Modeling SOC and NPP responses of meadow steppe to different grazing intensities in Northeast China

Yuhui Wang\textsuperscript{a,b}, Guangsheng Zhou\textsuperscript{a,b,*}, Bingrui Jia\textsuperscript{a}

\textsuperscript{a} State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, the Chinese Academy of Sciences, Beijing 100093, PR China
\textsuperscript{b} Institute of Atmospheric Environment, China Meteorological Administration, Shenyang 110016, PR China

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A B S T R A C T
Grassland ecosystems play an important role in Chinese terrestrial ecosystems. However, great demand and excessive utilization of human beings on grassland resources have made it more susceptible to rapid degeneration in ecosystem properties and soil carbon levels. Among them, grazing is one of the key factors to make grassland ecosystems degraded. Therefore, it is very important to graze sustainably on grassland for preventing the degradation of grasslands. In this paper, as a case study, we simulated the potential changes of soil organic carbon (SOC) and net primary productivity (NPP) of meadow steppe dominated by \textit{Leymus chinensis} under different grazing intensities based on CENTURY model (V4.0) in order to evaluate the effects of different grazing intensities and to pursue for optimal grazing intensity. The results showed that NPP and SOC of meadow steppe dominated by \textit{Leymus chinensis} were very sensitive to grazing intensity. The optimal grazing intensity could be expressed by live shoots, and it should be less than 40\% of whole live shoots per month, in order to mitigate the degradation of \textit{Leymus chinensis} grassland and maintain its sustainable development.

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1. Introduction

Grasslands are one of the most widespread vegetation types, covering approximately 40\% of the land surface (Frank et al., 2000; Glenn et al., 1993; World Resources, 1986) and containing approximately 30\% of global soil carbon stocks (Anderson, 1991). Ranging from the savannas of Africa to the North American prairies and the converted grasslands of Latin America and South-East Asia, these ecosystems play a very important role in regulating global carbon cycle by plant and soil organic matter (SOM) in grasslands and providing meat and grain for human beings.

However, with the development of industrialization and the increase in population, great demand and excessive utilization of human beings on natural resources have made grassland ecosystems more susceptible to rapid degeneration in ecosystem properties and soil carbon levels (Archer et al., 1994; Ojima et al., 1994). The decrease, degradation and exhaustion of grassland resources have been universal. Among them, grazing is one of the key factors to make grassland ecosystems degraded. Carbon, which is translocated from plant parts to herbivores, is usually 25–50\% or more of above-ground net primary productivity (NPP) (McNaughton, 1976, 1985; Lauenroth and Milchunas, 1992) and perhaps 25\% of...
the belowground productivity (Coleman, 1976; Ingham and Detling, 1984; Lauenroth and Milchunas, 1992). These changes would not only contribute to the increase of "greenhouse gas", especially CO₂ concentration in the atmosphere, but also affect surface temperatures through boundary changes in vegetation cover and alter significantly the biogeochemistry, especially carbon cycling, through affecting NPP and soil carbon storage of grassland, and consequently may lead to feedback to components of climate change (Burke et al., 1991).

China is one of the countries in the world with the fast industrialization and urbanization during recent two decades. Due to large-scale reclamation of grassland and overgrazing as well as climate change characterized by ‘global warming’, the area of degraded grassland in China amounts to 8.667 × 10⁷ hm², and occupies about one third of the available grassland area. The desertification area at present reaches about 2.622 × 10⁸ hm², occupying about 27.3% of the land (Tian and Ma, 2001).

*Leymus chinensis* grassland distributed in the east part of Euroasian continent grassland region plays a very important role in temperate grassland ecosystems. It is a kind of zonal grassland type, and occupies about 4.2 × 10⁷ hm² in the world. Among them, more than half is located in China (Wu et al., 1995). As a typical grassland type in China, it is a very important base of livestock farming in northern China. With the increase of population and livestock, the degradation of *Leymus chinensis* grasslands has been serious. The area of degraded grassland at present makes up about 50% of the total available grassland area in Inner Mongolia, and nearly 20% of it is seriously degraded grassland. In the famous Hulunbeir and Xilingole steppes, the areas of degraded and serious degraded rangeland reached about 23 and 41%, respectively (Li et al., 2002). The conflict between grazing demand and grassland enduring capacity has been a serious challenge to human being.

Studies of the effects of grazing on above ground productivity and carbon sequestration have generated varying results (Milchunas and Lauenroth, 1993). Grazing by domestic herbivores has been shown to reduce both primary productivity and C sequestration for a mid- and tall-grass community in the North American Great Plains (Derner et al., 2006) and for Festuca swards in southwestern Alberta (Dormaar and Willms, 1998). However, grazing does not always reduce soil organic carbon and the effects may vary with stocking rate (Schuman et al., 1999, 2001) and nitrogen application in ecosystems (Mortenson et al., 2004). In European grassland sites, the net carbon storage also tends to increase when the amount of carbon removed by cutting and grazing is reduced (e.g. extensive management) (Milchunas and Lauenroth, 1993). Therefore, it is very important to estimate an appropriate grazing strategy in order to maintain a sustainable grassland ecosystem.

During the past two decades, a number of simulation models about grassland grazing systems had been developed, which encompass a variety of complexity, processes, data needs and data availability (Wright and Dent, 1969; Innis, 1978; Parton et al., 1987; Hunt et al., 1991; Coughenour, 1992; Thornley, 1998; Rabi et al., 2000; Britta Tietjen and Florian Jeltsch, 2007; Badini et al., 2007). However, relatively few of these models have been rigorously tested across a range of environmental conditions. The need and desirability for model validation and sensitivity analysis has been repeatedly stressed in the literature, but most models have been tested over a limited set of conditions (Gilmanov et al., 1997).

CENTURY model, as a ecosystem-level biogeochemical model of plant-soil nutrient cycling, had been successfully applied and tested across seasonal and long-term dynamics of plant production, decomposition and nutrient cycling in various grassland ecosystems in North and Central America, Africa, Europe, and Asia (Parton et al., 1993, 1995; Xiao et al., 1995; Gilmanov et al., 1997; Ardö and Olsson, 2003; Wang et al., 2007). And Overall performance of CENTURY in predicting SOM dynamics is comparable with other soil organic models such as RothC, CANDY, DNDC, DAISY and NCSOIL (Smith et al., 1997). Therefore, as a case study, we would simulate the potential changes of soil organic carbon and NPP of meadow steppe dominated by *Leymus chinensis* under different grazing intensities based on CENTURY model (V4.0). The objectives of this study were (1) to analyze the responses of SOC and NPP to different grazing intensities. (2) To establish an appropriate grazing intensity for *Leymus chinensis* meadow steppe in Songnen plain.

2. Methods

2.1. Research site

This study was carried out in Songnen grasslands in Northeastern China (43°30′–48°40′, 121°30′–127°00′, Fig. 1). The average altitude of this area is about 141 m. Most of the region has meadow chernozem soil, with 3.5–6.0% organic matter in the surface layer. The soil organic layer reaches 20–30 cm deep; soil texture is 35% clay, 45% silt, and 20% sand on average, bulk density is 1.54 g/cm³, average soil pH is about 8.7 (Xiong and Li, 1987; Wang and Ripley, 1997). It belongs to semiarid temperate monsoon climate, and the mean annual temperature is about 5 °C, varying from −18 °C in January to 23 °C in July. The >10 °C accumulated temperature ranged from 2579 to 3144 °C. Mean annual precipitation is about 564 mm, and 70% falls from June to August. Mean potential evaporation is 1368 mm (Wang, 2004).

In Songnen meadow steppe, about 167 plant species was noted with 25 xerophil species (about 15% of total species) and 125 mesophyte species (about 75% of total species; Zheng and Li, 1993); and dominated by *Leymus chinensis*, *Camagrostis epigejos*, *Potentilla flagellaris*, *Puccinellia communis* and *Cnoliris vigata*. It turns green in early April, reaches peak aboveground biomass in late August, and senescence the aboveground part in early October. Thus, the August biomass represents the total maximum production of *Leymus chinensis* community within a year (Zhu et al., 2004).

2.2. Sampling methods

In this study, the biomass in August were collected at the ground surface and in late August, reaches peak aboveground biomass in early September, and senescence the aboveground part in early October. Thus, the August biomass represents the total maximum production of *Leymus chinensis* community within a year (Zhu et al., 2004).
oven dried at 65 °C to constant weight, then converted to NPP (Guo and Zhu, 1994; Zheng and Li, 1993). Climate data from 1954 to 1995 were obtained from the Changling County weather station in Leymus chinensis meadow steppe.

2.3. CENTURY model

CENTURY model is an ecosystem-level model, has been widely used to simulate biogeochemical fluxes of C, N, P and S, primary production and water balance at monthly time step (Parton et al., 1987, 1988, 1993). The primary purpose of CENTURY model is to supply a tool for ecosystem analysis enabling the evaluation of changes in climate and the management of ecosystems (Ardö and Olsson, 2003). Originally, it was designed to simulate SOM dynamics in the Great Plains Grasslands (Parton et al., 1987, 1988), and so far, it had been modified and expanded to simulate agricultural systems, forest systems and savannah systems in the world.

CENTURY model consists of three major submodels: (1) SOM submodel that calculates dynamic C and N flows in soil and litter pools; (2) biophysical submodel which calculates hydrological and temperature driver variables; and (3) grassland production submodel which simulates above- and belowground vegetation processes (Parton et al., 1993).

The model calculates NPP at monthly time step as the smaller of two rate-limited estimates:

\[ \text{NPP} = \min(\text{NPP}_C, \text{NPP}_N) \]  

(1)

where NPP\(_N\) (g DW m\(^{-2}\) a\(^{-1}\)) expresses the constraints of nutrient availability on NPP; NPP\(_C\) expresses climatic limitations on NPP as a function of soil temperature, available water and a self-shading factor using the following equation:

\[ \text{NPP}_C = \text{NPP}_{\text{max}} \times f_T(T) \times f_M(M) \times f_S(S) \]  

(2)

where \(\text{NPP}_{\text{max}}\) is the theoretical maximum NPP, \(f_T(T)\) is the effect of temperature \(T\) on growth, \(f_M(M)\) is the effect of soil water and \(f_S(S)\) is the effect of self-shading. The equations for estimating \(f_T(T), f_M(M)\) and \(f_S(S)\) are given by Parton et al. (1993).

The grazing event in CENTURY model can be parameterized to remove defined fractions of aboveground live and standing dead plant material each month. The fractional returns of C, N, P, and S are specified, having allowed for losses in animal carcasses and milk, transfer of dung and urine off the area being simulated, volatile losses of N from dung and urine patches, and leaching of N and S under urine patches. The proportion of N, P, and S returned in organic forms is also specified as the lignin content of the feces.

The effect of grazing on plant production is represented in the model by using data from Holland et al. (1992) and Ojima et al. (1990). Grazing removes vegetation, returns nutrients to the soil, alters the ratio of root to shoot, and increases the N content of live shoots and roots (Holland et al., 1992). The model has three options (grazing parameter) for dealing with the impact of grazing on the system. For option 1 there are no direct impacts of grazing on plant production except for the removal of vegetation and return of nutrients by the animals. Option 2 is referred to as the lightly grazed effect (Holland et al., 1992) and includes a constant root:shoot ratio (not changing with grazing) and a linear decrease in potential plant production with increasing grazing intensity. Option 3 is referred to as the heavy grazed (Holland et al., 1992) option and includes a complex grazing optimization curve where aboveground plant production is increased for moderate grazing and decreasing sharply for heavy grazing levels. The root:shoot ratio is constant for low to moderate grazing levels and decreases rapidly for heavy grazing levels. Among all three options the nutrient content of new shoot will increase in relation to the residual biomass.

The soil submodel consists of eight organic matter pools. Four represent surface and root litter, and the other four represent SOM. The SOM pools include two ‘active’ fractions that have rapid turnover times (1–5 years) and represent microbial biomass and metabolism divided into a surface and a soil pool; a ‘slow’ fraction with an intermediate turnover time (20–40
years) that represents stabilized decomposition products; and a ‘passive’ fraction with a slow turnover time (200–15,000 years) that represents highly stabilized organic matter. Carbon fluxes between these pools are controlled by decomposition rate and microbial respiration parameters, both of which are expressed as functions of soil texture. The turnover times of all pools vary with a soil abiotic decomposition parameter and are calculated as a function of monthly temperature and precipitation (Parton et al., 1993; Peng and Apps, 1999).

The model simulates SOM dynamics by separating SOM into three pools (microbial biomass, slow and passive SOM) and simulating the cycling of SOM in these pools. The flow of SOM between pools is controlled by an abiotic decomposition factor which is calculated as a function of the actual evapotranspiration rate and monthly soil temperature. Nutrients are mineralized as a result of the cycling SOM in the different pools. Most of the carbon respiration and nutrient mineralization results from the turnover of the microbial biomass pool.

Major driving variables of CENTURY model include (1) monthly precipitation and monthly average minimum and maximum temperatures. (2) Lignin content of plant material, (3) plant N, P, and S contents, (4) soil texture, (5) atmospheric and soil N inputs, and (6) initial soil C, N, P, and S levels (Parton et al., 1993).

The simulation output variables are organized into eight groups. They are (1) water and temperature output variables: they described soil water and temperature, precipitation, mean air temperature, decomposition factor; (2) soil C output variables, which described soil and litter C pools, erosion and deposition; (3) crop/grass C output variables which described crop and grass above and belowground production; (4) forest C output variables which described forest above and belowground production, NPP; (5) CO₂ output variables which described respiration; (6) nitrogen output variables; (7) phosphorus output variables; and (8) sulfur output variables.

Site-specific parameters and initial conditions of *Leymus chinensis* grassland at Changling grassland research station, Northeast Normal University, such as soil texture (clay, silt and sandy contents), bulk density, soil pH, soil C content for 0–20 cm layer and drainage characteristics of soil were shown in Table 1. And the simulated capacity of CENTURY model to Leymus chinensis meadow steppe has been validated (Wang et al., 2007).

### 2.4. Modeling design

CENTURY V4.0 simulations were run for 5000 years to reach soil carbon equilibrium under natural conditions by repeating mean monthly temperature and CENTURY’s stochastic precipitation generator. Values of monthly mean maximum and minimum temperatures and precipitation were calculated by CENTURY V4.0 using 43-year normal data (1953–1995) from Changling County weather station. The sensitivities of NPP and soil organic carbon to grazing intensities were simulated by running for 50 years under different grazing intensities and were compared by calculating mean values of the last 10 years of the simulation.

Simulations were performed to examine the changes of NPP and soil organic carbon under following different patterns and intensities of grazing scenarios: (1) 10% of live shoots was removed by grazing event per month (G-10%); (2) 30% of live shoots was removed by grazing event per month (G-30%); (3) 40% of live shoots was removed by grazing event per month (G-40%); (4) 60% of live shoots was removed by grazing event per month (G-60%); (5) 80% of live shoots was removed by grazing event per month (G-80%).

### 3. Results

#### 3.1. Responses of soil organic carbon to grazing intensity

In order to understand the impacts of grazing on soil organic carbon of meadow steppe dominated by *Leymus chinensis*, the last 10-year average annual soil organic carbon under different grazing patterns over 50-year were compared with those values without grazing human disturbance over 50 years based

<table>
<thead>
<tr>
<th>Grazing pattern</th>
<th>Soil organic carbon (g C/m²)</th>
<th>Changes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No disturbance</td>
<td>5358.87 ± 14.93 %***</td>
<td>0</td>
</tr>
<tr>
<td>G-10%</td>
<td>5225.51 ± 19.59 %***</td>
<td>−2.49</td>
</tr>
<tr>
<td>G-30%</td>
<td>5054.77 ± 26.90 %***</td>
<td>−5.68</td>
</tr>
<tr>
<td>G-40%</td>
<td>4288.64 ± 64.83 %***</td>
<td>−19.97</td>
</tr>
<tr>
<td>G-60%</td>
<td>3570.50 ± 93.67 %***</td>
<td>−33.37</td>
</tr>
<tr>
<td>G-80%</td>
<td>2686.25 ± 92.68 %***</td>
<td>−49.87</td>
</tr>
</tbody>
</table>

(−) Decrease of soil organic carbon and ***significant difference (P<0.001). The values followed by the same letter are not significantly different between grazing patterns at P<0.001 according to Duncan’s multiple range tests.

### Table 1 – Site parameters and grassland conditions at *Leymus chinensis* meadow steppe in Changling County, Jilin Province

<table>
<thead>
<tr>
<th>Location</th>
<th>44.67° N, 126.67° E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude above sea level</td>
<td>147 m</td>
</tr>
<tr>
<td>Mean monthly air temperature (°C)</td>
<td>Minimum – 18 °C (January)</td>
</tr>
<tr>
<td>Mean monthly precipitation (mm)</td>
<td>Minimum 2.07 (January)</td>
</tr>
<tr>
<td>Soil organic matter content (%)</td>
<td>3.5–6.0% organic matter in the surface layer</td>
</tr>
<tr>
<td>Soil texture</td>
<td>35% clay, 45% silt, and 20% sand</td>
</tr>
<tr>
<td>Bulk density</td>
<td>1.54 g/cm³</td>
</tr>
<tr>
<td>Soil pH</td>
<td>8.7</td>
</tr>
<tr>
<td>Vegetation type</td>
<td>Meadow steppe</td>
</tr>
<tr>
<td>Dominated species</td>
<td>Leymus chinensis</td>
</tr>
</tbody>
</table>

### Table 2 – Changes of soil organic carbon of *Leymus chinensis* meadow steppe under different grazing patterns

<table>
<thead>
<tr>
<th>Grazing pattern</th>
<th>Soil organic carbon (g C/m²)</th>
<th>Changes (%)</th>
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<td>G-80%</td>
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<td>−49.87</td>
</tr>
</tbody>
</table>

(−) Decrease of soil organic carbon and ***significant difference (P<0.001). The values followed by the same letter are not significantly different between grazing patterns at P<0.001 according to Duncan’s multiple range tests.
on the simulation of CENTURY model (Table 2) and one-way ANOVA method.

Grazing activities would lead to the change of soil organic carbon. With the increase of grazing intensities from G-10% to G-80%, soil organic carbon seriously decreased from 2.49 to 49.87%. And the effects of grazing were significantly different among different grazing intensities ($P < 0.001$). When 40% live shoots of meadow steppe was removed by grazing event per month, about 20% soil organic carbon was lost. When 80% of live shoots was removed by grazing event per month, about 50% of soil organic carbon would be lost. It indicated that when the live shoots of meadow steppe was removed more than 40%, the degradation of soil property would be serious. Thus, the high grazing intensities would have higher probability for Leymus chinensis meadow steppe to release more carbon into atmosphere and would result in carbon source of grassland ecosystems.

3.2. Responses of net primary productivity to grazing intensity

The last 10-year average annual NPP under different grazing patterns over 50 years were compared with the last 10-year average values without grazing disturbance over 50-year based on the simulation of CENTURY model V4.0 and one-way ANOVA (Table 3).

The change pattern of NPP was different with soil organic carbon under different grazing intensities. The NPP under G-10% has a slightly increase by about 3.29% compared with those without grazing disturbance. With the increase of grazing intensity, NPP decreased gradually. From G-30% to G-80%, NPP decrease by 9.88, 13.53, 57.54 and 99.98%, respectively. However, NPP does not have significantly difference among no disturbance (G-0%), G-10%, G-30% and G-40%, while it has significant difference for G-60% and G-80% ($P < 0.001$). That is to say, when 60% of the live shoots was removed by grazing event per month, NPP of Leymus chinensis meadow steppe would decrease obviously. Its NPP only amounted to 40% of that without grazing disturbance. When 80% of the live shoots was removed by grazing event per month, the NPP would be close to zero. Under this situation, Leymus chinensis meadow steppe would have higher probability to become bare.

### Table 3 – Changes of NPP of Leymus chinensis meadow steppe under the different grazing patterns

<table>
<thead>
<tr>
<th>Grazing pattern</th>
<th>NPP (g m$^{-2}$ year$^{-1}$)</th>
<th>Changes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No disturbance</td>
<td>225.12 ± 71.81$^a$</td>
<td>0</td>
</tr>
<tr>
<td>G-10%</td>
<td>232.53 ± 71.37$^a$</td>
<td>+3.29</td>
</tr>
<tr>
<td>G-30%</td>
<td>202.88 ± 57.88$^a$</td>
<td>-9.88</td>
</tr>
<tr>
<td>G-40%</td>
<td>194.65 ± 60.73$^a$</td>
<td>-13.53</td>
</tr>
<tr>
<td>G-60%</td>
<td>95.58 ± 25.07$^b$</td>
<td>-57.54</td>
</tr>
<tr>
<td>G-80%</td>
<td>0.049 ± 0.000001$^c$</td>
<td>-99.98</td>
</tr>
</tbody>
</table>

($^-$) Decrease of NPP; ($^+$) increase of NPP; significance level: $P = 0.001$. The values followed by the same letter are not significantly different between grazing patterns at $P < 0.001$ according to Duncan’s multiple range tests.

4. Discussion

Rangeland management plays an essential role in sustaining ecological integrity within grazed ecosystems (Hsin-i Wu et al., 1996). Appropriate grazing would contribute to the growth of plant because it could decrease the mature tissue of plant and improve remained leaf photosynthesis rate and soil water and nutrient cycle (Wang et al., 2001; Li and Wang, 1999). However, improper grazing pressure and stocking rate would severely degrade grassland productivity.

CENTURY model, as an ecosystem-level model, had been used to produce guidance for grazing policy even in this study. The simulated results show that in Leymus chinensis meadow steppe, when 10% of the live shoots was removed by grazing event per month (G-10%), its NPP increased 3.92% compared with non-grazing situation. However, when the more live shoots were removed by grazing event, its NPP decreased gradually. Its NPP would decease 57.54% under G-60%, and would be close to zero under G-80%. It implicated that proper grazing intensity would stimulate the vegetation growth in Leymus chinensis meadow steppe, but overgrazing would degrade the meadow steppe productivity, even leaving vast areas with barren, exposed soil.

Grazing events would affect not only on NPP of meadow steppe but also on soil organic carbon. Grazing would cause the loss of soil organic carbon of Leymus chinensis meadow steppe. Especially under G-60% or G-80%, the soil organic carbon would decrease about 33.37% and 49.87%, respectively. Zhao et al. (2007) also reported that grazing decreased soil organic carbon but increase soil bulk density in typical Leymus chinensis steppe in Inner Mongoloia. Overgrazing lead to soil organic carbon decrease through (a) reducing carbon inputs from litter fall due to vegetation destruction of plant cover and litter consumption by herbivores (Morello and Saravia-Toledo, 1959); (b) increasing in soil temperature in vegetation-denuded areas that favors microbial activity, SOM decomposition (Amelung et al., 1998) and increase the soil respiration, contribute to the carbon release (Abril and Bucher, 2001); and (c) accelerating wet–dry cycles in denuded areas where strong compaction and high surface temperatures favor rapid desiccation after the rains, causing breakdown of soil aggregates and, consequently, SOM degradation (Kay, 1998). However, proper grazing management had been estimated to increase soil C storage on US rangelands from 0.1 to 0.3 Mg C ha$^{-1}$ year$^{-1}$ and new grasslands have been shown to store as much as 0.6 Mg C ha$^{-1}$ year$^{-1}$ (Schuman et al., 2002). Derner et al. (1997) also found that increased soil C storage under grazed compared to ungrazed shortgrass steppe in northeastern Colorado.

Therefore, it is vital to devise a site-independent sustainable grazing policy for long-term conservation and proper utilization of Leymus chinensis meadow steppe in Songnen plain. The simulated results showed that NPP and soil organic carbon of meadow steppe were sensitive to grazing disturbance. By the comparison, we found that 40% of live shoots was removed by grazing event per month was a very important threshold for maintaining the sustainable development of Leymus chinensis meadow steppe. When the intensity of grazing was less than G-40%, NPP and soil organic carbon
of Leymus chinensis meadow steppe would keep in stable or decrease slightly; while it is more than 40%, its NPP and soil organic carbon would decrease obviously and more and more soil organic carbon would be lost and more and more soil would be exposed. Therefore, it is important to restrict grazing intensity and make removed live shoots less than 40% of whole live shoots per month in order to mitigate the degradation of Leymus chinensis meadow steppe and maintain its carrying capacity for livestock.

Acknowledgements

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