. A full overview of model parameters and their standard values, respectively value range is displayed in Table 1. Though our model is conceptualized in a very general way to be applicable to different systems, we parameterized it to resemble the High Plateau in Morocco. Model parameters for the vegetation submodel have been calibrated in a sensitivity analysis by Schulze [2011]. For economic parameters, sheep price is taken from Charaani [2008], values for biomass intake are based on Les-Vegetaliseurs [2011] and Lazarev [2008], the range for movement costs is based on own sensitivity analysis.

2.2 Model analysis

The main question that we want to answer with this model is, whether mobility is always positive for pasture and livestock conditions or if mobility can also have negative effects. In a first analysis we therefore tested two hypotheses:

1) What influence does agent density have on pasture and livestock condition? Is there a density level at which pastures are prone to degradation if we assume no movement costs, i.e. high mobility is possible for every agent?
2) Does reduced mobility (incorporated in the model by higher costs for movement) lead to an improvement of pasture and livestock conditions? Can we find an optimal cost level to maximize these conditions?

If we can find a positive answer for question 2, a third question would obviously be:

3) What are the reasons for this relationship? How does movement behaviour change with increased agent density and movement costs?

To address these questions, we performed parameter variations for:

a) The number of agents within the system: $n_a \in [1,20]$, in steps of 1.
b) The movement costs of the agents: $cM \in [0.5,10]$, in steps of 0.5.

All other parameter values were kept fixed, especially the number of patches $n_p = 20$ and the implicit value of a sheep that is kept on the pasture $cVP = 5$. For each parameter combination 500 simulations have been run. As main output variables we selected reserve biomass $R$ as proxy of pasture conditions and herd size $L$ as proxy for livestock condition. The model was implemented as an object-oriented C++ program, values for all output variables were saved in spreadsheets and processed using the R Statistical Computing language (R Development Core Team, 2011).

3 RESULTS

3.1 The influence of agent density and movement costs

The parameter variation of the number of agents in the simplest case that assumes no movement costs shows a clear decline of pasture condition in terms of reserve biomass and livestock size for increasing agent density. Especially at medium agent densities, the amount of reserve biomass that is available on average on a patch at the end of a simulation drops down about 64% for a 10% increase of agent density from 10 to 12 agents. Comparably, mean livestock numbers drop from...
about 27 head to 9 head (67% decline) for the same scenario. For higher densities, both biomass and livestock quickly approach zero. Therefore, the results suggest that unconstrained mobility can lead to an unsustainable pasture usage already for a very moderate density of agents in the system under our model assumptions.

The second parameter variation did investigate the role of movement costs $c_M$. At the same time the number of agents was varied, resulting in a 20 x 20 matrix of parameter combinations. Again we compared the results at the end of the simulation and Figure 3 shows matrix plots of biomass and livestock with contour lines superimposed onto them. Additional bold lines highlight the optimal movement cost level, which generates the highest biomass, livestock etc. respectively for a fixed agent density. Here we can see several patterns:

1) Biomass and livestock variables decrease in general for increased agent density, as seen in the case of unconstrained movement. For low agent densities ($\leq 40\%$), movement costs seem to have no pronounced influence on all variables and biomass amount and livestock numbers are generally highest. Optimal values are reached for low movement costs except for green biomass over, which represent the amount of biomass that is not consumed at the end of a simulation and can therefore be interpreted as an indicator for pasture resting. This indicates that higher movement costs lead to a higher resting of pastures, but the difference at these low density levels is barely noticeable.

2) For medium agent densities (40-70%), the values for all four variables decrease very rapidly with increasing $n_a$, but higher movement costs lead to an improvement of pasture and livestock conditions, which is especially emphasized by the sudden jump of optimum curve of green biomass and reserve biomass from the lowest to the highest movement costs for $n_a = 6$. An

**Figure 3.** Variation of movement costs $c_M$ and agent density $n_a$. Average results for green biomass $G$, green biomass over $G_{over}$, reserve biomass $R$ and livestock $L$ at time step $t=100$ are shown. Bold line highlights the optimal movement cost level $c_M$, which generates the highest biomass, livestock etc. respectively for a fixed agent density $n_a$. 


equivalent threshold value exists for livestock at \( n_a = 9 \), only here the optimum is reached for \( cM = 8 \). The density increase leads to a penalization of high mobility because pastures don’t have enough time to regenerate between usages. Also, the differences between minimum and maximum values for a given cost value \( cM \) increase and reach an absolute maximum for reserve biomass, green biomass and livestock at \( n_a = 13 \) with values of 255 and 114 kg biomass/ha and 12 head respectively for the three variables.

3) At high densities (\( \geq 70\% \)), the optimum curve drops down to medium values of \( cM \) for all four variables. Not only too high mobility but also too low mobility results in worse pasture conditions, respectively livestock numbers. Intermediate movement costs penalize extreme mobility but still allow agents to move so that pastures can regenerate. Although the absolute difference between maximum and minimum values decreases with increased density (after the optimum value described in 2) ), the relative difference even increases for all four variables and stays constant at about 85\% higher values for \( n_a \geq 15 \). This means that with intermediate movement costs agents can maintain about 85\% more livestock and pastures carry about 85\% more biomass than for very high or very low movement costs.

3.2 Evaluation of agent movement

To fully understand the patterns and the mechanism that lead to them, we need to have a closer look on agent movement behaviour and how it changes with respect to agent density and movement costs. As the evaluation of section 3.1 suggests, different levels of movement costs seem to be important to optimise, respectively sustain the condition of pasture and livestock for different system densities. But how do these costs modify the specific movement behaviour of the agent? Figure 4 shows how often agents change their patches on average in one simulation, i.e. the frequency of movement, in relation to agent density \( n_a \) and movement costs \( cM \). The maximum frequency is obviously constrained by the number of time steps in one simulation (100). The amount of patch changes decreases with increasing density but more significantly with increasing costs – highest density but lowest movement costs still lead to 59 patch changes on average, whereas in the opposite case we only find a mean of 26 patch changes (this represents the bottom right and top left corners of Figure 4 respectively). If we compare the movement frequency of the agents with the results in Figure 3, we see that especially for low to medium agent densities, agent mobility decreases with rising costs but agents are still able to maintain approximately the same number of livestock and amount of biomass on the patches (comparing the shape of contour lines in both figures: straight vs. diagonal). A decrease in mobility therefore seems to forestall a worsening of the system conditions. At first sight it seems counter-intuitive that movement still happens when agent density is 100\% (i.e. \( n_a = n_p = 20 \)), therefore it is helpful to look at a realised movement pattern of an individual simulation for better understanding, shown in Figure 5 for low, medium and high costs and two different agent densities. Every coloured line represents average amount of patch changes of an agent in one simulation (=100 time steps) in relation to agent density and movement costs.
one agent and tracks his movement across patches over time. For a density of 60%, low movement costs lead to a quasi-chaotic movement pattern of the agents, they tend to move in almost every time step. With increasing values of \(cM\) movement becomes more and more regular, on average agents tend to stay longer on the same patch. But also for high costs, movement is still happening and we see that patches are quite often rested for a certain amount of time. For the extreme case of \(n_a = 20\), the movement starts chaotic as well for low costs but this pattern changes after about 20 time steps. Costs are so low that agents use every possibility to move so that also small amounts of remaining biomass are used, with the consequence that no pastures are rested. In the other extreme of \(cM = 10\), costs are too high to allow even small-distance movement; agents stay only on the same patch and pastures are not rested. Intermediate movement costs provide a tradeoff, where costs are low enough to allow movement but high enough to prevent constant usage of all pastures, so that resting of pastures is applied. We can see that not all agents are moving at all times and some patches are also used simultaneously by several agents. This emphasizes our hypothesis that there is an optimal level of mobility that can improve both pasture condition and livestock size over the long term.

4 DISCUSSION

As we have shown with our model, mobility is not positive per se but can also have negative effects on pasture and livestock conditions if it becomes too high and agent density is high. But still the model needs more analysis and refinement. One of the main advantages of the agent-based modelling approach is that we can address individual agents and track their decisions throughout the simulation and are still able to evaluate the system condition as a whole. Incorporating an optimisation criterion that also incorporates future livestock value can then become very complex because decisions of all other agents need to be incorporated as well. This would be an ultimate goal for a refinement of the model. Also keeping the
Table 2. Interpretation of effects of agent density and movement costs on biomass and livestock.

<table>
<thead>
<tr>
<th></th>
<th>Low density</th>
<th>Medium density</th>
<th>High density</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low costs</strong></td>
<td>System only sparsely populated No negative effects of mobility.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Medium costs</strong></td>
<td>Mobility too high. Negative effects on pasture conditions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>High costs</strong></td>
<td>Costs too low. All biomass reserves are used. No resting of pastures.</td>
<td></td>
<td></td>
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</tbody>
</table>

sheep price not as a fixed value but rather coupled to rainfall to create a more realistic economic scenario would be desirable. We conclude that mobility is not an answer to all problems pastoralism faces. The crucial mechanism behind is appropriated resting for the pasture. Mobility may enhance resting, but also can impede resting (see Table 2). Consequently to ensure ecologically and economically sustainable resource use in (semi-)arid areas, sufficient areas of pasture lands are the prerequisite. In current times this is reduced to a large extent by land grabbing and agricultural expansion on (falsely) so-called “no man’s land” – communal land of pastoralists.

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