Agricultural Systems 217 (2024) 103916

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Effects of grazing and climate change on aboveground standing biomass and sheep live weight changes in the desert steppe in Inner Mongolia, China

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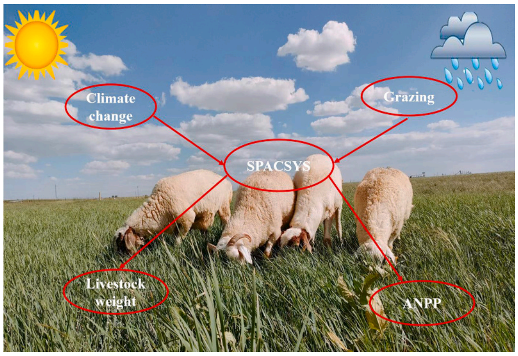
HIGHLIGHTS

- The interactions of climate change and grazing on grassland are complex that need to be studied by process models.
- The model can accurately simulate aboveground standing biomass and sheep live weight in desert steppe.
- The model can make adaptive management strategies for desert steppe in climate change and grazing.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Grazing
Climate change
SPACSYS model
Aboveground standing biomass
Sheep live weight

ABSTRACT

CONTEXT: The *Stipa breviflora* desert steppe ecosystem is fragile and sensitive to climate change and grazing disturbance. Previous studies have reported the effects of climate change and grazing on aboveground standing biomass of the plant community and sheep live weight, however, the interaction between climate change and grazing remains unclear. Process models have become ideal tools for the evaluation of the effects of grazing management practices under climate change.

OBJECTIVE: We used the Soil-Plant-Atmosphere Continuum System (SPACSYS) model to investigate aboveground standing biomass and the live weight of sheep in the desert steppe of Inner Mongolia under future climate change scenarios and different grazing management. The results will be used to inform adaptive management strategies.

METHODS: The grazing experiment consisted of four treatments: no grazing (0 sheep ha^{-1} half $year^{-1}$), light stocking rate (0.91 sheep ha^{-1} half $year^{-1}$), moderate stocking rate (1.82 sheep ha^{-1} half $year^{-1}$), and high stocking rate (2.71 sheep ha^{-1} half $year^{-1}$). We used observed data on soil temperature, soil volumetric water content, changes to sheep live weight, and aboveground standing biomass of plant community to provide

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https://doi.org/10.1016/j.agsy.2024.103916
Received 16 August 2023; Received in revised form 5 February 2024; Accepted 3 March 2024
Available online 11 March 2024

parameterization and validation for the SPACSYS model. We then predicted aboveground standing biomass of the plant community and sheep live weight changes for different grazing management under three representative concentration pathways (RCP) scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) from 2021 to 2100.

RESULTS AND CONCLUSIONS: Moderate and high stocking rates decreased aboveground standing biomass and sheep live weight changes more than the light stocking rate. A light stocking rate can maintain higher aboveground standing biomass and sheep live weight as well as meet production requirements. Therefore, a light stocking rate is a potentially effective management approach to improve food production security and combat global climate change in the desert steppe.

SIGNIFICANCE: The model can inform management strategies for grazing in the desert steppe under climate change, supporting efforts to maintain the stability of the steppe ecosystem and increase economic benefits, while also providing a theoretical basis for adaptive management in the desert steppe.

1. Introduction

Grasslands are one of the main ecosystems in the world, covering about 40.5% of land area (excluding Greenland and Antarctica, Bai and Cotrufo, 2022). They not only provide production materials and habitat for humans and herbivores (Kemp et al., 2013), but also play important roles in the carbon cycle.

The *Stipa breviflora* desert steppe is a transition zone from steppe to desert that has unique plant composition and community structure and important ecological and production functions (Kemp et al., 2013). Recently, demand for meat, fur, and milk products has risen as population increases, leading the desert steppe to suffer unprecedented grazing pressure to devastating effect (Louhaichi et al., 2012). To prevent further degradation, it is, therefore, urgent to establish a sustainable stocking rate for this landscape.

The change in sheep live weight is an ideal indicator to determine the optimal stocking rate, as well as age of the sheep, ecological site type, class of grazing animals, and aboveground standing biomass (Wang et al., 2011). The aboveground standing biomass of the plant community is an indicator of the function and structure of grassland ecosystems. Previous research has shown that the aboveground standing biomass of the plant community in the desert steppe decreased by 44.6% under long-term overgrazing (Zhang et al., 2018). This decline may have occurred for several reasons: (1) The leaves and stems of plants were eaten by livestock reducing aboveground biomass. (2) An increase in the presence of poisonous and harmful forbs caused overgrazing (Louhaichi et al., 2012). (3) Plant diversity loss was caused by overgrazing (Zhang et al., 2018; Zuo et al., 2018). However, other research has found that aboveground standing biomass increased under a moderate stocking rate through compensatory or over-compensatory growth and decreasing competitiveness in the community (McNaughton, 1979). This suggests that optimal stocking rates can be win-win strategies for aboveground standing biomass and livestock growth.

Not only is aboveground standing biomass of a plant community related to the stocking rate, but also to changes in climatic conditions. Over the past three decades, the annual mean temperature has increased by >1.0 °C (Fang et al., 2018); however, the effects of climate warming on aboveground standing biomass of plant communities vary. Climate warming can promote physiological and biochemical processes in plants that improve photosynthesis, thereby increasing aboveground standing biomass of plant communities (Albert et al., 2011). However, Ma et al. (2017) and Su et al. (2019) found that warming had no effect on the aboveground standing of plant community, primarily because warming did not affect the species richness of plant community (Ma et al., 2017; Su et al., 2019). Another study has shown that the aboveground standing biomass of plant communities actually decreased under warmer conditions, which may be caused by plants usually choosing to reduce leaf area or light saturation point to adapt to drought and hot environments, leading to the reduction of vegetation community coverage and aboveground standing biomass (Jiao et al., 2018). Additionally, climate warming can also enhance the competition among plants in the community (Li et al., 2018), resulting in decreases in the aboveground standing biomass.

Precipitation is the main limiting factor in the desert steppe, and a decrease in precipitation will lead to a decrease in plant transpiration rate or leaf area, causing aboveground standing biomass of the plant community to decrease (Felsmann et al., 2017). Both Jia et al. (2020) and Xu et al. (2016) found that increased precipitation can increase the aboveground standing biomass of plant communities by improving the availability of soil water (Jia et al., 2020; Xu et al., 2016). However, Gao et al. (2013) found that increasing precipitation leads to the loss of soil nutrients, thus reducing the aboveground standing biomass of plant communities (Gao et al., 2013).

The Intergovernmental Panel on Climate Change (IPCC) predicts that CO_2 concentrations will be >900 μmol·mol^{-1} by the end of the century (IPCC, 2013), and increasing CO_2 emissions will significantly increase plant community productivity (Fernández-Martínez et al., 2018). However, a study in California found that increased temperature, nitrogen deposition, or precipitation (alone or in combination) tended to increase plant productivity, while increasing CO_2 concentrations inhibited plant productivity (Shaw et al., 2002). Excessive carbon dioxide emissions may reduce plant productivity (Liu et al., 2021), and it is speculated that plant productivity and carbon uptake will continue to decrease as water and nutrient resources become limited (Peñuelas et al., 2017). This will lead to greater pressure on grassland ecosystems with highly degraded vegetation and reduced biodiversity (Waters et al., 2016).

Although previous studies have reported the effects of grazing, climate warming, and precipitation change on the aboveground standing biomass of plant communities (Fan et al., 2021; Wang et al., 2022; Li et al., 2020), most studies are based on single-factor experiments, which may cause uncertainties (Bai et al., 2020). The impact of the interaction between climate factors and grazing on the aboveground standing of plant communities has been comparatively understudied. The combined impact of multiple factors is not a simple additive or antagonistic effect between factors, and the interaction of multiple factors is difficult to predict (Rillig et al., 2019). To quantify the impacts of the interacted environmental and management variables on aboveground standing biomass of plant communities and livestock growth, a systematic approach is necessary. Many quantitative methods, such as partial derivative analysis, multivariate analysis, and principal component analysis, have been widely used to assess the effects of climate change and stocking rate on aboveground standing biomass, these methods have ignored the ecological process, which may lead to uncertainty in the estimation results (Zhang et al., 2016). Process modeling could help to overcome this challenge, as process models can take into account the complex nonlinear relationships between plant growth and climate, soil, and management practices. In addition, they can be used to assess and formulate food production policies in response to climate change (Quan et al., 2022). Therefore, process models are widely used especially to predict future climate change impacts on crop production (Liu et al., 2020).

The Soil-Plant-Atmosphere Continuum System (SPACSYS) model is an ideal tool for assessing the impacts of environmental change and field management practices (Wu et al., 2007, 2015, 2022). It has been applied to grassland systems to assess greenhouse gas emissions, animal and grass growth, water use and quality, and nutrient load under different climate scenarios (Abalos et al., 2016; Wu et al., 2022). To quantify the effects of the interaction of future climate change scenarios and different stocking rate management approaches on desert steppe aboveground standing biomass, a 3-year field experiment was used to evaluate the performance of the model. The specific objective of this study are:(1) to evaluate the performance of the model in simulating aboveground standing biomass of the plant community, soil temperature, volumetric water content, and sheep growth dynamics; (2) to use the model to predict the effects of climate change and stocking rate on aboveground standing biomass of the plant community and sheep live weight change in the desert steppe, and (3) to propose stocking rate adaptation strategies for the desert steppe under climate change.

2. Materials and methods

2.1. Study site and experimental design

The experiment site was located at the Chinese Academy of Agricultural and Animal Husbandry Sciences in the Siziwang Banner desert steppe in Inner Mongolia (N41°47 ‘17 “, E111°53’ 46 “). It is located at an altitude of 1450 m. The average precipitation is 230 mm (2004–2016), with about 90% occurring during the growing season from May to September. The constructive species at the site is *Stipa breviflora*, and the dominant species are *Cleistogenes songorica* and *Artemisia frigida*. The main associated species are *Convolvulus ammannii*, *Heteropappus altaicus*, *Neopallasia pectinate, Kochia prostrata, Caragana stenophylla, Leymus chinensis* and *Agropyron cristatum*. The grass community average height is low (7–10 cm).

The grazing experiment was established in 2004, using a complete block design with three blocks, and four stocking treatments were randomly arranged in each block. The area of each treatment was 4.4 ha. The stocking rates were 0 sheep ha^{-1} half year^{-1} (no grazing, NG), 0.91 sheep ha^{-1} half year^{-1} (light stocking rate, LG), 1.82 sheep ha^{-1} half year^{-1} (moderate stocking rate, MG), and 2.71 sheep ha^{-1} half year^{-1} (high stocking rate, HG). Grazing time was from 6 am to 6 pm every day from June to November each year.

The soil in this area is light chestnut. The soil physical and chemical properties are shown in Table 1.

2.2. Measurements

2.2.1. Soil samples

Soil samples were collected with three samplings in each treatment, and every sample was mixed at two points in time every month, mid-month and end of the month, from May to September in 2014, 2015, and 2016. Each point was sampled to a depth of 10 cm and with a diameter of 3.5 cm. Fresh soil samples were weighed and then dried in an oven for 48 h at 65 °C. The dry soil was weighed, and the weights of the fresh and dried soil samples were used to calculate soil volumetric water content.

Table 1
Soil physical and chemical properties in 2004.

Treatment	Depth cm	Silt %	Sand %	Clay %	pH	SOM g kg^{-1}
No stocking rate	0–10	36.81	58.95	4.21	7.67	26.82
	10–20	33.81	62.56	3.63	8.08	23.16
Light stocking rate	0–10	34.18	61.53	4.29	7.57	24.52
	10–20	31.95	65.64	2.41	7.97	19.52
Moderate stocking rate	0–10	32.03	62.10	5.87	7.67	23.56
	10–20	30.34	64.87	4.79	7.96	20.47
High stocking rate	0–10	33.42	62.67	3.91	7.85	23.92
	10–20	30.54	66.15	3.31	8.14	20.51

SOM, soil organic matter. Clay$<$0.001 mm, 0.001 mm $<$ Silt$<$0.05 mm and 0.05 mm $<$ Sand.

Soil temperature was measured at the same time as soil volumetric water content with a soil geothermometer (SP-E-17, China) Three samples and two replicates were collected from each treatment to measure the soil temperature from 0 to 10 cm depth.

Soil volumetric water content and temperature were parameterized in the no grazing treatment, and the data from the light, moderate, and high grazing treatments were used to validate the model.

2.2.2. Sheep live weight

Accurate measurement of the weights and daily grass intake of sheep are necessary for accurate aboveground biomass estimates of the grazing system in the simulation. Sheep weight was monitored on an empty stomach on June 1st, July 1st, and October 31st in 2014, 2015, and 2016. Sheep live weight under the LG condition was used as the parameterization for the model; MG and HG treatments were used for validation of the model.

2.2.3. Plant samples

The aboveground standing biomass of the plant community was used to parameterize the NG treatment, and aboveground standing biomass during the growing season for the LG, MG, and HG treatments were used to validate the model. Samples were taken at the end of each month from May to September from 2014 to 2016. Aboveground standing biomass was measured in each treatment. Ten 1 m × 1 m quadrats were randomly harvested on the ground level and dried in a drying box at 65 °C for 48 h.

2.3. Model description

The SPACSYS model is a process model with a daily time step. It is weather-driven and takes into account carbon cycling, nitrogen (N) cycling, phosphorus cycling, water cycling, and plant growth development. The model can also accurately simulate weight changes in livestock (Wu et al., 2022). Detailed descriptions of the model can be found in Wu et al. (2007, 2015, 2016; 2022).

The main processes concerning plant growth in the model are plant development, assimilation, respiration, and partitioning of photosynthate and estimated nutrient uptake to different plant organs, as well as N fixation for legume plants and root growth and development. Nitrogen cycling coupled with carbon cycling in the model covers the transformation processes for organic matter (OM) and inorganic N. The organic matter pool is further divided into fresh OM, dissolved OM, a litter pool as well as a humus pool. Inorganic N includes a nitrate pool and an ammonium pool. The main processes and transformations causing size changes to soluble N pools are mineralization, nitrification, denitrification and plant N uptake. Most of these are dependent on soil water content and temperature that are simulated in the model. Nitrate is transported through the soil profile and into field drains or deep groundwater by water movement. A biological-based component for the denitrification process has been implemented that can estimate N gaseous emissions. The model has shown good performance on soil volumetric water content and aboveground standing biomass of the plant community under climate change scenarios (Wu et al., 2016).

2.4. Parameterization and validation

Wu et al. (2016) conducted a study on grasslands using the SPACSYS model. The study utilized a trial-and-error approach to parameterize the soil water redistribution, heat transformation, soil carbon and nitrogen cycling, plant photosynthesis and development, and nitrogen migration parameters in the NG condition, while using LG, MG, and HG to validate the model. The approach used in Wu et al. (2022) to test livestock performance parameterized sheep live weight under LG and then used sheep live weight under MG and HG to validate. The data on sheep live weight was from 2014 to 2016.

Based on the approach developed by Wu et al., the parameters listed in Table 2 were input into the model.

2.5. Climate change scenarios

Three climate representative concentration paths (RCPs) from the Fifth Assessment Report of the IPCC were used to input weather data for the model from 2021 to 2100. The three climate scenarios are RCP 2.6, RCP 4.5, and RCP 8.5. Climate scenario data for 2021 to 2100 were downloaded from the HadGEM2-ES model (Collins et al., 2011). The average annual temperature tended to increase from 2021 to 2100 across the three climate scenarios (Table.3, $P < 0.01$). The average annual temperature under the RCP 8.5 was the highest. There was no significant difference in precipitation under the three climate scenarios ($P > 0.05$).

2.6. Statistical analysis

The evaluation methods followed Wu et al. (2022) and mainly include the coefficient of determination (R^2), Kling-Gupta efficiency (KGE), Root Mean Square Error (RMSE), and Percent Bias (PBIAS). These equations are as follows:

$$R^2 = \left(\frac{\sum_{i=1}^{N} (M_i - \overline{M_i})(S_i - \overline{S_i})}{\sqrt{\sum_{i=1}^{N} (M_i - \overline{M_i})} \sqrt{\sum_{i=1}^{N} (S_i - \overline{S_i})}} \right)^2 \quad (1)$$

Table 2

Parameters in the SPACSYS model.

Type	Parameters
Daily weather elements	Maximum and minimum temperatures
	Precipitation
	Wind speed
	Relative humidity
	Global short-wave radiation
Plant parameters	Accumulated temperatures required from emergence to flowering
	Accumulated temperatures required from flowering to maturity
	Coefficient in the photoperiod response function
	Critical photoperiod without light impaction for vegetative stage
	Threshold temperature for emergence
	Threshold temperature for vegetative stage
	Threshold temperature for reproductive stage
	Minimum temperature for photosynthesis
	Optimal temperature for photosynthesis
	Maximum temperature for vernalisation
	Minimum temperature for vernalisation
	Optimum temperature for vernalisation
	Extinct coefficient
	Leaf transmission coefficient
	Photochemical efficiency at optimal temperature, water and N conditions
	Lowest leaf N concentration required for photosynthesis
	Leaf N concentration for stable photosynthesis
	Q_{10} value for respiration maintenance
	Specific leaf area
	Critical herbage mass
Sheep performance parameters	Animal number and age
	Turnout and removal date
	Initial live weight
	Energy requirement per unit weight
	Live weight at mature
	Metabolizable energy
	Energy requirements
	Gompertz constant
	Physical ability on herbage intake
	Metabolizable energy requirement for maintenance
	Metabolizable energy requirement for growth and fattening

Table 3

Predicted average temperature and precipitation from 2021 to 2100 in the study area.

Climate scenarios	Average annual temperature (°C)	Average annual precipitation (mm)
RCP 2.6	3.2 ± 0.1c	244.6 ± 6.7a
RCP 4.5	4.5 ± 0.2b	253.3 ± 8.2a
RCP 8.5	5.6 ± 0.2a	259.1 ± 7.7a

Note:The same letter indicate no statistically significant difference, and different letters indicate significant differences at the 0.01 level.

$$\mathrm{KGE} = 1 - \sqrt{(r-1)^2 - \left(\frac{\sigma_{\mathrm{S_i}}}{\sigma_{\mathrm{M_i}}} - 1\right)^2 + \left(\frac{\overline{\mathrm{S_i}}}{\overline{\mathrm{M_i}}} - 1\right)^2} \quad (2)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{S_i} - \mathrm{M_i})^2}{N}} \quad (3)$$

$$\mathrm{PBIAS} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{S_i} - \mathrm{M_i})}{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{M_i}} 100 \quad (4)$$

where N is the total paired number, S_i, M_i, $\overline{S_l}$, $\overline{M_l}$ are simulated value, observed value and the average of the simulated and observed values, respectively. r is the Pearson product-moment correlation coefficient (between simulated and measured), and σ_{S_i} and σ_{M_i} are the standard deviations for the simulated and measured data, respectively. The above indices were calculated in the 'hydroGOF' R package.

The R^2 value ranges from 0 to 1. When the value is closer to 1, there is a stronger relationship between the simulated and observed values. KGE is a measure of goodness-of-fit for comparing simulations to observations, and it incorporates the correlation coefficient r, the ratio between the means of the simulated and measured data and the variability ratio, ranging from $-\infty$ to 1. RMSE reflects the degree of difference between the simulated and observed values. The closer to 0 the index is, the better the simulation fits. PBIAS is an error-based index, and a value closer to 0 indicates higher accuracy model simulation. A negative PBIAS value indicates that the variable was underestimated.

Two-way ANOVA was used to analyze the effects of different grazing treatments and climate scenarios on aboveground biomass, and analysis at 0.05 level was used to determine significant differences ($P < 0.05$). R 4.1.2 software was used for all statistical analyses.

3. Results

3.1. Model performance

The statistical indices that indicate model performance for soil temperature, water content, sheep liveweight and aboveground

Table 4

Statistical indices for model performance compared with observations.

		ST	SWC	Sheep live weight	AGB
R^2	Parameterization	0.42***	0.67***	0.89***	0.85***
	Validation	0.54***	0.75***	0.95***	0.60***
KGE	Parameterization	0.59	0.48	0.58	0.90
	Validation	0.67	0.55	0.95	0.60
RMSE	Parameterization	4.52	4.98	4.74	14.20
	Validation	4.03	3.93	1.31	27.63
PBIAS	Parameterization	11.70	−48.00	−5.80	−5.70
	Validation	−8.60	−38.40	0.40	25.40

ST, soil temperature (0–10 cm), SWC, soil volumetric water content (0–10 cm), AGB, aboveground standing biomass.

standing biomass are shown in Table 4.

3.1.1. *Simulated soil volumetric water content and temperature*

Soil temperature ranged from 4.2 °C to 21.3 °C, and the simulated values were between 6.9 °C and 26.4 °C. the relationship between parameterization and validation were linear, and the R^2 values of the parameterization and validation were 0.42 and 0.54 ($P < 0.001$, Fig. 1 and Table 4), respectively. The KGE of soil temperature for the parameterization and validation were 0.59 and 0.67 (Table 4), respectively. The RMSE values of soil temperature for the parameterization and validation were 4.52 and 4.03 (Table 4). The PBIAS value of soil temperature for the parameterization was 11.70%, indicating that it was overestimated. However, the PBIAS value for validation is −8.60%, indicating that soil temperature was underestimated. The PBIAS values of soil temperature were both positive and negative, which showed that the SPACSYS model did not overestimate and underestimate soil temperature as a whole.

The observed values of soil volumetric water content ranged from 3.61% to 18.41%, and the simulated values were from 0.83% to 16.09%. The relationship between observed and simulated values is positive, and the R^2 values for the parameterization and validation of soil volumetric water content were 0.67 and 0.75 ($P < 0.001$, Fig. 2, Table 4), respectively. The KGE value of soil volumetric water content was 0.48 for the parameterization and 0.55 for the validation (Table 4). The RMSE values of soil volumetric water content for the parameterization and validation were 4.98 and 3.93 (Table 4), respectively; however, the PBIAS values of soil volumetric water content for the parameterization and validation were − 48% and − 38.40%, indicating an underestimation of soil volumetric water content.

3.1.2. *Simulated aboveground standing biomass*

The aboveground standing biomass of the plant community was simulated by the SPACSYS model and showed good performance (Table 4). The RMSE of the aboveground standing biomass of the plant community parameterization and validation were 14.20 and 27.63 g m^{-2}, the R^2 values were 0.85 and 0.60, and the KGE values were 0.90 and 0.60, respectively. The PBIAS value of the parameterization was −5.70%, indicating that aboveground standing biomass under NG was underestimated while being overestimated by 25.40% under LG, MG, and HG. These results show that the SPACSYS model can be used to simulate aboveground standing biomass of plant communities in the desert steppe ($P < 0.001$, Fig. 3, Table 4).

3.1.3. *Simulated sheep live weight*

The simulated value of sheep live weight corresponded well with the observed value (Table 4, Fig. 4). The R^2 values for the parameterization and validation were 0.89 and 0.95 ($P < 0.001$, Fig. 4, Table 4), respectively. The KGE values were 0.58 and 0.95, which are close to 1. The RMSE values were low for the parameterization (4.74) and validation (1.31). The PBIAS value of the parameterization was −5.80%, indicating an underestimation of sheep live weight under LG; however, the PBIAS value of the validation was 0.40%, indicating slight overestimation under MG and HG. In general, the SPACSYS model showed good performance in simulating sheep live weight.

3.2. *Impacts of stocking rates and climate change on aboveground standing biomass*

The aboveground standing biomass of the plant communities significantly decreased under the three RCPs scenarios for LG, MG and HG compared with NG ($P < 0.05$, Fig. 5). The aboveground standing biomass was highest under NG by 287.8 g m^{-2} and decreased by 7.85%, 15.93% and 22.54% for LG, MG and HG, respectively, under the RCP 2.6 scenario. Similarly, under RCP 4.5, aboveground standing biomass was 8.31%, 16.89% and 25.38% lower in the LG, MG and HG than under NG, and 7.76%,16.84% and 23.93%. lower than NG under RCP 8.5.

3.3. *Sheep liveweight change at different stocking rates under climate change scenarios*

In the RCP 2.6 climate scenario, sheep live weight change decreased with increasing stocking rates. Live weight changes under MG and HG are significantly lower than under LG by 32.68% and 56.50%, respectively. In the RCP 4.5 climate scenario, sheep live weight change were 25.43% lower under MG and 90.63% under HG than under LG. A similar finding was observed In the RCP 8.5 climate scenario, where sheep live weight change under MG (76.31%) and HG (189.12%) were significantly lower than under LG (Fig. 6).

Under the LG treatment, sheep live weight change were 24.91% lower in RCP 4.5 and 53.90% less in RCP 8.5 than in RCP 2.6. Under the MG treatment, sheep live weight change under the RCP 4.5 and RCP 8.5 climate scenarios were 16.83% and 83.78% lower than in RCP 2.6. The decreases were even greater under the HG treatment, with sheep live weight change 83.82% less under RCP 4.5 and 194.44% less under RCP 8.5 compared to RCP 2.6. (Fig. 6).

The relationships between simulated sheep live weight change and time are not significant in the LG, MG and HG treatments under RCP 2.6 (Fig. 7). Under RCP 4.5, there were negative relationships between the two variables in the LG, MG and HG treatments, and sheep live weight decreased by 1.1 kg, 0.8 kg, and 1.4 kg per decade, respectively. Similarly, simulated live weight declined by 2.4 kg, 0.8 kg, and 1.4 kg per decade for LG, MG, and HG under RCP 8.5 (Fig. 7).

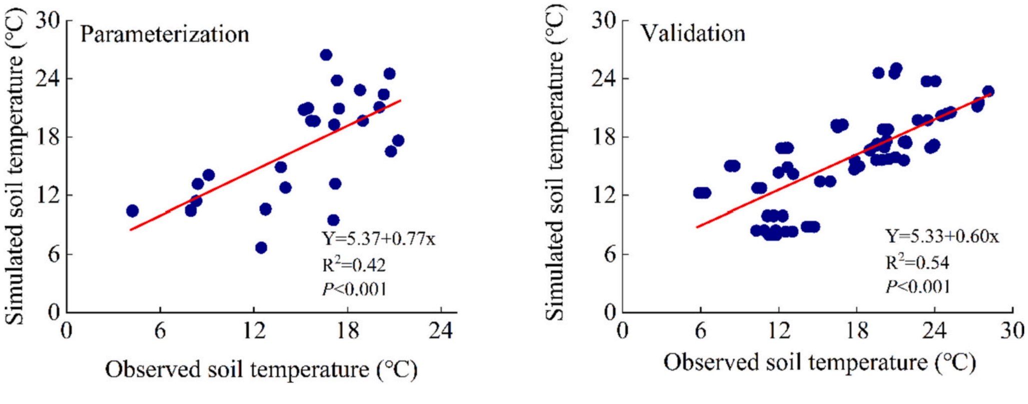

Fig. 1. Relationship between simulated and observed soil temperature of the parameterization and validation.

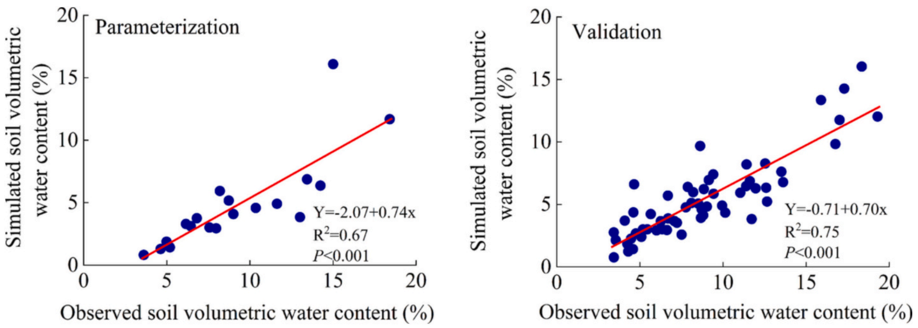

Fig. 2. Relationship between simulated and observed soil volumetric water content of the parameterization and validation.

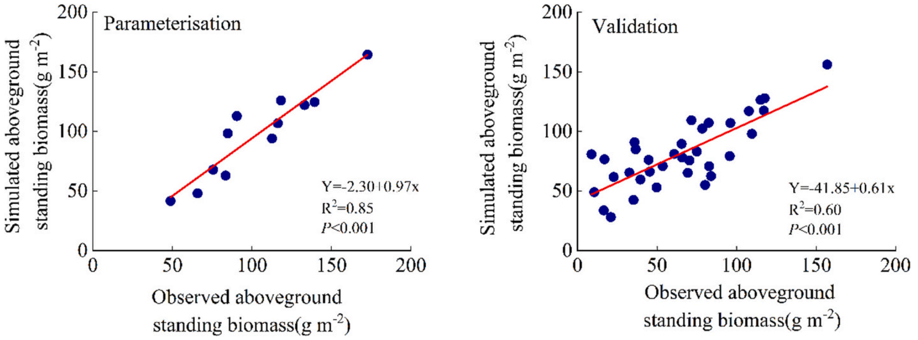

Fig. 3. Relationship between simulated and observed aboveground biomass of the parameterization and validation.

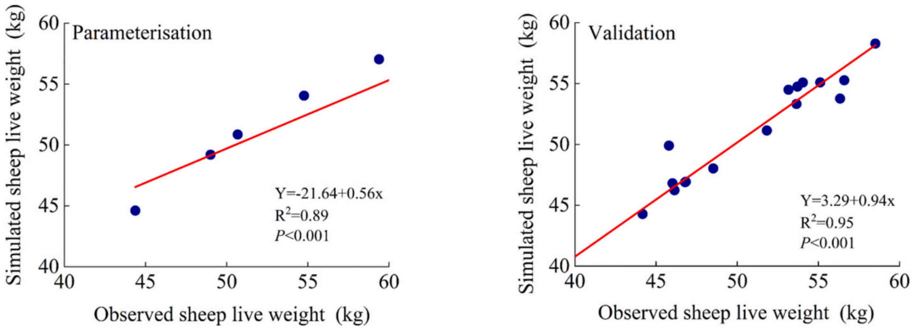

Fig. 4. Relationship between simulated and observed sheep live weight for the parameterization and validation.

4. Discussion

4.1. Model performance of aboveground standing biomass of the plant community

Previous studies showed that the SPACSYS model has performed well for simulating yields of wheat and maize (Liu et al., 2022; Liang et al., 2019). Wu et al. (2015) used the SPACSYS model to simulate grassland production for several countries including Germany, Italy, Switzerland, the Netherlands, Israel, and the United Kingdom, and these results showed that simulated values were consistent with observed values (Wu et al., 2015). Liu et al. (2022) used the SPACSYS model to simulate the yields of winter wheat and maize in northern China, finding that the simulated grain yield of wheat was 17.3% higher than the observed value, while the simulated grain yield of maize was 6.3% lower than the observed value (Liu et al., 2022). In this study, the aboveground standing biomass of the plant community were either overestimated or underestimated likely because of the following reasons: 1)Some unmeasured soil physical and chemical properties are estimated using the model, and they may be different from the true values, leading to inaccurate estimation of aboveground standing biomass; 2) SPACSYS performance is insufficient for the simulation of soil volumetric moisture content, and the soil volumetric water content were underestimated by 38–48% (Table 4); 3) The effects of extreme weather on plants were not considered (Quan et al., 2022); 4) The simulated values of aboveground standing biomass of the plant community represent the average value across the entire study area; however, the observed values were randomly sampled from this study area (Liang et al., 2019); and 5) The temperature at each stage of plant growth was sourced from literature and experimental observations, which affected the simulated accuracy of aboveground standing biomass. Similarly, the simulated soil temperature may be inaccurate, further affecting the estimate of aboveground standing biomass.

The aboveground standing biomass of the plant community is related to the soil nutrient pool; however, the parameter sensitivity analysis of the SPACSYS model found that variation of the soil nutrient pool depended on external nutrient input, denitrification, mineralization, and decomposition processes. Therefore, the variability, uncertainty, and quality of observed values for setting SPACSYS parameters should be taken into account as they may directly affect the accuracy of the

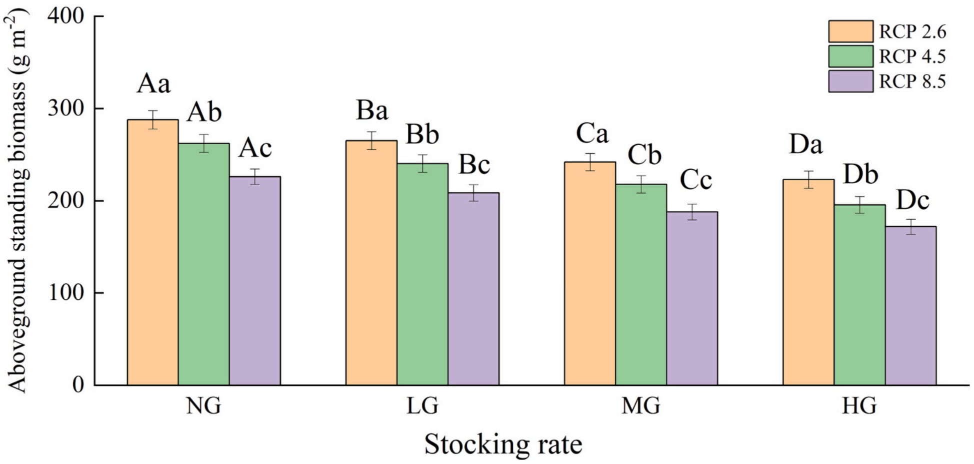

Fig. 5. Simulated aboveground standing biomass of the plant community under different stocking rates and climate scenarios from 2021 to 2100. Different capital letters indicate significant differences between stocking rate treatments under the same climate scenario ($P < 0.05$), while different lowercase letters indicate significant differences between different climate scenarios with the same stocking rate ($P < 0.05$). Same capital letters or lowercase letters means no significant difference ($P > 0.05$).

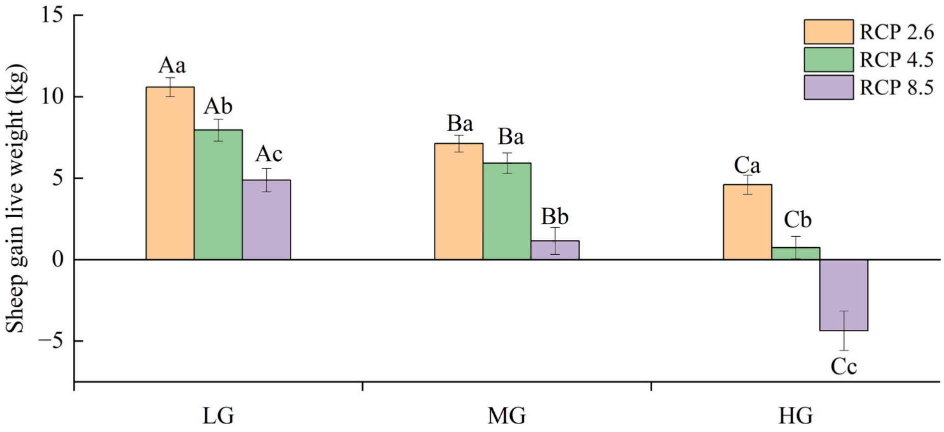

Fig. 6. Sheep weight change under different stocking rates and climate scenarios from 2021 to 2100.

model simulation (Shan et al., 2021).

4.2. Aboveground standing biomass changes at different stocking rates under climate change scenarios

The SPACSYS model predicted declines in aboveground standing biomass of the plant community under the same stocking rate treatment from 2021 to 2100 across the climate warming scenarios. Aboveground standing biomass decreased the most under the RCP 8.5 climate scenario. These results may be explained by several reasons: (1) Climate change, as modelled under the RCP 4.5 and RCP 8.5 climate scenarios, will increase temperature, CO_2 concentration, and change precipitation. Previous research has found that increasing temperature by 2 °C decreased aboveground biomass by 52% (Xu et al., 2016), and an increase in CO_2 concentration further decreased soil water content because of increased temperature (Dorji et al., 2018). The decrease in soil water with an increasing soil evaporation rate and temperature exacerbates drought in the desert steppe, thereby decreasing aboveground standing biomass (Xu et al., 2016). (2) Increasing temperature will shorten the phenological period of plants. Tian et al. (2022) found that increasing temperature shortened the flowering and reproductive growth time in the *Stipa breviflora* desert steppe and then decreased aboveground standing biomass (Tian et al., 2022; Wu, 2019). Moreover, extreme weather, such as warmer temperatures, can also greatly decrease plant productivity (Teixeira et al., 2013).(3) When the environment's CO_2 concentration increases, plant respiration declines, which eventually inhibits photosynthesis and limits soil nutrients (Shaw et al., 2002). Other studies have argued that an appropriate concentration of CO_2 can provide a carbon dioxide fertilizer for plants to improve photosynthetic efficiency, thereby increasing aboveground standing biomass (Picon-Cochard et al., 2004; Yang et al., 2019; Dijkstra et al., 2002). Additionally, increasing CO_2 concentration can also decrease leaf conductivity and transpiration and improve plant water status, thus increasing aboveground standing biomass (Morgan et al., 2004). However, Xiong et al. (2007) found that rain-fed maize yields decreased under CO_2 fertilization. Liang et al. (2019) also found that even with the effect of CO_2 fertilization, maize yield would decline because of increased precipitation and temperature in Northeast China, which may be due to a shorter growing season and lower solar radiation (Wang et al., 2014; Liu et al., 2022).

In this study, aboveground standing biomass did not increase with increasing CO_2 concentration, which may be because it also depends on plant community composition, nutrient status, and soil and plant water dynamics (Bloor et al., 2010). In general, although warming, increasing CO_2 concentration, and changes in precipitation may stimulate plant growth, grazing can directly decrease aboveground standing biomass, which will eliminate the growth effects of climate change on plants. Therefore, it is expected that the current aboveground standing biomass of the plant community will decrease under grazing and climate change (Shi et al., 2022).

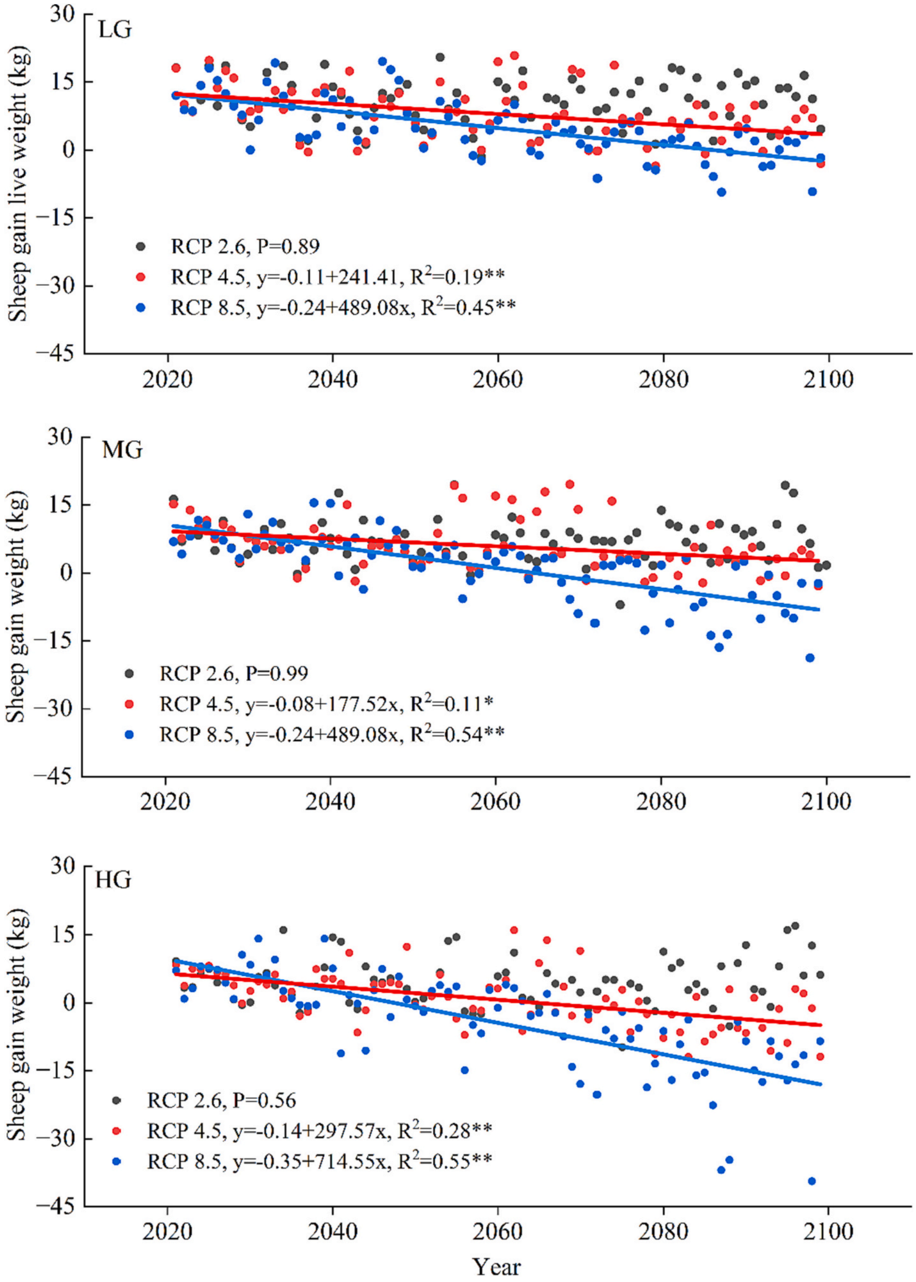

Fig. 7. Simulated annual sheep live weight change between 2021 and 2100 at the light (top panel), moderate (mid-panel) and high (bottom panel) stocking rate under climate scenarios. * $P < 0.05$; ** $P < 0.01$.

4.3. Sheep live weight changes at different stocking rates under different climate change scenarios

In this study, sheep live weight significantly decreased with the intensification of climate change from 2021 to 2100. This finding conflicts with some previous research. A study has shown that the sheep weight increased with rising temperatures in southern Norway, suggesting that different sites exhibit inconsistent responses to climate change (Johannesen et al., 2013). The desert steppe ecosystem of Inner Mongolia is relatively fragile. The climate is dry with little rainfall (230 mm average per year), and under the climate change scenarios of RCP 4.5 and RCP 8.5, the area shows an overall increase in temperature but no significant increase in precipitation (Table 3). Climate is key factor in the desert steppe, affecting both aboveground standing biomass and animal husbandry. Changes in precipitation and temperature lead to decreases in sheep live weight via changes in aboveground standing biomass of plant community. A high stocking rate leads to a greater reduction in aboveground standing biomass of plant community (Zhang et al., 2018), further exacerbating the decline in sheep live weight. As the results showed, under the same stocking rate, sheep live weight significantly decreased across the climate change scenarios.

Animal husbandry is the main production activity in the desert steppe, and long-term climate change has resulted in a decline in grassland production, water quality and quantity, and animal production and reproductive performance, and an increase in disease occurrence (Fiseha Lomiso, 2020). Additionally, both higher temperatures and precipitation decrease sheep resistance to diseases, which may result in declines in sheep live weight. In response, sheep may lower feeding intake and increase resting time, which may also lead to a decrease in livestock weight.

To support the adaptation of animal husbandry to climate change and grazing pressure in the desert steppe, we propose the following recommendations: (1) Protect and improve the ecological environment of pasture, increase biodiversity and improve soil quality, reduce the overuse of grassland and maintain the sustainability of the ecosystem. (2) adopt advanced livestock management techniques, using more environmentally friendly and low-carbon feeding and nutrition practices.(3) regularly monitor the health of animals and strengthen disease prevention and control to ensure the growth and production performance of animals. An integrated application of these measures can help animal husbandry achieve better adaptability and resilience to climate change, improve production efficiency and achieve sustainable development.

5. Conclusion

Our results show that the SPACSYS model performed well and can be used to simulate aboveground standing biomass of the plant community, soil temperature, volumetric water content, and sheep growth dynamics. The aboveground standing biomass of the plant community and sheep live weight in LG treatment are higher than under MG and HG under the three climate change scenarios. Additionally, we also found that aboveground standing biomass and sheep live weight under the grazing treatments decreased with the intensification of climate change; however, our results indicate that the LG rate is the optimal grazing strategy for maintaining aboveground standing biomass and sheep live weight in the desert steppe. In the future, optimizing grazing management could be an effective measure to adapt to climate change, benefiting the development of animal husbandry and addressing the dual challenges of climate change and overgrazing in the desert steppe.

CRediT authorship contribution statement

Yuehua Wang: Conceptualization, Software, Writing – original draft, Writing – review & editing. **Zhongwu Wang:** Investigation, Software, Writing – original draft. **Lianhai Wu:** Software, Writing – original draft, Writing – review & editing. **Haigang Li:** Software, Writing – original draft. **Jiangwen Li:** Investigation. **Aimin Zhu:** Investigation. **Yuxi Jin:** Investigation. **Guodong Han:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We would like to thank Dr. Daniel Petticord at the University of Cornell for his assistance with English language and grammatical editing of the manuscript. We thank the anonymous reviewers, as well as team members for collecting data in the field. This work was supported by the National Natural Science Foundation of China (32192463, 31760146), the innovative team on Grassland Resources in the Ministry of Education (IRT-17R59), and the Inner Mongolian Committee of Science and Technology Projects (zdzx2018020, 2019CG069). Yuehua Wang received funds from the China Scholarship Council (No. 202008150087).

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