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An agent-based model for assessing grazing strategies and institutional arrangements in Zeku, China

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ABSTRACT

The assessment of grassland grazing strategies and institutional arrangements is essential for ensuring the sustainable development of grassland grazing systems. By employing per-pixel grazing information derived from remote sensing data, this paper presents an agent-based model of grassland grazing (ABMGG) for Zeku, China that was designed as a framework for assessing the effects of different combinations of grazing strategies and institutional arrangements on grassland status. By calibrating the parameter values of the ABMGG to the system status values under a policy that has already been implemented, the ABMGG can help us to understand grassland degradation in response to management interventions for each patch of land. In the Zeku implementation, it was found that although different grazing policy scenarios could not significantly improve or decrease the overall grassland leaf area index, a rotational group grazing scenario with a land market tenure system did produce a smaller number of severely degraded grass patches than other policy scenarios (except regional continuous grazing). This provides a new perspective on the consequences of grassland management practices where past research has concentrated more on overall grassland productivity. The ABMGG can extend the ability of policy assessment tools to a high resolution level with pixel-specific real-time remote sensing data, making the assessment results more accurate and representative.

1. Introduction

Grazing is the most common activity on grassland that can affect the grassland system (Adler et al., 2001). There is evidence for the impact of different grazing patterns on: the movement and persistence of other organisms (Gonzalez et al., 1990; Hahn and Höfle, 2001; Qu et al., 2016); plant functional traits (Cingolani et al., 2005); and, the redistribution of species composition (Frank et al., 2016) and nutrients (Ford et al., 2016). Particularly in semi-arid terrestrial grasslands, grazing plays a critical role in the continuous and directional changes of grasslands at different time-scale and compositional gradients (Moreno García et al., 2014; Porensky et al., 2016).

For grazing grasslands that are overseen by herders or managers, grazing strategies are important management tools. Rotational and continuous grazing strategies may have little effect on the frequency, severity or variation of grazing-led grass defoliation (Hart et al., 1993) and its botanical composition (Taylor, 1989) if the stocking rates remain the same. Compared to standard rotational grazing, grasslands subject to intensive rotational grazing, with a higher number of subdivisions given over to longer resting periods, preserve the storage biomass more closely to maximum yield, and therefore can maintain higher stocking rates (Barnes et al., 2008; Jakoby et al., 2014; Savory and Parsons, 1980; Teague et al., 2011). The rotational grazing strategy increases income and improves rangeland conditions, but might demand high management costs (Beukes et al., 2002) and the risk of forage shortage if livestock stocking rates are too high (Hart et al., 1993).

In addition, institutional arrangements can affect grassland systems. Research on the institutional arrangements targeting grazing removal on grasslands, which have largely been implemented in Sanjiangyuan, China (Lu et al., 2015; Wang et al., 2010), suggests such policies run the risk of exacerbating both poverty and degradation (Yeh, 2009). Land market institutional arrangements can aggregate grazing land into larger units, which can better achieve an efficient allocation of grassland resources and economies of scale in livestock production (Gongbuzeren et al., 2016). The complex and comprehensive nature of the impact of different grazing strategies and institutional arrangements (Briske et al., 2015) on the ecological, socio-economic and climatic conditions (Campbell et al., 2006) of grassland systems should be considered before selecting robust management strategies and institutional arrangements (Hart et al., 1993; Thornton et al., 2009).

In the last few decades, the policies and institutions have changed

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dramatically, and in many places, a great deal of common grasslands are being privatised to households by contract, or are being permanently redistributed (Archambault, 2014; Humphrey and Sneath, 1999; Ojanen et al., 2014; Wisner, 2012). The initial motivation of privatisation was to create a better incentive for herders to improve the productivity of grasslands (Conte and Tilt, 2014; Fernandez-Gimenez et al., 2015; Moritz et al., 2015). With the privatisation of grasslands, the behaviours and decision-making of herders have changed in response to dramatic changes in the relationship between herders and institutions (Jun et al., 2013), for example, the herders can rent or lease lands from the other herders, rather than competitively maximize the use of common grasslands. The decision-making of herders can be affected by high-level institutional arrangements, which, in some places, essentially amount to group management. For example, in China's grasslands, the government has encouraged the herders to join a grazing group by investing their land or livestock (Xiaoyi, 2007). How these new institutional arrangements and grassland policies affect the performance of the grassland grazing system is an important topic in sustainable grassland development. At this point, agent-based modelling has proved to be an effective tool for evaluating the effects of different institutional arrangements on the grassland grazing system caused by herders' decision-making (Jun et al., 2013).

The agent-based model of the grassland grazing is usually linked to ecological and socio-economic sub-models. The ecological sub-system is a simplified version of the more comprehensive model, and the relations are usually empirically based Gross et al. (2006). As such, an example would be a socio-economic sub-system that typically affects the decision-making of the 'regulator' or the behaviour of pastoralists. The regulator comprises the policy and institutional environment within which pastoralists make management decisions. The decision-making processes of the regulator or the pastoralists should ideally be based on theory (although *ad hoc* assumptions are widely used in ABMs) (Abel, 1998), involving cultural anthropology, economics, organisational and management practice, and political-economic background (Levin et al., 2013). Janssen et al. (2000) built an adaptive agent model, which included the competition between grassland shrub and heterogeneity in the vegetation growth rate, but the *ad hoc* assumptions, such as the linear relationship between stocking rate and grass biomass, assumed a threshold of good and bad conditions that limited the use of this model in other regions. Similar research was carried out by Gross et al. (2006), who built a conceptual framework of an adaptive ABM, trying to link climatic conditions, biophysical processes and institutional arrangements; however, the fixed stocking rate assumption, and the assumed values of the parameters in both the biophysical and pastoral sub-models made the results susceptible to uncertainties caused by such settings. Jun et al. (2013) analysed the socio-ecological performance of different institutional arrangement experiments using an ABM that revealed cooperation mechanisms under climate change adaptation (Jun et al., 2013), but the absence of explicit per-pixel productivity and livestock grazing data in the model make the results less convincing. Sakamoto (2016) developed an ABM based on remote sensing data. In this model, the movement behaviours of the pastoralists were driven by the availability of local resource, as represented by vegetation index and movement costs. The spatiotemporal patterns of land use intensity caused by movement of the pastoralists were produced; however, there were numerous *ad hoc* assumptions related to the behaviour of the pastoralists (for example, grazing range, frequency and carrying capacity) that, made the model less credible when applied to a place where conditions violated those assumptions. The results of the model have not been validated, and the effects of different grazing strategies and institutional arrangements were not considered in the model. In addition, Troost and Berger (2014) analysed the uncertainty of the ABM at the farm level. The importance of interactions among agents was highlighted in this fully connected ABM, addressing the uncertainty in the model structure, as well as gaps and fuzziness caused by data uncertainty and *ad hoc* model assumptions, but finding that uncertainties can be reduced by cautious calibration and a comprehensive uncertainty analysis.

To conclude, it appears from the literature that the common characteristics of the approach and its defects in modelling of grassland grazing are:

- the biophysical parts in the ABM of grassland grazing systems are commonly empirically based, which means that the development of the vegetation is highly dependent on historically observed data, and so such ABMs share all of the defects that are present in the empirical model;
- ABMs of grassland grazing systems usually involve input from a lot of datasets, parameter values and *ad hoc* or theory-based assumptions, and they are sometimes derived from data containing uncertainties. However, there are few types of research that address such uncertainty, which is partly due to the difficulty of collecting data or carrying out experiments. It is also important to balance modelling complexity with uncertainty (Holling, 2001); and
- the aggregated overall regional/farm/site-scale dynamic of the vegetation or the livestock can be well represented in the model output, but spatial distribution patterns are rarely seen in the existing research, especially models with patch-specific real-world data.

In summary, prior research has been limited by the absence of data on one or more of: patch-specific grazing; individual grazing strategies; and institutional arrangements. This paper presents an Agent-based Model of Grassland Grazing (ABMGG) that attempts to address the drawbacks of the current state-of-the-art. By incorporating per-pixel grazing information derived from remote sensing data, the aim is to assess land degradation status under different combination of grazing strategies and institutional arrangements based on individual interactions and decision-making centred on patch-specific grazing information. In addition, the uncertainty of the model will be explored, which will further credit the reliability of the modelling results.

2. Methods

2.1. A proxy of plant status: leaf area index

As summarised above, the lack of patch-specific grazing and grassland productivity data hinders further research on grazing systems, especially large-scale studies. This study used leaf area index (LAI) as a proxy for plant status. The LAI is generally defined as the total one-sided green leaf area per unit ground area for flat broadleaf plants (Monteith and Reifsnyder, 1974) or one-half the total green leaf area per unit ground area for conifers needles (Chen and Black, 1992). In this study, the LAI after grazing was the focus because:

- LAI after grazing is an indicator for the evaluation of grassland status, and whether LAI after grazing is significantly different under various grazing management scenarios was to be explored through the ABMGG; and
- degraded patches (see Section 2.3) are classified based on the ratio of LAI after grazing and full-growth LAI, and the number of degraded patches is another important concern in the evaluation of overall grassland status.

The patch-specific grazing-led LAI changes and the full-growth LAI (theoretical LAI if no grazing happens) were calculated following Yu et al. (2018):

$$L_{full\,growth} = L_m + L_0 e^{k_1 t - k_2 t^2 + C} \quad (1)$$

where $L_{full\ growth}$ is the theoretical LAI value without the effects of previous grazing or current grazing; t is the day of the year, and for

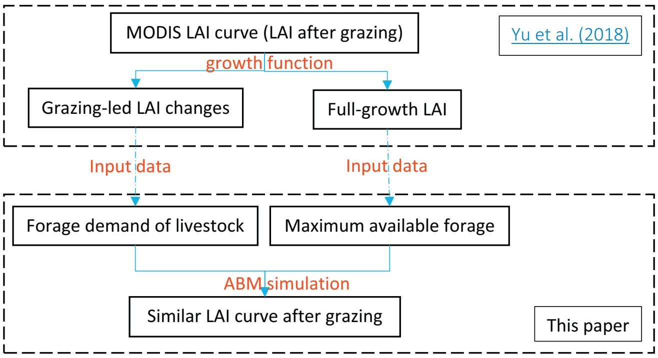

Fig. 1. The patch-specific data source in the ABMGG.

example, $t = 1$ means the beginning of the calendar year (January 1st); L_m is the background LAI, L_0 is the initial LAI, k1, k2 and C are the parameters describing growth and senescence of the grass, as estimated by Yu et al. (2018). In this paper, the grazing-led LAI changes (direct changes in LAI caused by grazing) were used as forage demand for every eight-day period for each patch, and the full-growth LAI was used as the maximum available forage in each patch (Fig. 1). The aim was to produce a similar LAI curve after grazing (by calibration) as it has been observed in the MODIS LAI. Then, a scenario analysis was carried out in order to assess the effects of different grazing strategies and institutional arrangements on grassland status.

2.2. Grazing strategies and institutional arrangements in Zeku, China

The ABMGG was designed to assess the effects of different combinations of grazing strategies and institutional arrangements on grassland status. Grazing strategies include rotational, continuous and ungrazed land use (land reserved for winter use or other purposes). There are two institutional arrangements in Zeku—group grazing and land market tenure. Group grazing is essentially a cooperative farming policy in which herders share individually tenured land parcels. Rotational grazing is ubiquitously adopted in group grazing in the case study area—Zeku, China. In land market tenure, one herder rents or leases land from another herder at the beginning of the year, and then they can put some of their livestock on that rented land. This is a kind of smaller-scale group grazing, but in line with market demand. As with other areas in China, the land market occupies only a small proportion of the overall institutional arrangements due to a lack of willingness to lease land to strangers and the high costs of renting (Wang et al., 2013).

2.3. LAI after grazing in the ABMGG

This section provides an introduction to the key process of the ABMGG—LAI after grazing. Per-pixel grass growth and grazing data were used to assess the effect of grazing strategies and institutional arrangements on the grassland status caused by individual herders' decision-making. A detailed overview, design, concept and detail and decision (ODD + D) description of the ABMGG can be found in Appendix A, where each part of the model is introduced in a standardised way.

The LAI after grazing is the key proxy for evaluating grassland status after grazing in this paper. Below, we explain how it was simulated by the ABMGG before providing a detailed description of the model itself. We designed the model landscape to match the MODIS LAI maps. Each land patch in the ABMGG represents a grassland area of $463 \times 463\ m^2$. For each continuous and rotational grazing patch, a livestock agent associated with it at the start of the year.

In order to simulate the group grazing behaviour of the livestock in Zeku, all the rotational grazing patches were assigned a group and subgroup identification; the livestock on the same group patches have the same group identification. The livestock can only move in and out of patches with the same group identification. For each step, the total grass feeding demand of the group was calculated by:

$$LDT_t = \sum_{i=1}^{m} LDI_{i,t} \tag{2}$$

where m is the number of livestock agents in the group and t is the time step. $LDI_{i,t}$ represents the grass feeding demand of the individual agent and, LDT_t is the total grass feeding demand of the group. For continuous grazing patches, $m = 1$, which means only one herder agent on the patch, and their livestock continuously graze on those patches.

For each rotational grazing patch in the sub-group, the LAI decrease caused by grazing was assumed to be proportional to its current available LAI, which means that selective foraging behaviour of the livestock was not considered in the model. That is, the greater the currently available LAI of the patch, the bigger the LAI decrease caused by grazing. This can be expressed by:

$$LGI_{i,t} = LDT_t \times LCI_{i,t} / \sum_{i=1}^{n} LCI_{i,t} \tag{3}$$

where $LGI_{i,t}$ is the LAI decrease of a grazed patch in the sub-group, $LCI_{i,t}$ is the current LAI before current grazing of each patch in the sub-group, $\Sigma_{i=1}{}^{n} LCI_{i,t}$ is the total available LAI in the sub-group and, n is the total number of patches in the sub-group. For continuous grazing patches, $LGI_{i,t}$ is the LAI decrease of the individual patch, and is not affected by the other patches.

The current LAI before grazing ($LCI_{i,t}$) for each patch was calculated as the subtraction of the effect of previous grazing on LAI from the full-growth LAI:

$$LCI_{i,t} = L_{full\ growth} - LAI_{previous\ effect} \tag{4}$$

where $LCI_{i,t}$ is the current LAI before grazing, and $LAI_{previous\ effect}$ is the effect of previous grazing on the LAI.

Finally, the LAI after grazing was calculated by taking the difference between the current available LAI and the grazing-led LAI changes (the grazing demand on the LAI, or the effect of current grazing). The effect of current grazing is the total livestock consumption during the eight-day period, which can be calculated by Eq. 3. The livestock will eat forage production on grassland, and the LAI of the grassland will change accordingly. The effect of previous grazing was calculated through averaging of previous LAI after grazing and full-growth LAI from the next iteration (average of the two neighbouring LAI time-series). At the beginning of each simulation year, the effect of both previous and current grazing is 0 (no grazing happening); while for continuous or rotational grazing patches where previous grazing had occurred, the effect of previous grazing cound be calculated by:

$$LAI_{previous\ effect} = L_{full\ growth} - (LAI_{after\ grazing-1} + LAI_{full\ growth+1})/2 \tag{5}$$

where $LAI_{after\ grazing-1}$ is the $LAI_{after\ grazing}$ value at its previous iteration and $LAI_{full\ growth+1}$ is the $L_{full\ growth}$ value at the next iteration. At the beginning of each simulation year, the effect of both previous and current grazing is 0 (that is, $LAI_{previous\ effect} = 0$, no grazing is happening). The rest of work was then to make sure that $LAI_{after\ grazing}$ derived from ABMGG matched the LAI observed from the MODIS LAI dataset and to examine how $LAI_{after\ grazing}$ changed with different policy scenarios.

One model iteration (step) accounted for eight days of simulated time (this is the temporal resolution of the MODIS LAI data). Simulations lasted for 46 time steps, representing the years for which data was available (2011). The livestock owned by rotational herder agents could move from one sub-group of patches to another sub-group of patches. For continuous grazing land, once livestock entered the land patch, they did not move to other land patches. The LAI decreased accordingly after livestock grazing, with the LAI after grazing for each patch at each time step being calculated by (variables introduced in Eqs. 3 and 4):

$$\boldsymbol{LAI_{after\ grazing} = LCI_{i,t} - LGI_{i,t}} \tag{6}$$

2.4. Policy assessment criteria: Grassland degradation under grazing

In this paper, we focus on the degradation status of patches. Land degradation is defined as a long-term loss of functionality and productivity (Bai et al., 2008). Although grassland degradation is a synthesis of results from multiple criteria relating to the soil and plants (Akiyama and Kawamura, 2007), it can be measured using remotely sensed data. As a proxy, we used a decrease in LAI to measure grassland degradation. The number of degraded patches were simply counted, according to one of the Chinese national criteria in the 'Parameters for degradation, sandification and saltfication of rangelands' (Su et al., 2003). That is, if the decrease in LAI is less than 10% of expected LAI, it will be classified as an unaffected grassland type ('no effect' in this paper), which means the patch has not been degraded. If it is between 10% and 20%, the land patch is classified as slightly degraded type; with medium degraded land patch involving a decrease of LAI of between 20% and 50%, and a severely degraded land exceeding 50%. While more sophisticated multiple criteria approaches could be used, this gives a solid, policy-orientated metric.

To demonstrate how grazing strategies and institutional arrangements affect grassland status (measured by LAI after grazing, and by the number of degraded patches), we first calibrated the model by ensuring that the output matched the remote sensing derived grazing pattern (degraded patches) well. Following this, we then explored the impact of different combinations of group grazing, and the moving and marketing behaviours of herders, on the model outputs. To begin with, we explain the simulated the patch-specific LAI after grazing (the most important model output).

2.5. Model evaluation

After building the ABMGG, the rest of the work involved making sure it worked reasonably well; that is, to ensure the parameter values, interactions, process and output were working in the same manner as the real grassland grazing system, thereby allowing the policy assessment to proceed. In fact, the process of policy assessment was intimately tied to the validation and scenario analysis of the ABMGG (Fig. 2). The evaluation process consisted of model verification, a Partial (Rank) Correlation Coefficient (PCC/PRCC) sensitivity analysis and Approximate Bayesian Computing (ABC) calibration; detailed descriptions of these processes can be found in Appendix B. After calibration, the R^2 between simulated and observed grazing-led LAI changes is 0.978, and the *p*-value of the T-test is 0.66, which indicates they are still statistically similar.

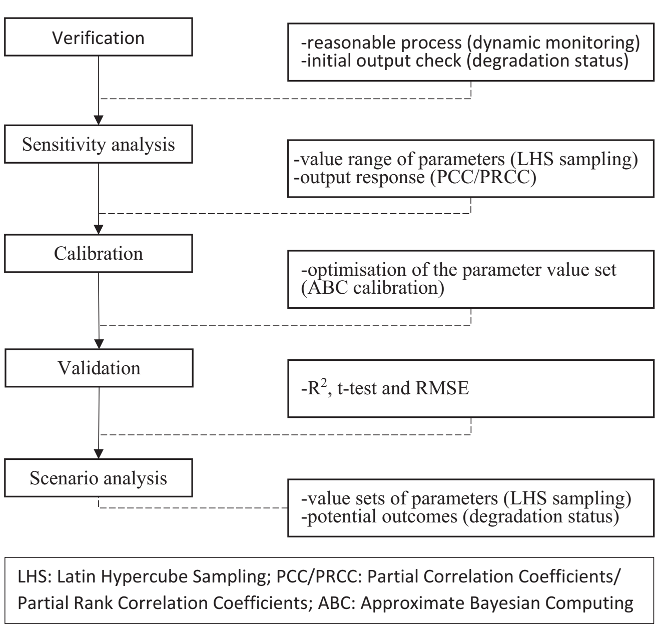

Fig. 2. Validation and scenario analysis framework for policy assessment.

Following the evaluation, the policy scenario analysis proceeded through analysis of the outputs by changing the value sets of the model parameters.

2.6. Scenario analysis of different grazing strategies and institutional arrangements

The scenario analysis was intended to explore the potential outcomes of the combination of different grazing strategies and institutional arrangements at the study site (see Section 2.2). The experiments in the scenario analysis simulated how the number of degraded patches changes under different strategies. Are the current grazing strategies and institutional arrangements the best choice, or is there an alternative? Eight experiments were conducted in order to answer these questions, involving varying the behaviour of the herder agents. For each scenario, the model was run for 50 replicates. The combinations of all these rules are listed in Table 1.

3. Results of the scenario analysis

3.1. LAI after grazing under different scenarios

The regional average (continuous and rotational grazing patches) of the LAI after grazing is shown in Fig. 3. The average LAIs after grazing under FFF (regional continuous grazing without market scenario) and FFT (regional continuous grazing with market scenario) were the highest among all the scenarios; TFT (group continuous grazing with market scenario) and TFF (group continuous grazing without market scenario) gave the lowest average LAIs after grazing among all the scenarios. The standard deviation of the 50 simulations for each scenario was too small to be presented in Fig. 3, and did not significantly affect the statistical analysis later.

Although the *t*-test can report the significance level of the difference, it is only suitable for two-sample comparisons. In order to know whether these differences among the eight scenarios were statically significant, Tukey's honest significance (TukeyHSD) test was employed. It has been designed for multiple comparisons (more than three samples). The TukeyHSD test showed they were statistically the same, where the zero difference line is within the range of all 99% confidence levels of the difference pairs. This is similar to previous studies (Jerrentrup et al., 2015; Woodward et al., 1995) that showed that different grazing strategies or institutional arrangements cannot improve or decrease the productivity of the grassland (herein, the productivity of the grassland is represented by the LAI) significantly.

3.2. Number of degraded patches

Another important output of the ABMGG was the number of degraded patches, which were calculated for each time step for all 50 replicates. The mean values for each time step were plotted against the current choice scenario (Fig. 4). The standard deviations of those 50 simulations, however, were too small to be presented in Fig. 4, indicating that the stochastic uncertainties in the ABMGG had limited effect on the results of the scenario analysis.

Overall, the regional continuous grazing scenarios (FFF and FFT) produced the smallest average number of severely degraded patches and the largest number of unaffected patches. The land market could have a positive effect on the number of unaffected patches, but a negative effect on the number of slightly, medium and severely degraded patches, which indicates that an appropriate land market strategy could

Table 1
Combinations of different grazing strategies and institutional arrangements.

ID	Grouping	Moving	Marketing	Explanation
TTT	√	√	√	**Current choice scenario (group rotational grazing scenario)**: parameter values exactly the same as validation experiment (mean value of parameter values after calibration). Grazing groups are formed on rotational grazing patches, and the livestock can move from one sub-group to another sub-group during grass growth period; herders on the continuous grazing patches can rent/lease land from/to other continuous grazing herders.
TTF	√	√	×	**No market scenario**: similar to TTT, but there is no leasing/renting behaviour among continuous grazing herders.
TFF	√	×	×	**Group continuous grazing without market scenario**: grazing groups are formed on rotational grazing patches, but livestock owned by the rotational grazing herders cannot move from one land patch to another, and they continuously graze on the land in the group; there are no land market behaviours.
FFT	×	×	√	**Regional continuous grazing with market scenario**: herders can lease/rent land from other herders on continuous grazing lands; there are no grazing groups, and the livestock does not move among patches; herders on the continuous grazing lands can lease/rent lands.
FTT	×	√	√	**Random moving with market scenario**: there are no grazing groups, but the livestock owned by rotational grazing herders can move randomly among all the rotational grazing patches;
TFT	√	×	√	**Group continuous grazing with market scenario**, it is similar to TFF, but the herders on the continuous grazing lands can rent/lease lands from the other continuous grazing herders.
FTF	×	√	×	**Random moving without market scenario**: similar to FTT, but the herders on the continuous grazing lands can rent/lease lands from the other continuous grazing herders.
FFF	×	×	×	**Regional continuous grazing without market scenario**: there are grazing groups on the rotational grazing patches, and also no leasing/renting behaviours of the herders on continuous grazing patches.

Note: √ means scenario include that behaviour, while × means it does not; grouping—whether agents on rotational grazing lands form local grazing groups; rotation—whether livestock owned by herder agents on rotational grazing lands will move in/out based on a pre-defined order, which is randomized; marketing—whether the leasing/renting relationship of herders exists in the model, and there is an overall percentage of marketing herders, but the herders are randomly selected.

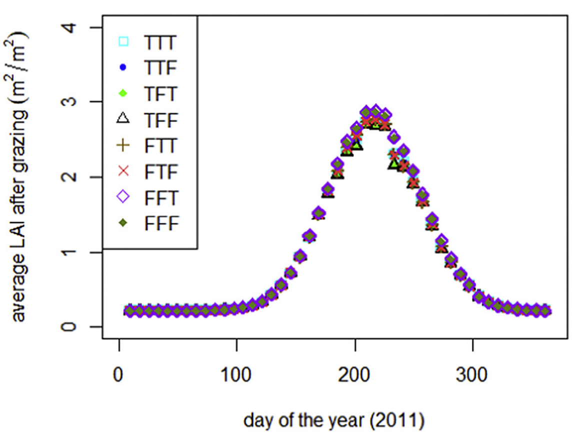

Fig. 3. The LAI after grazing for all combinations of grazing strategies and institutional arrangements.

improve the grassland status under grazing, as it produces fewer slightly, medium and severely degraded patches, and the greater number of unaffected patches. Group continuous grazing scenarios (TFF and TFT) can produce a smaller number of severely degraded patches than that of the current choice scenario (TTT), but they also produce a higher number of the slightly and medium degraded patches, and a smaller number of unaffected patches than the current choice scenario (TTT). Regional randomly moving scenarios (FTT and FTF) produced the largest number of severely degraded patches compared to all the other scenarios, but also produced a smaller number of slightly and medium degraded patches, and a greater number of unaffected patches compared to the current choice scenario.

4. Discussion

Policy assessment is critical for successful policy development and implementation, especially in the complex grassland grazing system. However, assessment of such natural resource related policies has usually been neglected and a substantial gap is emerging between theory and practice (Wallace et al., 1995), which may lead to unsuccessful or harmful policy implementations (Sallis et al., 1998; Sarewitz et al., 2000). An example can be seen in the effect of long-term exclusion policies, which have been implemented to improve grassland productivity, but infact have caused loss of plant cover and diversity in arid regions (Oba et al., 2000). The same is true for institutional changes in Inner Mongolia, where market and protection policies have actually suppressed local incentives for grassland conservation (Robinson et al., 2017).

Existing methods and models for the assessment of the coupled human and natural system have not provided an integrated evaluation that is sensitive to household decision-making, policy/institutional arrangements and natural constraints (Bellamy et al., 2001). The bottom-up ABM discussed in this paper accounts for the heterogeneity in grassland resources, individual herder' decision-making and plant-livestock interactions. After calibration with real grassland situations, the ABMGG has the capability to assess the effect of different policies on grassland status. This provides a new perspective through which to undertake policy assessment for grassland grazing system.

It was found that different grazing management scenarios have no effect on the LAI after grazing, that is, different grazing management scenarios could not significantly improve or decrease grassland LAI. This is similar to findings from previous studies (Jerrentrup et al., 2015; Woodward et al., 1995), suggesting that grazing intensity, rather than grazing strategy, is the main factor in changes in grassland productivity. Importantly, however, the grassland *status* was different under those scenarios. Although the regional continuous grazing scenario performed best, with more unaffected patches and fewer slightly, medium and severely degraded patches, compared to the other scenarios, the proportionally spatial distribution assumption of the livestock grazing intensity to the available forage on the patches in the regional continuous grazing scenario could make it quite difficult to be implemented, due to potentially high management costs. Compared to the group continuous grazing scenario and regional randomly moving scenario, the group rotational grazing (current choice scenario) was a reasonable grazing management implementation for Zeku; it is a group level management strategy, which involves subdividing the land patches in the groups.

The grassland degradation status was different under different policy scenarios, however. Group grazing with land market tenure was the best with regard to fewer severely degraded patches and more unaffected patches. It reduced the spatial heterogeneity of forage distribution. The livestock on low-productivity land with a relatively high stocking rate could move to high-productivity land rather than

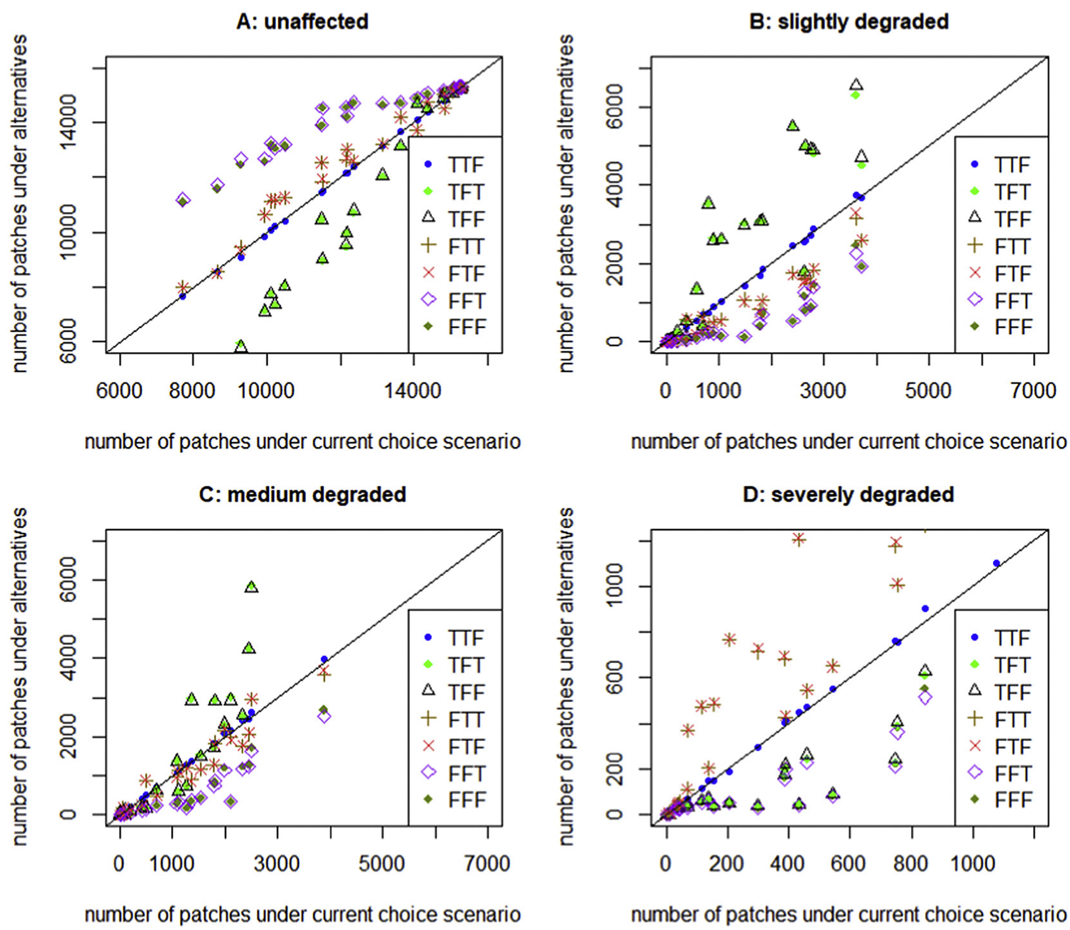

Fig. 4. Effects of different combination of grazing strategies and institutional arrangements on number of degraded patches (unit for all axes is: number of degraded patches).

continuously graze on that land. Compared to standard rotational grazing, grasslands with intensive rotational grazing, with a higher number of subdivisions that have longer resting periods, preserve storage biomass closer to maximum yield, and therefore can maintain higher stocking rates (Barnes et al., 2008; Jakoby et al., 2014; Savory and Parsons, 1980; Teague et al., 2011). The rotational grazing strategy increases income and improves rangeland conditions, but might demand high management costs (Beukes et al., 2002), and the risk of forage shortage if livestock stocking rates are too high (Hart et al., 1993). However, although rotational and continuous grazing strategies may have little effect on the frequency, severity or variation of the grazing-led defoliation of grass (Hart et al., 1993) and its botanical composition (Taylor, 1989) if maintained at the same stocking rates, this research reported similar results (see Fig. 3), although the degradation structure of the land would change with different grazing strategies and institutional arrangements (see Fig. 4).

Under the current grazing intensity in Zeku, regional continuous grazing appears to be the best choice, as it can produce a greater number of unaffected patches and a smaller number of slightly, medium and severely degraded patches. However, such continuous grazing assumes that all the land patches are being grazed proportionally according to their available forage. This is a quite strong assumption that all the livestock are also distributed proportionally, according to the available forage of the land patches, which is difficult to manage in reality. One of the key parts of grassland management is to manage the heterogeneity (both the grass resources and herbivores) of the grassland (Bonari et al., 2017; Stewart and Pullin, 2008); although regional continuous grazing scenario could reduce such heterogeneity, but there are also other difficulties such as dealing with the local land tenure systems across villages in the whole region.

Group continuous grazing was worse than the current choice with regard to the grassland status, indicating a rotational grazing strategy would be more suitable than continuous grazing at the group level for Zeku. That is, compared with group continuous grazing, group rotational grazing with the land market (current choice scenario, TTT) is a reasonable choice, with regard to fewer slightly, medium and severely degraded patches, and more unaffected patches. This reduces the spatial heterogeneity of forage distribution. Livestock on low productivity land with a relatively high stocking rate can move to high-productivity land rather than continuously graze on one land patch. This also supports field experiments in north-central Texas, USA, where evidence suggested that, for large paddocks, rotational grazing allowed recovery from, and reduced degradation caused by, patch overgrazing (Teague and Dowhower, 2003).

The behaviours of the agents herein were estimated from regional aggregated statistical properties, but these could hide the influence of kinship, community and the individual interactions among herders, which are potentially important elements in the complexity of the grazing system. Another possible improvement would be integration with other models, such as climate, solar radiation, vegetation distribution, productivity and even economic models, which could improve the flexibility of ABMGG. However, such integration should be pursued with caution, as more detailed models for some of the simple abstracted parameters in the current ABMGG model would dramatically increase the complexity of the model, and this could cause the problem of “more is different” (Anderson, P.W., 1972). The more detailed components in the model, the less relevance the science behind such overly detailed structure of it. In addition, using more detailed models as a replacement for simple abstracted parameters in the current ABMGG would dramatically increase the complexity of the model, which would surely be more computationally expensive to evaluate.

5. Conclusions

A novel ABM, which was integrated with near real-time remote sensing data for the assessment of various grazing policies, was presented. Although there are some drawbacks, ABMs constitute an ideal methodology for grassland grazing systems that are characterised by individual interactions, and contain hierarchical grazing strategies and institutional arrangements. Eight combinations of grazing strategies and institutional arrangements were evaluated. The model was able to estimate the number of degraded patches based on individual-level interactions under those combinations. It was found that different grazing management scenarios had no effect on the LAI after grazing; that is, different grazing management scenarios could not significantly improve or decrease grassland LAI. The assessments highlighted, however, that rotational group grazing performs best in terms of producing a smaller number of degraded patches. The results can be used as tools to assess the impact of policies on grassland grazing systems, in turn contributing to the sustainable development of grassland grazing systems.

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References

Abel, T., 1998. Complex adaptive systems, evolutionism, and ecology within anthropology: interdisciplinary research for understanding cultural and ecological dynamics. J. Ecol. Anthropol. 2, 6–29.
Adler, P., Raff, D., Lauenroth, W., 2001. The effect of grazing on the spatial heterogeneity of vegetation. Oecologia 128, 465–479.
Akiyama, T., Kawamura, K., 2007. Grassland degradation in China: methods of monitoring, management and restoration. Grassl. Sci. 53, 1–17.
Archambault, C., 2014. Young perspectives on pastoral rangeland privatization: intimate exclusions at the intersection of youth identities. Eur. J. Dev. Res. 26, 204–218.
Bai, Z.G., Dent, D.L., Olsson, L., Schaepman, M.E., 2008. Proxy global assessment of land degradation. Soil Use Manag. 24, 223–234.
Barnes, M.K., Norton, B.E., Maeno, M., Malechek, J.C., 2008. Paddock size and stocking density affect spatial heterogeneity of grazing. Rangel. Ecol. Manag. 61, 380–388.
Bellamy, J.A., Walker, D.H., McDonald, G.T., Syme, G.J., 2001. A systems approach to the evaluation of natural resource management initiatives. J. Environ. Manag. 63, 407–423.
Beukes, P.C., Cowling, R.M., Higgins, S.I., 2002. An ecological economic simulation model of a non-selective grazing system in the Nama Karoo, South Africa. Ecol. Econ. 42, 221–242.
Bonari, G., Fajmon, K., Malenovský, I., Zelený, D., Holuša, J., Jongepierová, I., Kočárek, P., Konvička, O., Uřičář, J., Chytrý, M., 2017. Management of semi-natural grasslands benefiting both plant and insect diversity: the importance of heterogeneity and tradition. Agric. Ecosyst. Environ. 246, 243–252.
Briske, D.D., Zhao, M., Han, G., Xiu, C., Kemp, D.R., Willms, W., Havstad, K., Kang, L., Wang, Z., Wu, J., Han, X., Bai, Y., 2015. Strategies to alleviate poverty and grassland degradation in inner Mongolia: intensification vs production efficiency of livestock systems. J. Environ. Manag. 152, 177–182.
Campbell, B.M., Gordon, I.J., Luckert, M.K., Petheram, L., Vetter, S., 2006. In search of optimal stocking regimes in semi-arid grazing lands: one size does not fit all. Ecol. Econ. 60, 75–85.
Chen, J.M., Black, T., 1992. Defining leaf area index for non-flat leaves. Plant Cell Environ. 15, 421–429.
Cingolani, A.M., Posse, G., Collantes, M.B., 2005. Plant functional traits, herbivore selectivity and response to sheep grazing in Patagonian steppe grasslands. J. Appl. Ecol. 42, 50–59.
Conte, T.J., Tilt, B., 2014. The effects of China's grassland contract policy on pastoralists' attitudes towards cooperation in an inner Mongolian banner. Hum. Ecol. 42, 837–846.
Fernandez-Gimenez, M.E., Batkhishig, B., Batbuyan, B., Ulambayar, T., 2015. Lessons from the Dzud: community-based rangeland management increases the adaptive capacity of Mongolian herders to winter disasters. World Dev. 68, 48–65.
Ford, H., Roberts, A., Jones, L., 2016. Nitrogen and phosphorus co-limitation and grazing moderate nitrogen impacts on plant growth and nutrient cycling in sand dune grassland. Sci. Total Environ. 542, 203–209.
Frank, D.A., Wallen, R.L., White, P., 2016. Ungulate control of grassland production: grazing intensity and ungulate species composition in Yellowstone Park. Ecosphere 7.
Gongbuzeren, Zhuang, M., Li, W., 2016. Market-based grazing land transfers and customary institutions in the management of rangelands: two case studies on the Qinghai-Tibetan Plateau. Land Use Policy 57, 287–295.
Gonzalez, J.M., Sherr, E.B., Sherr, B.F., 1990. Size-selective grazing on bacteria by natural assemblages of estuarine flagellates and ciliates. Appl. Environ. Microbiol. 56, 583–589.
Gross, J.E., McAllister, R.R.J., Abel, N., Smith, D.M.S., Maru, Y., 2006. Australian rangelands as complex adaptive systems: a conceptual model and preliminary results. Environ. Model. Softw. 21, 1264–1272.
Hahn, M.W., Höfle, M.G., 2001. Grazing of protozoa and its effect on populations of aquatic bacteria. FEMS Microbiol. Ecol. 35, 113–121.
Hart, R.H., Clapp, S., Test, P.S., 1993. Grazing strategies, stocking rates, and frequency and intensity of grazing on western wheatgrass and Blue Grama. J. Range Manag. 46, 122–126.
Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405.
Humphrey, C., Sneath, D., 1999. The End of Nomadism? Society, State and the Environment in Inner Asia. Duke University Press, Durham.
Jakoby, O., Quaas, M.F., Müller, B., Baumgärtner, S., Frank, K., 2014. How do individual farmers' objectives influence the evaluation of rangeland management strategies under a variable climate? J. Appl. Ecol. 51, 483–493.
Janssen, M.A., Walker, B.H., Langridge, J., Abel, N., 2000. An adaptive agent model for analysing co-evolution of management and policies in a complex rangeland system. Ecol. Model. 131, 249–268.
Jerrentrup, J.S., Seither, M., Petersen, U., Isselstein, J., 2015. Little grazer species effect on the vegetation in a rotational grazing system. Agric. Ecosyst. Environ. 202, 243–250.
Jun, W., Daniel, G.B., Rick, L.R., Scott, E.P., Arun, A., 2013. Exploratory analyses of local institutions for climate change adaptation in the Mongolian grasslands: an agent-based modeling approach. Glob. Environ. Chang. 23, 1266–1276.
Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., De Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., Daily, G., 2013. Social-ecological systems as complex adaptive systems: modeling and policy implications. Environ. Dev. Econ. 18, 111–132.
Lu, X., Yan, Y., Sun, J., Zhang, X., Chen, Y., Wang, X., Cheng, G., 2015. Short-term grazing exclusion has no impact on soil properties and nutrients of degraded alpine grassland in Tibet, China. Solid Earth 6, 1195–1205.
Monteith, J., Reifsnyder, W.E., 1974. Principles of Environmental Physics. Phys. Today 27, 51.
Moreno García, C.A., Schellberg, J., Ewert, F., Brüser, K., Canales-Prati, P., Linstädter, A., Oomen, R.J., Ruppert, J.C., Perelman, S.B., 2014. Response of community-aggregated plant functional traits along grazing gradients: insights from African semi-arid grasslands. Appl. Veg. Sci. 17, 470–481.
Moritz, M., Handa, S., Chen, Y.J., Xiao, N.C., 2015. Herding contracts and pastoral mobility in the far north region of Cameroon. Hum. Ecol. 43, 141–151.
Oba, G., Stenseth, N.C., Lusigi, W.J., 2000. New perspectives on sustainable grazing management in arid zones of sub-Saharan Africa. Bioscience 50, 35–51.
Ojanen, M., Miller, D.C., Zhou, W., Mshale, B., Mwangi, E., Petrokofsky, G., 2014. What are the environmental impacts of property rights regimes in forests, fisheries and rangelands? A systematic review protocol. Environ. Evidence 3, 19.
Porensky, L.M., Mueller, K.E., Augustine, D.J., Derner, J.D., 2016. Thresholds and gradients in a semi-arid grassland: long-term grazing treatments induce slow, continuous and reversible vegetation change. J. Appl. Ecol. 53, 1013–1022.
Qu, T.-b., Du, W.-c., Yuan, X., Yang, Z.-m., Liu, D.-b., Wang, D.-l., Yu, L.-j., 2016. Impacts of grazing intensity and plant community composition on soil bacterial community diversity in a steppe grassland. PLoS One 11, e0159680.
Robinson, B.E., Li, P., Hou, X., 2017. Institutional change in social-ecological systems: the evolution of grassland management in Inner Mongolia. Glob. Environ. Chang. 47, 64–75.
Sakamoto, T., 2016. Computational research on mobile pastoralism using agent-based modeling and satellite imagery. PLoS One 11 e0151157.
Sallis, J., Bauman, A., Pratt, M., 1998. Environmental and policy interventions to promote physical activity. Am. J. Prev. Med. 15, 379–397.
Sarewitz, D., Pielke Jr., R.A., Byerly Jr., R., 2000. Prediction in Science and Policy. Prediction: Science, Decision Making, and the Future of Nature. pp. 11–22.
Savory, A., Parsons, S.D., 1980. The Savory grazing method. Rangelands 234–237.
Stewart, G.B., Pullin, A.S., 2008. The relative importance of grazing stock type and grazing intensity for conservation of mesotrophic 'old meadow' pasture. J. Nat. Conserv. 16, 175–185.
Su, D., Zhang, Z., Chen, Z., Hu, X., 2003. GB 19377–2003 Parameters for Degradation, Sandification and Saltfication of Rangelands (in Chinese). General Administration of Quality Supervision, Inspection and Quanrantine of the People's Republic of China.
Taylor, C.A., 1989. Short-duration grazing: experiences from the Edwards Plateau region in Texas. J. Soil Water Conserv. 44, 297–302.
Teague, W.R., Dowhower, S.L., 2003. Patch dynamics under rotational and continuous grazing management in large, heterogeneous paddocks. J. Arid Environ. 53, 211–229.
Teague, W.R., Dowhower, S.L., Baker, S.A., Haile, N., DeLaune, P.B., Conover, D.M., 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agric. Ecosyst. Environ. 141, 310–322.
Thornton, P.K., van de Steeg, J., Notenbaert, A., Herrero, M., 2009. The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. Agric. Syst. 101, 113–127.
Troost, C., Berger, T., 2014. Dealing with uncertainty in agent-based simulation: farm-

level modeling of adaptation to climate change in southwest Germany. Am. J. Agric. Econ. 97, 833–854.
Wallace, M.G., Cortner, H.J., Burke, S., 1995. Review of policy evaluation in natural resources. Soc. Nat. Resour. 8, 35–47.
Wang, Z., Song, K., Hu, L., 2010. China's largest scale ecological migration in the three-river headwater region. AMBIO: A J. Human Environ. 39, 443–446.
Wang, J., Brown, D.G., Riolo, R.L., Page, S.E., Agrawal, A., 2013. Exploratory analyses of local institutions for climate change adaptation in the Mongolian grasslands: an agent-based modeling approach. Glob. Environ. Chang. 23, 1266–1276.
Wisner, B., 2012. Socio-economic change and land use in Africa: the transformation of property rights in Maasailand. J. Peasant Stud. 39, 1198–1201.
Woodward, S.J.R., Wake, G.C., McCall, D.G., 1995. Optimal grazing of a multi-paddock system using a discrete time model. Agric. Syst. 48, 119–139.
Xiaoyi, W., 2007. Undermining Grassland Management through Centralized Environmental Policies in Inner Mongolia. World Resources Institute. The Contributors, Washington, DC.
Yeh, E.T., 2009. Greening western China: a critical view. Geoforum 40, 884–894.
Yu, R., Evans, A.J., Malleson, N., 2018. Quantifying grazing patterns using a new growth function based on MODIS leaf area index. Remote Sens. Environ. 209C.