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Exploratory analyses of local institutions for climate change adaptation in the Mongolian grasslands: An agent-based modeling approach

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ABSTRACT

There has been a decrease in grazing mobility in the Mongolian grasslands over the past decades. Sedentary grazing with substantial external inputs has increased the cost of livestock production. As a result, the livelihoods of herders have become more vulnerable to climate variability and change. Sedentary grazing is the formal institutional arrangement in Inner Mongolia, China. However, this may not be an efficient institutional arrangement for climate change adaptation. Self-organized local institutions for climate change adaptation have emerged and are under development in the study area. In this study, we did exploratory analyses of multiple local institutions for climate change adaptation in the Mongolian grasslands, using an agent-based modeling approach. Empirical studies from literature and our field work show that sedentary grazing, pasture rental markets, and reciprocal pasture-use groups are three popular institutional arrangements in the study area. First, we modeled the social–ecological performance (i.e., livelihood benefits to herders and grassland quality) of these institutions and their combinations under different climate conditions. Second, we did exploratory analyses of multiple social mechanisms for facilitating and maintaining cooperative use of pastures among herders. The modeling results show that in certain value-ranges of some model parameters with assumed values, reciprocal pasture-use groups had better performance than pasture rental markets; and the comparative advantage of cooperative use of pastures over sedentary grazing without cooperation becomes more evident with the increase in drought probability. Agent diversity and social norms were effective for facilitating the development of reciprocal pasture-use groups. Kin selection and punishments on free-riders were useful for maintaining cooperation among herders.

1. Introduction

In the semiarid and arid grasslands of the world, such as Africa and Inner Asia (i.e., Southern Russia, Mongolia, and Northern China), seasonal and interannual migrations used to be the dominant livestock management strategies of herders to live with the highly variable climate. Flexible property boundaries, reciprocal use of pastures, and underlying social networks allowed herders to use pastures efficiently and to survive in the regions with frequent climate hazards (Fernandez-Giménez and Le Febre, 2006; Humphrey and Sneath, 1999; Mwangi, 2007). Those institutions have evolved over centuries and are well suited to the biophysical characteristics of the local grassland ecosystems. Over the past decades, social-institutions in those traditional grazing societies have changed dramatically, and the traditional communal pastures have been privatizing to individual households (Humphrey and Sneath, 1999; Mwangi, 2007). The local governments of those societies anticipated that private ownership could create incentives for herders to adopt better pasture-use practices, which could consequently improve pasture-use efficiency and livelihood benefits to herders (Mwangi, 2007; Williams, 2002; Zhang, 2007). With social-institutional changes in recent decades, there has been a decrease in grazing mobility in the traditional grazing systems of Africa and Inner Asia (Humphrey and Sneath, 1999; Mwangi, 2007; Sneath, 1998).

In this study, we focus on the grazing systems on the Mongolian plateau, including Mongolia and the Inner Mongolia Autonomous Region, China. Mongolia and Inner Mongolia experienced privatization in the early 1990s and mid-1980s, respectively (Li and Li, 2012; Sneath, 1998). In Mongolia, pastures are managed under a combination of customary rights and formal-use rights (Upton, 2009). Mobile grazing is still the

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dominant livestock management strategy in Mongolia. However, the distances and frequencies of seasonal and interannual migrations have decreased (Olonbayar, 2010). Because of the retreatment of governmental investments after economic reforms, herders with limited household endowments tend to migrate less frequently or to be sedentary grazing (Humphrey and Sneath, 1999). In Inner Mongolia, most pastures have been contracted to individual households and fenced, which is known as "household production responsibility systems (HPRS) (Li et al., 2007; Williams, 2002; Zhang, 2007)." Livestock grazing in most parts of Inner Mongolia has been sedentarized. Along with grazing sedentarization, the social norms of reciprocal use of pastures that the traditional nomadism was relied on have been disappearing (Li and Huntsinger, 2011; Upton, 2009). Besides social-institutional changes, climate change and pasture degradation have been evident on the Mongolian plateau over the past 50 years. Since the early 1960s, climate on the Mongolian plateau has been getting warmer and drier (Wang et al., 2013). The frequencies of climate hazards in Mongolia have increased, and they have caused disastrous effects on livestock production over the past 30 years (Fernandez-Giménez et al., 2012; Vernooy, 2011). Large-scale ecological surveys show that the average grassland biomass productivity in Inner Mongolia and Mongolia both has decreased about 50% over the past 50 years (IMIGSD, 2011; IOB, Mongolia, 2011). Decreased grazing mobility, climate change, and pasture degradation have increased livelihood vulnerability of herder communities in the Mongolian grasslands.

Social adaptation is the responses to risks and environmental stressors (Agrawal, 2009; O'Brien et al., 2004; Smit and Wandel, 2006; Wilbanks and Kates, 2010). In the context of multiple stressors discussed above, social adaptation has become increasingly important for livelihood sustainability of herder communities in the Mongolian grasslands. Studies have found that local institutions play the key role in shaping livelihood adaptation of rural communities to climate change (Agrawal, 2010). Agrawal (2010) argued that local institutions shape the impact of climate change on rural communities and the way they respond to climate change. Institutions, including formal and informal rules, are humanly devised constraints that shape human interactions and reduce social uncertainties (North, 1990; Ostrom, 1990). In the analytical framework focused on adaptation, institutions, and livelihoods (AIL), Agrawal classified local institutions into three major types: governmental/public institutions, market/private institutions, and communal/civic institutions (Agrawal, 2009). Previous studies have contributed to the understanding of social adaptation to climate variability and change on the Mongolian plateau (Fernandez-Giménez et al., 2012; Li and Huntsinger, 2011; Vernooy, 2011; Wang, 2013). Most of the previous studies focused on analyzing livelihood adaptation strategies of herders to climate change. Comparative studies of multiple local institutions for climate change adaptation in the Mongolian grasslands are still missing.

In this work, we focus on exploratory analyses of multiple local institutions for climate change adaptation in the semiarid and arid Mongolian grasslands with highly variable climate. We aim to answer the following question: what are efficient institutional arrangements that can improve social–ecological outcomes (i.e., livelihood benefits to herders and grassland quality) of pasture-use in the context of climate change? For example, sedentary grazing is the formal institutional arrangement in the grassland areas of China. However, this may not be an efficient institutional arrangement for climate change adaptation in the semiarid and arid grassland areas with highly variable climate. We hypothesized that in grassland areas with highly variable climate, the institutional arrangements that could facilitate cooperative use of pastures could generate better social–ecological performance (i.e., livelihood benefits to herders and grassland quality) than sedentary grazing without cooperation. First, we did exploratory analyses of the social–ecological performance of multiple local institutions under different climate conditions, using an agent-based modeling platform. Second, we ran computational experiments to analyze multiple social mechanisms for facilitating and maintaining cooperative use of pastures among herders for climate change adaptation. Agent-based modeling is a useful tool for dynamically examining social processes and their interactions involved in multiple institutional arrangements.

Agent-based modeling is a promising quantitative methodology for social science research (Axerold, 1997; Epstein, 2007; Epstein and Axtell, 1997; Miller and Page, 2007). Agent-based models are process-based models that can be used to explain empirical phenomena, to help design and choose institutions, and to generate scenarios of agent actions and interactions. Agent heterogeneity, learning and adaptation, and social interactions can be easily included in the computational models. In the field of natural resource and environmental studies, agent-based models have been used in modeling urban sprawl and ecological effects (Brown et al., 2008), deforestation, reforestation, and ecological conservations (An et al., 2005; Chen et al., 2012; Manson and Evans, 2007), pasture dynamics and management (Bell, 2011), environmental migrations (Kniveton et al., 2011), and the institutions for sustainable governance of natural resources (Bravo, 2011; Deadman et al., 2000; Janssen and Ostrom, 2006). The decision-making process of agents (e.g., land users and managers) and agent interactions can be explicitly included in the models. Although agent-based models are effective tools for exploring different scenarios of human–environment interactions, they should be built on social theories that can explain agent actions and interactions.

The development of local institutions for climate change adaptation usually involves collective action of local people. The free-rider problem is an innate problem of collective action. The existence of free-riders affects the maintenance of cooperation. For example, in a pasture-use group where herders pool their pastures for communal grazing, some herders may overgraze communal pastures to increase their own benefits, and some herders may not let other herders access their pastures. The free-rider problem can cause the collapse of collective action. In this work, we did exploratory analyses of multiple social mechanisms for maintaining cooperative pasture-use groups among herders using an agent-based modeling platform. Over the past decades, several social mechanisms have been identified for solving the free-rider problem in collective action. The first mechanism is to keep the size of a cooperation group small, which is also known as "small-scale collective action (Olson, 1965)." The organization cost of cooperation increases with the increase in the size of a cooperation group. Communication and monitoring become difficult when the size of a cooperation group is large. Kinship is an important mechanism for maintaining cooperation (Nowak, 2006). Kinship can lower the organization cost of cooperation by making communication and trust easier. The third mechanism is the rights of free entry and exit of a cooperation group, which is also known as "voluntary games (Nowak, 2006)." If agents cannot benefit from being in a cooperation group and they cannot afford the exit cost of leaving a cooperation group, free-riding will be the dominant strategy for the agents. Otherwise, the rights of free entry and exit create "threats" for members in a cooperation group who plan to turn into free-riders. Punishing free-riders, which is also known as negative selective incentives (Nowak, 2006; Olson, 1982), is another important mechanism for maintaining cooperation. Punishment creates a cost to free-riders in collective action.

2. Empirical background

The agent-based model of local institutions for climate change adaptation was developed based on empirical studies of sedentary grazing, pasture rental markets, and reciprocal pasture-use groups in the Mongolian grasslands. According to the AIL framework (Agrawal, 2009), privatization and sedentary grazing are governmental institutions; pasture rental markets are market institutions; and reciprocal pasture-use groups are communal institutions. We collected empirical evidence of these institutional arrangements in the Mongolian grasslands through literature reviews and household surveys. Under the institutional arrangement of privatization and sedentary grazing, livestock and pastures are privately owned by herder households. Herders cannot migrate to other places when climate hazards happen. They have to store forage and build shelters to cope with uncertainties in precipitation. Therefore, sedentary grazing has increased the cost of livestock production. Over the past decades, self-organized institutions (i.e., pasture rental markets and reciprocal pasture-use groups) for climate change adaptation have emerged and are under development in the Mongolian grasslands (Bijoor et al., 2006; Li and Huntsinger, 2011; Vernooy, 2011; Zhang, 2007). In pasture rental markets, herders can rent pastures from others to minimize the loss caused by climate hazards. Herders leasing pastures to others can gain benefits from pasture rental fees. Empirical studies show that there are barriers to the development of pasture rental markets in Inner Mongolia (Li and Huntsinger, 2011; Zhang, 2007). First, most herders are only willing to lease pastures to their relatives and friends because strangers may overgraze their rented pastures and/or destroy water facilities. Second, the cost of transportation for migrations and the pasture rental fee are usually too expensive for local herders. Therefore, herders usually do not choose to rent pastures, except when they may lose most of their animals in climate hazards. In reciprocal pasture-use groups, herders share their pastures with each other when climate hazards happen. These cooperation groups were mostly self-organized by relatives, friends, and neighbors for adapting to climate variability and change (Vernooy, 2011).

Besides empirical evidence in literatures, we designed a household survey to study livelihood adaptation strategies of herders and local institutional facilitators in the context of climate change. The content of the household survey includes four sections: (1) basic socioeconomic information, pasture-use and management, and livestock management information; (2) livelihood adaptation strategies of herders and local institutional facilitators; (3) historical climate hazards and fluctuations in the prices of livestock products; and (4) formal and informal resource institutions. The survey was implemented in three broad vegetation types (i.e., meadow, typical, and desert steppes) of Inner Mongolia and Mongolia (Fig. 1). The survey questions were pretested and revised iteratively based on interviews with local herders. We conducted field work in Inner Mongolia and Mongolia in autumn 2010 and spring 2011, respectively. Local grassland survey experts from the Institute of Botany (IOB), Mongolia, and the Inner Mongolian Institute of Grassland Survey and Design (IMIGSD), China, helped us conduct the field work. Overall, we surveyed 541 herder households (15 villages) in Inner Mongolia and 210 herder households (seven soums) in Mongolia. Our survey data show that sedentary grazing was the dominant livestock management strategy of herders in Inner Mongolia. Pasture rental markets emerged in some of our field sites. For example, about 35% of the surveyed households in meadow steppe of Inner Mongolia chose to rent pastures for migrations when climate hazards happened. In Inner Mongolia, sedentary grazing and pasture rental markets were mainly shaped and facilitated by local governmental and market institutions. Mobile grazing was the dominant livestock management strategy of herders in Mongolia. Reciprocal pasture-use groups emerged in our field sites of Mongolia and Inner Mongolia. These cooperation groups were mainly facilitated by local communal institutions (e.g., traditional norms of mobile grazing).

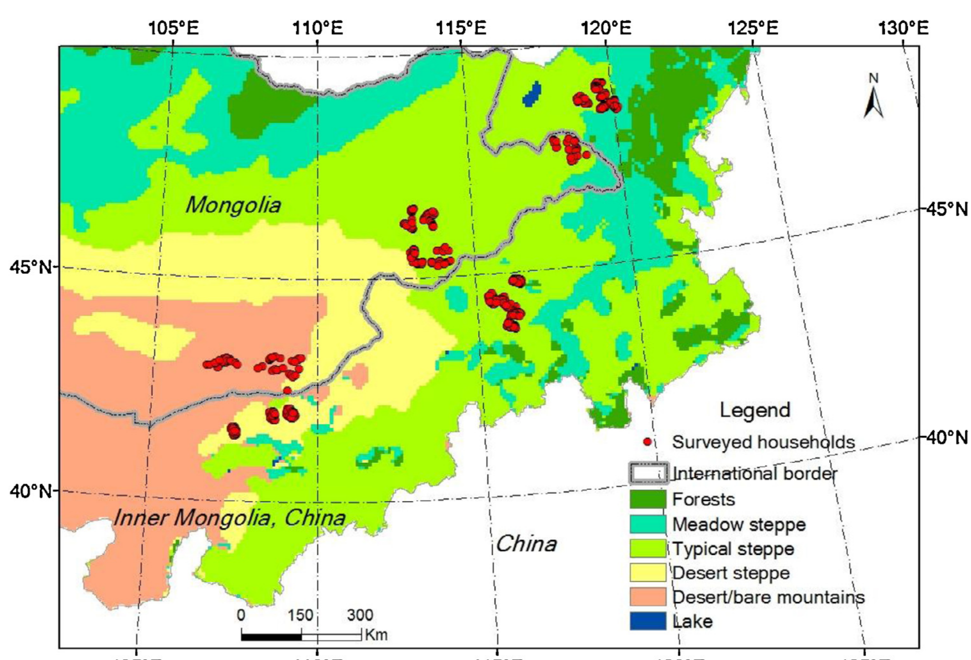

Fig. 1. The major vegetation types (shaded color) and the surveyed herder households (red dots) in the Mongolian grasslands. The vegetation data of Mongolia and Inner Mongolia were from the Institutes of Botany, Mongolia (1980s) and China (1990s), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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3. The conceptual agent-based model

3.1. The agent landscape and agents

In this work, we focus on exploratory analyses of local institutions for climate change adaptation in the semiarid and arid Mongolian grasslands with highly variable climate. The agent-based model of local institutions is theoretically oriented. We designed an abstract agent landscape with equally divided pasture parcels. Pastures and sheep are owned privately by herder agents. Grass productivity is drawn from a normal distribution with a mean and a standard deviation. Drought is the exogenous driver that causes the change in grass productivity. Drought hits pastures in the agent world randomly with a probability, and each parcel has the same probability to be hit. The grass productivity of the parcel hit by drought and its neighborhood parcels (i.e., within a radius) are influenced by drought. The impact of drought on grass productivity was simplified by setting a hypothetical look-up table. When drought happens, agents tend to overgraze their pastures if they cannot find available parcels for migrations. Overgrazing lowers grass productivity (i.e., pasture degradation) for the subsequent model step. We assume that if the biomass left after grazing is less than 10% of the initial grown biomass, the parcel will have decreased grass productivity. The decreased grass productivity is used to represent the damage to plants and roots that can occur when a parcel is overgrazed (Wang et al., 2008). A parcel with decreased grass productivity is counted as a degraded parcel. Biomass for each parcel is set to zero at the end of each model step, and grass grows from zero at the beginning of the next step. This is used to represent the seasonal nature of biomass production.

Agents with the same last name are connected as relatives. Otherwise, they are strangers. Agents with the same last name are distributed randomly in the agent world. Agents are assigned into rich and poor agents based on the number of sheep they have. Rich and poor agents are distributed randomly in the agent world. Agents graze their sheep on their pastures, and the number of sheep owned by each agent produces the same number of sheep offspring. At the end of each model step, agents sell their sheep offspring to gain benefits. We assume that the number of sheep owned by each agent is stable over time. The influence of market incentives on livestock management behaviors of herders is not included in the model. When drought happens, agents will lose some proportions of their sheep and grass productivity, and agents will purchase sheep and fodder from markets to make up for the loss caused by drought. In the real world, the restoration of livestock populations after climate hazards is from both natural reproductions and purchasing livestock from markets (Zhang, 2007). The complicated natural reproduction process of sheep is not included in the model. Our survey data show that livestock prices in normal and drought years were usually different. In the model, we set different sheep prices for normal and drought years.

3.2. Sedentary grazing

Agents graze their sheep on their own pastures. Agents cannot migrate to other parcels when drought happens. They have to bear the loss caused by drought. The net benefits of agents under the institutional arrangement of sedentary grazing are calculated by

$$U_{1i}(n_i) = n_i \cdot B_i - C_i \tag{1}$$

where U_{1i} is the net benefit of agent i, n_i is the number of sheep owned by the agent i, B_i is the benefit from selling one sheep, and C_i is the cost of buying sheep and fodder when climate hazards happen.

3.3. Pasture rental markets

When drought happens, agents will search in their neighborhoods for available pasture parcels to migrate to. The number of migrants one agent can support is based on how much biomass they have left on the basis of without causing pasture degradation in the subsequent model step. In the real world, rich and poor herders usually have different searching and migration radii because they have different household endowments to support these activities (Zhang, 2007). In the model, we set that poor agents had a smaller searching radius than rich agents. The searching agents bid on available pastures in their neighborhoods. The price that an agent is willing to pay is based on the budget of the agent and a random component, which is drawn from the standard normal distribution. The budget of each agent is based on the number of sheep they have. The price that an agent is willing to ask is drawn from a normal distribution with a mean and a standard deviation. The values of these model parameters will be introduced in the following section.

As one way to represent the bounded rationality of agents, we assume that a searching agent can bid on at most three parcels. If an agent offers the highest price for an available parcel, it will put that parcel on its final selection list. Then, the agent will calculate whether it can benefit from migrating to the nearest parcel in its selection list. If it can benefit from the migration, it will pay the pasture rental fee and the cost of transportation. Otherwise, it will stay on its own pasture. The percentage of agents willing to lease pastures to strangers is a parameter of the model. The agents willing to lease pastures to strangers are distributed randomly in the agent world. At the end of each model step, all migrant agents move back to their pasture parcels. The net benefits of agents in pasture rental markets are calculated by

$$U_{2i}(n_i) = n_i \cdot B_i + B_{0i} - C_{0i} - C_{1i} - C_{2i} \tag{2}$$

where U_{2i} is the net benefit of agent i, n_i is the number of sheep owned by the agent i, B_i is the benefit from selling one sheep, B_{0i} is the benefit from leasing pastures to others, C_{0i} is the cost of renting pastures, C_{1i} is the cost of leasing pastures, and C_{2i} is the transportation cost of migrations. If agents cannot find available parcels for migrations through pasture rental markets, they calculate their net benefits by Eq. (1).

3.4. Reciprocal pasture-use groups

When drought happens, agents hit by drought will search for cooperators in their neighborhoods. Being cooperators means that they will share pastures with each other when drought happens. The cooperation is based on reciprocity. If agents can find cooperators with enough biomass to support migrants, they will migrate to the pastures of their cooperators without paying pasture rental fees or taking the risk that no available pastures can be found in the competitive pasture rental markets. The searching radii for rich and poor agents are set as the same as in pasture rental markets. Because of the economies of scale, the benefit of cooperation increases with the increase in the size of a cooperation group. In the real world, the economies of scale can result from the increasing bargaining power and resulting higher livestock sale prices with the increase in the size of a cooperation group. Cooperators have to pay the organization cost of cooperation. The organization cost of cooperation increases with the increase in the size of a cooperation group. This mechanism is contradictory to the effect of the economies of scale in the development of reciprocal pasture-use groups. Cooperators have to pay the transportation cost when migrations happen. The migration distance is expected to decrease as more agents join a cooperation group. The net benefits of agents in reciprocal pasture-use groups are calculated by

$$U_{3i}(n_i) = n_i \cdot B_i \cdot (1 + \lambda_i) - C_{1i} - C_{2i} \cdot (1 + \beta_i) - C_{3i} \cdot (1 + \gamma_i) \quad (3)$$

where U_{3i} is the net benefit of agent i, n_i is the number of sheep owned by the agent i, B_i is the benefit from selling one sheep, C_{1i} is the cost of sharing pastures, C_{2i} is the transportation cost of migrations, C_{3i} is the organization cost of cooperation, λ_i is the increased proportion of cooperation benefit, β_i is the decreased proportion of the transportation cost with the increase in the number of cooperators, γ_i is the increased proportion of the organization cost with the increase in the size of a cooperation group, and λ_i, β_i, and γ_i are functions of the number of agents in a cooperation group. At each model step, agents make decisions about whether to stay in or leave a cooperation group based on whether they can benefit from being in a cooperation group, i.e., they compare their utility in a reciprocal pasture-use group with the expected utility of sedentary grazing. If agents cannot find cooperators for migrations, they will calculate their net benefits by Eq. (1).

3.5. The free-rider problem in reciprocal pasture-use groups

We have discussed the mechanism of free entry and exit rights for maintaining a cooperation group (Nowak, 2006). In this institutional scenario, we set an exit cost of leaving a reciprocal pasture-use group. The exit cost of leaving a cooperation group is a theoretical topic that has been studied in the field of economics for a long time (Lin, 1993; Putterman and Sillman, 1992). In the model, if cooperators cannot benefit from being in a cooperation group, and they cannot afford the exit cost of leaving the cooperation group, they will turn into free-riders. We gradually changed the value of the exit cost to let free-riders emerge in reciprocal pasture-use groups. Being free-riders means that agents do not share their pastures with others, but they will migrate to the pastures of other cooperators when drought happens. The existence of free-riders causes the increase in the cost of sharing pastures for other cooperators. Free-riders still have to pay the organization cost of cooperation. The net benefits of agents for this institutional scenario are calculated by

$$U_{4i}(n_i) = n_i \cdot B_i \cdot (1 + \lambda_i) - C_{1i} \cdot (1 + \alpha_i) - C_{2i} \cdot (1 + \beta_i) - C_{3i} \cdot (1 + \gamma_i) - C_{4i} - C_{5i} \quad (4)$$

where U_{4i} is the net benefit of agent i, α_i is the increased proportion of the cost of sharing pastures, α_i is a function of the number of free-riders in a cooperation group, C_{4i} is the exit cost of leaving a cooperation group, C_{5i} is the cost of being found as a free-rider, and the other parameters in Eq. (4) have the same meaning with the parameters in Eq. (3).

4. Computational experiments

The agent-based model of local institutions was coded in Eclipse using Java and RepastJ 3.1 libraries (North et al., 2007). The values of some of the model parameters were set based on data from our household surveys and the literatures (Table 1). For example, percentages of rich and poor agents, numbers of sheep owned by rich and poor agents, sheep prices in normal and drought years, and the fodder price were set based on our household survey data. The values of the parameters related to pasture rental markets (e.g., the willingness to pay and the willingness to accept) were set based on the interviews with 25 herder households who conducted migrations through pasture rental markets in Inner Mongolia in the summer of 2006 (Zhang, 2007). These parameter values were set proportional to the original values for the convenience of calculations. We set the price of one sheep in a normal year as one unit, and the values of other parameters were set relative to the sheep price. Moreover, we set assumed values for some of the model parameters that we did not have empirical data to calibrate them (e.g., the organization cost of cooperation and the parameter related to the economies of scale).

The complexity of the agent-based model was represented by the social processes included in the model. By running experiments,

Table 1
The major parameters of the agent-based model of local institutions.

ID	Parameter name	Value	Source
1	Pasture size per parcel	100 ha	Assumed
2	Drought probability in the agent world	10%	This study
3	Consumption rate of grass per sheep	1 ton/year	This study
4	Grass productivity in a normal year	1.5 ton/ha (SD: 0.3)	IMIGSD (2011)
5	Grass productivity of the degraded parcels	1.0 ton/ha (SD: 0.2)	IMIGSD (2011)
6	Drought radius (number of parcels impacted by drought)	1 (9 parcels)	Assumed
7	Percentage of productivity loss: the parcel hit by drought	80%	Assumed
8	Percentage of productivity loss in drought: neighborhood parcels	50%	Assumed
9	Percentage of agents willing to share pastures to strangers	100%	Assumed
10	Searching radius of a rich agent	2	Assumed
11	Searching radius of a poor agent	1	Assumed
12	Maximum trials for searching available pastures	3	Assumed
13	Percentage of rich agents in the agent world	20%	This study
14	Number of sheep owned by a rich agent	50	This study
15	Number of sheep owned by a poor agent	30	This study
16	Sheep price in a normal year	1/sheep	This study
17	Sheep price in a drought year	0.5/sheep	This study
18	Fodder price	0.25/ton	This study
19	Percentage of sheep loss in drought without migrations	50%	Zhang (2007)
20	Transportation cost per distance	1/parcel distance	Zhang (2007)
21	Price willing to ask for leasing pastures	10 (SD: 2)	Zhang (2007)
22	Price willing to pay relative to the percentage of total benefit	25% (SD: 5%)	Zhang (2007)
23	Organization cost of cooperation for strangers	0.1/person	Assumed
24	Organization cost of cooperation for relatives	0.01/person	Assumed
25	Increasing rate of cooperation benefit with each additional agent	1%/person	Assumed
26	Exit cost of leaving a cooperation group	10	Assumed
27	Punishment cost of being found as a free-rider	20	Assumed

Note: SD means standard deviation.

we found that the agent world with the size of 10×10 was sufficient to represent the spatial relationships (e.g., agents search available pastures or cooperators in their neighborhoods) included in the model. Therefore, we used a small agent world with the size of 10×10 to analyze the social mechanisms and their interactions involved in the multiple institutional scenarios discussed in Section 3. The size of the agent world was scalable, although we used a small agent world here. For each experiment, we ran the model 20 steps to represent 20 years. In order to account for the random components in the model, we ran each experiment 30 times and averaged the modeling outcomes over 30 time runs. We had two observations for all of the following experiments. The social and ecological outcomes of pasture-use were measured by the average net benefit of agents and the number of undegraded parcels in the agent world, respectively.

4.1. The social–ecological performance of multiple institutional arrangements

In the first set of experiments, we ran three experiments to analyze the social–ecological outcomes of pasture-use under multiple institutional arrangements. We set 10% of the agents in the agent world so that they had the same last name, and the other 90% of the agents had random last names. In the first experiment, we analyzed the advantage of pasture rental markets over sedentary grazing. In the real world, not all herders are willing to lease pastures to strangers (Zhang, 2007). In the model, we changed the percentage of agents willing to lease pastures to strangers from zero to 50% and 100% to analyze the effect of the change on model outcomes. In the second experiment, we compared the performance of pasture rental markets and reciprocal pasture-use groups. In this experiment, we assumed that all agents were willing to lease pastures to strangers. For reciprocal pasture-use groups, we had two key parameters (i.e., the organization cost of cooperation and the parameter related to the economies of scale) with assumed values, which could affect comparing the performance of reciprocal pasture-use groups and pasture rental markets. Therefore, we ran sensitivity analyses of the modeling results related to the changes in the two parameters. The organization cost of cooperation was changed from zero per person (i.e., there is no organization cost of cooperation) to 0.5 per person (i.e., the organization cost will be equal to the gross benefit of a rich agent if all of the 100 agents are cooperators) in equal increment of 0.05. The increasing rate of cooperation benefit was changed from 1% per additional person (i.e., the total benefit of each agent will increase about two times if all of the 100 agents are cooperators) to 5% per additional person (i.e., the total benefit of each agent will increase about five times if all of the 100 agents are cooperators) in equal increment of 1%. In the above two experiments, we set a constant drought probability (i.e., 10%) in the agent world.

In the third experiment, we changed drought probability to analyze the performance of multiple institutional arrangements under different climate conditions. Besides sedentary grazing, pasture rental markets, reciprocal pasture-use groups, we also analyzed the performance of a combined institutional scenario of reciprocal use of pastures and pasture rental markets. When both reciprocity and pasture rental markets were included in the model, agents would search available parcels for migrations through pasture rental markets if they could not find reciprocal pasture-use groups to join. If agents could not find available parcels for migrations from either reciprocal pasture-use groups or pasture rental markets, they would stay on their parcels (i.e., sedentary grazing). In this experiment, drought probability in the agent world was changed from 10% to 30% in equal increment of 5%. This was used to analyze the performance of the four institutional scenarios under different conditions of drought probability. Similar to the second experiment, we assumed all agents were willing to lease pastures to strangers. The values of the organization cost and the parameter related to the economies of scale were set based on the results of the sensitivity analyses in the second experiment.

4.2. Social mechanisms for facilitating cooperative use of pastures

In the second set of experiments, we did exploratory analyses of two social mechanisms for facilitating the development of reciprocal pasture-use groups. We set a constant drought probability (i.e., 10%) in the agent world. The values of the organization cost of cooperation and the parameter related to the economies of scale were set as the same as in the third experiment of Section 4.1. First, we included the mechanism of agent diversity in the model. This mechanism means that agents play different roles in organizing reciprocal pasture-use groups. For example, our survey data show that rich herders were usually more capable of organizing cooperative pasture-use groups than poor herders. Because of lacking empirical data to calibrate the different roles of rich and poor agents in organizing cooperation groups, we used another mechanism to represent the effect of agent diversity on facilitating cooperation. We assumed that the organization cost of cooperation for relatives was 10% of the organization cost for strangers. Kinship cooperation is an important cooperation mechanism in the Mongolian grasslands. For centuries, herders used to rely on kinship networks to pool climate risks across social groups (Humphrey and Sneath, 1999). In this experiment, the percentage of agents with the same last name (i.e., kinship density) was changed from 10% (i.e., the other 90% of the agents had random last names) to 100% in equal increment of 10%.

The second social mechanism included in the model was the neighborhood effect through the formation of social norms. In this experiment, we focused on analyzing the effect of social norms on facilitating cooperation, and we turned off the mechanism of agent diversity. The traditional norms, such as flexible property boundaries and reciprocal use of pastures, used to play important role in facilitating cooperation among herders to live with the highly variable climate in the Mongolian grasslands (Fernandez-Giménez and Le Febre, 2006). In the model, the mechanism of social norms means that an agent will change its behavior to cooperate if a certain number of its neighbors choose to cooperate, and the agent can also benefit from changing its behavior to cooperate. The neighboring eight parcels of a parcel were defined as the neighbors of that parcel. The number of neighborhood agents with the same behavior for an agent to change its behavior was set as a parameter of the model (i.e., the neighborhood parameter). In this experiment, we changed the value of the neighborhood parameter from 100% (i.e., all of the eight neighbors choose to cooperate) to 12.5% (i.e., one of the eight neighbors choose to cooperate) in equal decrement of 12.5%. In this process, the criterion for an agent to change its behavior to cooperate was relaxed.

4.3. Social mechanisms for maintaining reciprocal pasture-use groups

In the third set of experiments, we did exploratory analyses of two social mechanisms for solving the free-rider problem in reciprocal pasture-use groups. We set a constant drought probability (i.e., 10%) in the agent world. The values of the organization cost of cooperation and the parameter related to the economies of scale were set as the same as in the third experiment of Section 4.1. First, we included the mechanism of kin selection in the model. This mechanism means that free-riders do not free-ride on relatives, and the organization cost of cooperation is lower for relatives than for strangers. The second

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part of this mechanism is the same as the mechanism of agent diversity in Section 4.2. In this experiment, the percentage of agents with the same last name was increased from 10% to 100% in equal increment of 10%. In the second experiment, we included the punishment mechanism in the model. This mechanism means that agents in a cooperation group will not turn into free-riders if they cannot afford the punishment cost of being found as free-riders. If the punishment cost is higher than the net benefit of an agent, the agent will not turn into free-riders. The punishment cost on free-riders was increased from 10% to 100% of the gross benefit of a poor agent in equal increment of 10%. In this experiment, we set a village manager agent in the agent world to operate the behavior of punishing free-riders. This was to avoid the second or higher order free-rider problem in cooperation (Boyd et al., 2010). The mechanism of kin selection was turned off in the second experiment.

5. Results

5.1. Local institutions and climate change adaptation

Sedentary grazing, pasture rental markets, and reciprocal pasture-use groups generated different patterns of agent activities (Fig. 2). When drought happened, some of the agents still could not find available parcels for migrations through the competitive pasture rental markets (Fig. 2B). Reciprocal pasture-use groups emerged after a few model steps (Fig. 2C). Under current value-settings of the related model parameters (Table 1), pasture rental markets had better social–ecological performance (i.e., the average net benefit of agents and the number of undegraded parcels) than sedentary grazing without cooperation. With increases in the percentage of agents willing to lease pastures to strangers (i.e., from zero to 50% and 100%), the percentage of agents could find available parcels for migrations increased from around 10–50% and 70%. As a result, the comparative advantage (i.e., the difference in the social–ecological performance) of pasture rental markets over sedentary grazing increased correspondingly.

The sensitivity analyses of the modeling results related to the changes in the organization cost of cooperation and the increasing rate of cooperation benefit (i.e., economies of scale) show that the social–ecological performance of reciprocal pasture-use groups decreased with the increase in the organization cost and the decrease in the economies of scale (Fig. 3). The development of reciprocal pasture-use groups was constrained by the values of the organization cost of cooperation and the economies of scale. By comparing the performance of reciprocal pasture-use groups and pasture rental markets under the same drought probability (i.e., 10%), we found that reciprocal pasture-use groups had better performance than pasture rental markets only when the organization cost of cooperation was less than 0.15 per person (i.e., half of the gross benefit of a poor agent) and the increasing rate of cooperation benefit was more than 1% per additional person.

Based on the results of the sensitivity analyses in the second experiment, we set the values of the organization cost and the economies of scale as 0.1 per person and 1% per additional person, respectively. Under these value-settings, reciprocal pasture-use groups have better performance than pasture rental markets. With increases in drought probability from 10% to 30%, the comparative

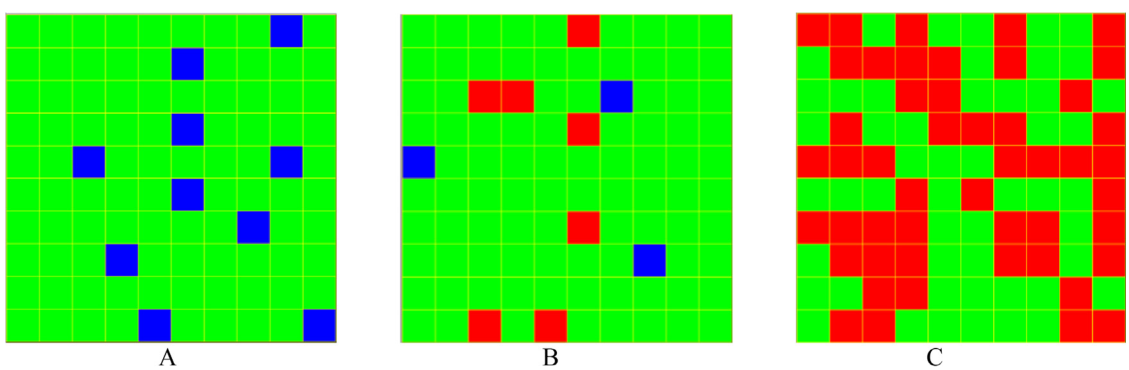

Fig. 2. The snapshots of the experiments for the three institutional arrangements. (A) Sedentary grazing. (B) Pasture rental markets. (C) Reciprocal pasture-use groups. The green blocks in (A), (B), and (C) were the parcels not hit by drought. The blue blocks in (A) were the parcels hit by drought. The blue blocks in (B) were the parcels hit by drought, and the agents did not find available parcels. The red blocks in (B) were the parcels hit by drought, and the agents found available parcels. The red blocks in (C) were cooperators. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

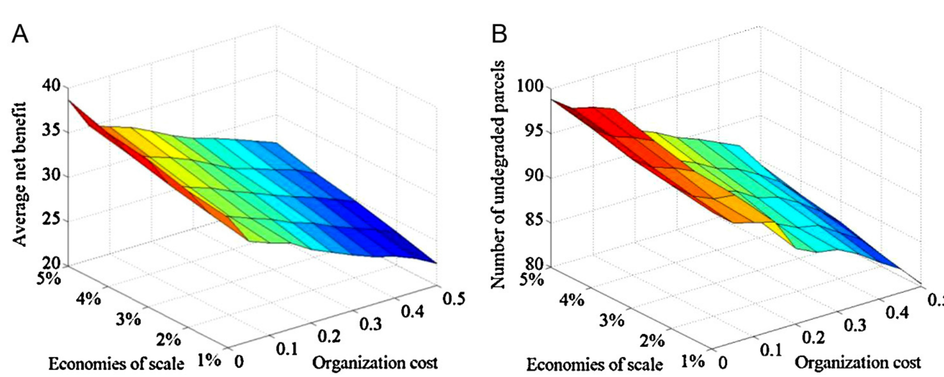

Fig. 3. The sensitivity analyses of the modeling results related to the changes in the organization cost of cooperation and the increasing rate of cooperation benefit (i.e., the economies of scale) for reciprocal pasture-use groups. (A) The average net benefit of agents. (B) The number of undegraded parcels.

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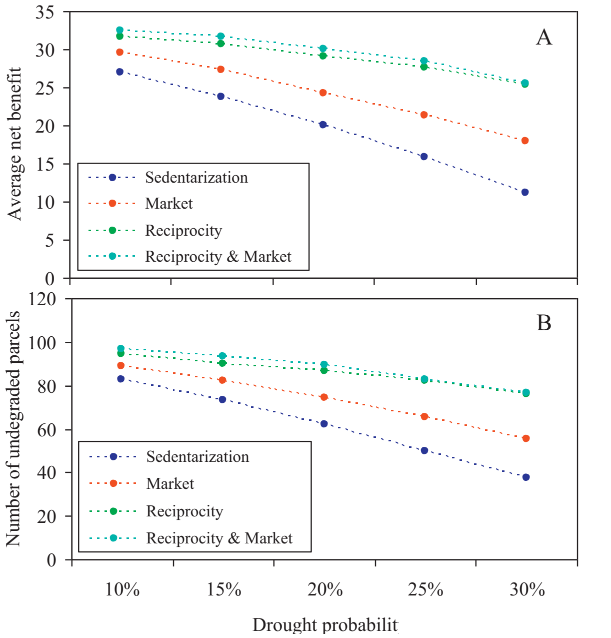

Fig. 4. The social–ecological performance of four institutional scenarios under different conditions of drought probability. (A) The average net benefit of agents. (B) The number of undegraded parcels. The standard deviations of the social and ecological outcomes of pasture-use under the four institutional scenarios are provided in the Supplemental materials (Appendix A).

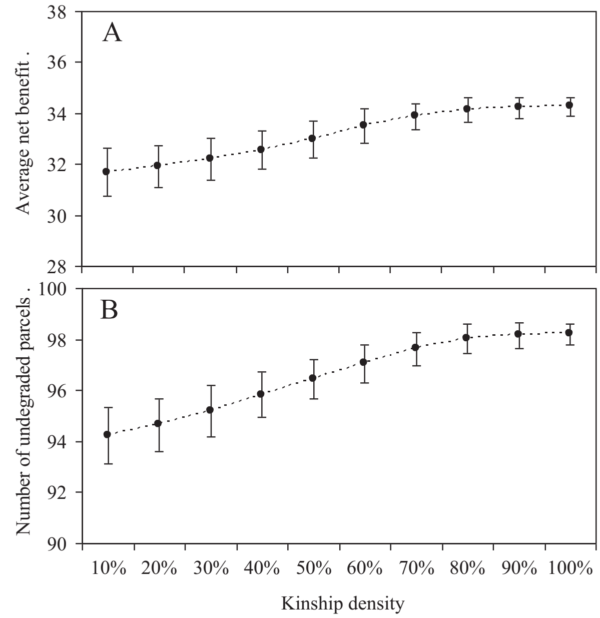

Fig. 5. The social–ecological outcomes of pasture-use in reciprocal pasture-use groups with the mechanism of agent diversity included in the model. (A) The average net benefit of agents. (B) The number of undegraded parcels. The error bars represent one standard deviation.

advantage of reciprocal pasture-use groups over pasture rental markets increased correspondingly (Fig. 4). When including both reciprocity and pasture rental markets in the model, the results did not change much. This indicates that reciprocity played a stronger role in facilitating cooperative use of pastures among agents than pasture rental markets. The comparative advantage of pasture rental markets over sedentary grazing also increased with the increase in drought probability. However, the performance of pasture rental markets and reciprocal pasture-use groups both decreased with the increase in drought probability. This was because there were fewer agents who were able to support migrants with the increase in drought probability.

5.2. *Effects of agent diversity and social norms on facilitating cooperative use of pastures*

With increases in the density of kinship connections, the social–ecological performance of reciprocal pasture-use groups increased gradually, and the standard deviations of the social–ecological outcomes of pasture-use decreased in the process (Fig. 5). The results also show that including the mechanism of agent diversity in the model facilitated cooperation among both relatives and strangers; and the number of strangers in cooperation groups increased. The organization cost of cooperation increased with the increase in the sizes of cooperation groups. Including the mechanism of agent diversity in the model relaxed the constraint and facilitated the development of reciprocal pasture-use groups.

Including the mechanism of social norms in the model provided incentives for agents who were not hit by drought to join reciprocal pasture-use groups. The results of the experiment with the mechanism of social norms included in the model (Fig. 6) were different from the results of the last experiment (Fig. 5). With decreases in the value of the neighborhood parameter, the social–ecological outcomes of pasture-use increased slowly at first. When the value of the neighborhood parameter was lower than 50% (i.e., less than four of the eight neighbors were cooperators), the social–ecological outcomes of pasture-use increased significantly. The standard deviations of the social–ecological outcomes decreased with the decrease in the value of the neighborhood parameter.

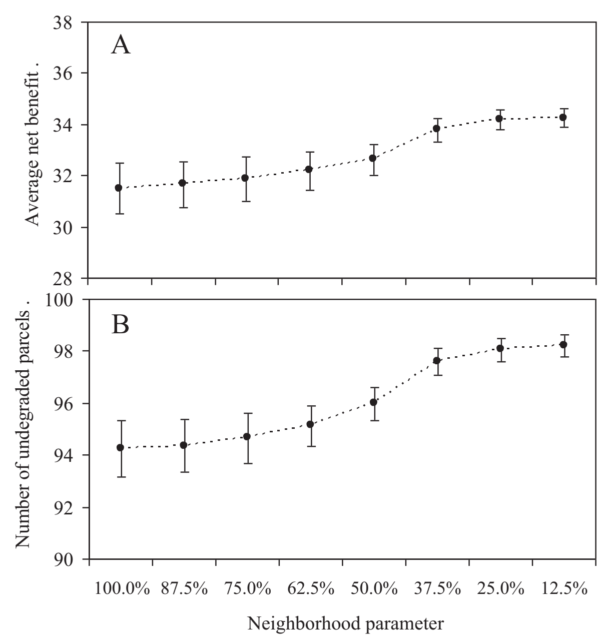

Fig. 6. The social–ecological outcomes of pasture-use in reciprocal pasture-use groups with the mechanism of social norms included in the model. (A) The average net benefit of agents. (B) The number of undegraded parcels. The error bars represent one standard deviation.

5.3. *Solving the free-rider problem in reciprocal pasture-use groups*

The social–ecological outcomes of pasture-use increased gradually with the increase in the density of kinship connections, and the standard deviations of the social–ecological outcomes of pasture-use decreased in the process. The effect of kin selection on

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maintaining cooperation was more prominent when the density of kinship connections was higher than 70% (Fig. 7). With increases in the density of kinship connections, the number of free-riders in cooperation groups decreased correspondingly. This was caused by two mechanisms. First, agents did not free-ride on relatives. Second, the organization cost of cooperation decreased with the increase in the density of kinship connections. With the decrease in the organization cost of cooperation, fewer cooperators had incentives to turn into free-riders. Therefore, including the mechanism of kin selection in the model helped to maintain reciprocal pasture-use groups.

The average net benefit of agents first decreased then increased with the increase in the punishment cost on free-riders (Fig. 8A). When the punishment cost on free-riders was low, some of the agents chose to turn into free-riders because they could take the punishment cost of being found as free-riders. However, when they were found as free-riders, they had to pay the punishment cost. Therefore, the average net benefit of agents decreased at first, and the standard deviations of the average net benefit of agents were high at first. With increases in the punishment cost on free-riders, fewer agents could take the cost of being found as free-riders. Therefore, the average net benefit of agents increased significantly when the punishment cost on free-riders reached a certain level. The number of undegraded parcels increased with the increase in the punishment cost on free-riders (Fig. 8B). This was because the number of free-riders decreased with the increase in the punishment cost on free-riders.

6. Discussion and conclusions

Previous studies have shown that local institutions play the key role in shaping climate change adaptation of rural communities (Agrawal, 2010). Local institutions shape the impact of climate change on rural communities and the way they respond to climate change. Using an agent-based modeling approach, we did exploratory analyses of local institutions (i.e., sedentary grazing, pasture rental markets, and reciprocal pasture-use groups) for climate change adaptation in the Mongolian grasslands with highly variable climate. Although the development of the agent-based model of local institutions was based on empirical studies in the Mongolian grasslands, we analyzed several key problems, such as privatization, grazing sedentarization, and climate change adaptation, which also existed in other semiarid and arid grassland areas of Inner Asia and Africa. For example, over the past decades, the traditional grazing societies of Africa also have experienced privatization and grazing sedentarization (Mwangi, 2007). Therefore, the exploratory analyses of local institutions for climate change adaptation in the Mongolian grasslands could have implications for climate change adaptation in some of the grassland areas in Africa.

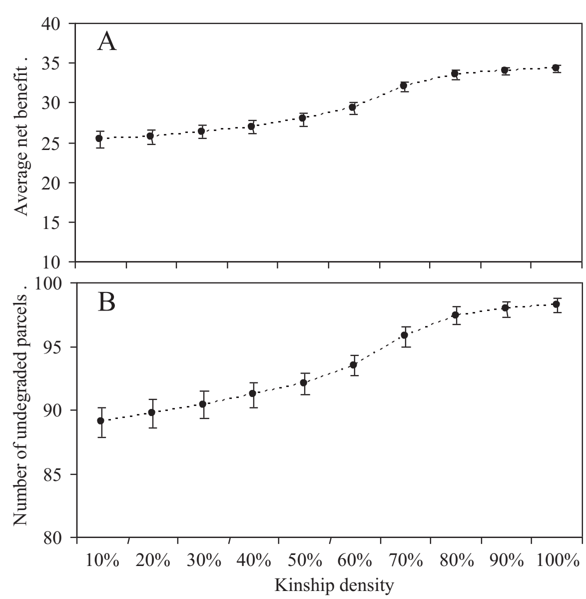

Fig. 7. The social–ecological outcomes of pasture-use in reciprocal pasture-use groups with the mechanism of kin selection included in the model. (A) The average net benefit of agents. (B) The number of undegraded parcels. The error bars represent one standard deviation.

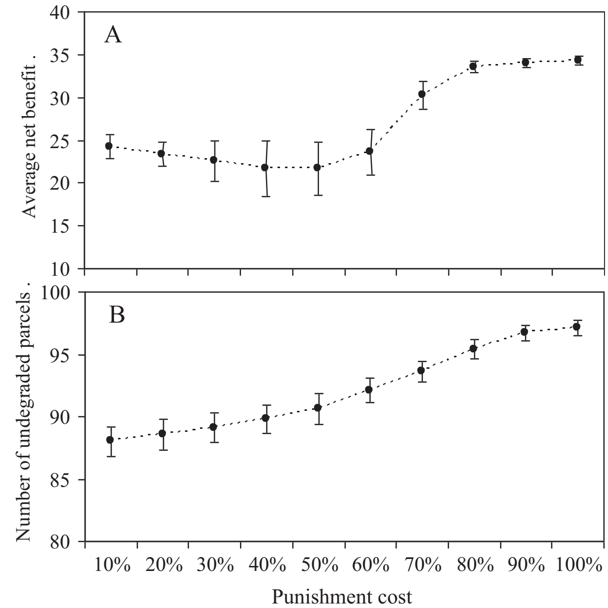

Fig. 8. The social–ecological outcomes of pasture-use in reciprocal pasture-use groups with the punishment mechanism included in the model. (A) The average net benefit of agents. (B) The number of undegraded parcels. The error bars represent one standard deviation.

We began analyzing the social–ecological performance of multiple local institutions by setting a baseline institutional scenario of sedentary grazing. Then, we included the cooperation mechanisms of pasture rental markets and reciprocal use of pastures in the agent-based model, separately and together, to analyze their social–ecological performance. The results show that under current value-settings of the related model parameters, pasture rental markets had better performance than sedentary grazing without cooperation. Although the values of most parameters related to pasture rental markets and sedentary grazing were set based on empirical data from our household surveys and the literatures (Table 1), we still had several model parameters with assumed values (e.g., the searching radii of rich and poor agents). Changing the values of the searching radii can influence the number of available pastures in their neighborhoods, and the social–ecological outcomes of pasture-use will be influenced as a result. In Inner Mongolia, privatization and grazing sedentarization have changed the social structures of herder communities. Consequently, the cost of searching available pastures for migrations has increased (Li and Huntsinger, 2011). If the local government of Inner Mongolia can collect and disseminate the demand and supply information of pastures when climate hazards happen, this will decrease the cost of searching pastures. As a result, the impact of climate hazards will be reduced through the development of pasture rental markets.

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In certain value-ranges of the organization cost and the economies of scale, reciprocal pasture-use groups had better performance than pasture rental markets; and the comparative advantage of reciprocal pasture-use groups became more evident with the increase in drought probability. Over the past decades, social-institutional changes in Mongolia and Inner Mongolia have undermined the traditional grazing norms and the underlying social networks for mobile grazing (Li and Huntsinger, 2011; Wang, 2013; Williams, 2002). These changes have increased the organization cost of developing cooperative pasture-use groups. In our surveyed field sites, cooperative pasture-use groups were mainly organized by local governmental officials or self-organized by relatives and/or neighbors for adapting to climate variability and change. Moreover, in recent years the local government of Inner Mongolia has been providing incentives (e.g., subsidies) for herders to organize cooperation groups in order to improve the efficiency of livestock production. The above social mechanisms found in our field sites lowered the organization cost of cooperation among herders. In this work, we explored two social mechanisms for facilitating cooperation among agents. The results show that the mechanisms of agent diversity and social norms were effective in facilitating the development of reciprocal pasture-use groups.

The formation of collective action needs external drivers and internal coordination mechanisms (Ostrom, 2005). The free-rider problem is an important problem related to the maintenance of collective action. In this study, we did exploratory analyses of the free-rider problem in reciprocal pasture-use groups. The existence of free-riders affects the maintenance of cooperation because it causes the increase in the cooperation cost of other cooperators. We analyzed two social mechanisms for solving the free-rider problem. The results show that kin selection and punishments on free-riders were effective in maintaining cooperation among agents. In the Mongolian grasslands, the traditional grazing organizations (i.e., *khot ail*) were usually consisted of several herder households with kinship/clanship relationships. Those cooperation groups helped herders to live with the highly variable climate (Fernandez-Giménez, 1997; Humphrey and Sneath, 1999; Li and Li, 2012). Over the past decades, social-institutional changes have changed the social norms of livestock grazing in the Mongolian grasslands (Humphrey and Sneath, 1999). The traditional cooperative use of pastures has become competitive use of pastures, and the number of conflicts over pasture-use has increased (Upton, 2009; Williams, 2002). Therefore, the free-rider problem explored in this study could be an important problem related to the maintenance of reciprocal pasture-use groups.

In this work, we focus on exploratory analyses of local institutions for climate change adaptation, using an agent-based modeling approach. One limitation of the agent-based model is that some of the model parameters were not empirically calibrated. This could affect the reliability of the modeling results. If the agent-based model is expected to be used as a tool for real-world policy analysis, further calibrations of the model parameters using empirical data are still needed. Second, two sub-systems of the grassland social–ecological systems on the Mongolian plateau were simplified, and these simplifications could also affect the reliability of the modeling results. First, the relationships between climate variability and the dynamics of grass productivity were simplified by setting a hypothetical look-up table. Second, we did not include the influence of the fluctuations in the prices of livestock products on livestock management behaviors of herders. Since the economic reforms in Mongolia and Inner Mongolia in the early 1990s and mid-1980s, respectively, market incentives have been playing an important role in influencing livestock management behaviors of herders, which consequently affect grassland quality. In the future, we could combine an accurate ecological sub-model of grassland dynamics and an economic sub-model of market influence on livestock management behaviors with the agent-based model of institutions for an integrated modeling of the grassland social–ecological systems on the Mongolian plateau.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.07.017.

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