

Spatial and temporal evolution of forage-livestock balance in the agro-pastoral transition zone of northern China postprint

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Abstract

Research on grassland carrying capacity (GCC) and forage-livestock balance is of great significance for promoting the harmonious development of human and grassland. However, the lack of understanding of GCC and forage-livestock balance in the agro-pastoral transition zone of northern China has limited the grassland sustainable development. Here, the spatial and temporal characteristics of GCC and forage-livestock balance in the grassland of agro-pastoral transition zone of northern China from 2000 to 2022 were analyzed using meteorological data and remote sensing data. Geographical detectors and geographically weighted regression were also used to identify the driving factors and their interactions with GCC changes. Moreover, future GCC trends were predicted using the Coupled Model Intercomparison Project Phase 6 dataset. Results revealed that: (1) GCC showed an overall upward trend from 2000 to 2022 but with significant inter-annual fluctuations. Its spatial distribution decreased gradually from north to south and from east to west. Precipitation, temperature, and cumulative solar radiation were the main drivers of the inter-annual variation of GCC, and the interaction between precipitation and temperature was the main influencing factor of the spatial distribution of GCC; (2) the forage-livestock balance was in an overloaded state in most years, but its index remained basically stable. Spatially, grazing overloading was mainly distributed in northeastern area and the severe overloading was mainly distributed in northwestern area; and (3) future projections indicated a downward trend in potential GCC. Under shared socioeconomic pathway (SSP)2-4.5 scenario, the potential GCC had a ranged of $1.38 \times 10^7 - 1.86 \times 10^7$ standard sheep unit (SHU) and a mean of 1.60×10^7 SHU. Meanwhile, the potential GCC under 8.5 scenario had a range of $1.18 \times 10^7 - 1.69 \times 10^7$ SHU and a mean of 1.49×10^7 SHU. These results indicated that although GCC of the agro-pastoral transition zone of northern China showed an overall increasing trend from 2000

to 2022, the forage-livestock balance index remained basically stable. The GCC was predicted to show a decreasing trend in the future. The findings provide a scientific basis for the sustainable development of grassland and the optimization of grazing management policies in this area.

Full Text

Preamble

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Spatial and temporal evolution of forage-livestock balance in the agro-pastoral transition zone of northern China

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Abstract: Research on grassland carrying capacity (GCC) and forage-livestock balance is of great significance for promoting harmonious development between human populations and grassland ecosystems. However, limited understanding of GCC and forage-livestock balance in the agro-pastoral transition zone of northern China has constrained sustainable grassland development. Here, we analyzed the spatial and temporal characteristics of GCC and forage-livestock balance in this zone from 2000 to 2022 using meteorological and remote sensing data. Geographical detectors and geographically weighted regression were employed to identify driving factors and their interactions with GCC changes. Moreover, future GCC trends were predicted using the Coupled Model Inter-comparison Project Phase 6 dataset. Results revealed that: (1) GCC showed an overall upward trend from 2000 to 2022 but with significant inter-annual fluctuations. Its spatial distribution decreased gradually from north to south and from east to west. Precipitation, temperature, and cumulative solar radiation were the main drivers of inter-annual GCC variation, while the interaction between precipitation and temperature was the primary influencing factor of GCC's spatial distribution; (2) The forage-livestock balance was in an overloaded state in most years, but its index remained basically stable. Spatially, grazing overloading was mainly distributed in the northeastern area, while severe overloading was concentrated in the northwestern area; and (3) Future projections indicated a downward trend in potential GCC. Under the shared socioeconomic pathway (SSP)2-4.5 scenario, potential GCC ranged from 1.38×10^7 to

1.86×10^7 standard sheep units (SHU) with a mean of 1.60×10^7 SHU. Meanwhile, potential GCC under the SSP5-8.5 scenario ranged from 1.18×10^7 to 1.69×10^7 SHU with a mean of 1.49×10^7 SHU. These results indicate that although GCC in the agro-pastoral transition zone of northern China showed an overall increasing trend from 2000 to 2022, the forage-livestock balance index remained basically stable. GCC is predicted to show a decreasing trend in the future. The findings provide a scientific basis for sustainable grassland development and optimization of grazing management policies in this area.

Keywords: grassland carrying capacity; climate change; forage-livestock balance; grassland ecosystem; grazing management

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1 Introduction

Grasslands are among the most important terrestrial ecosystems on Earth, regulating global climate change, preventing desertification advancement, maintaining biodiversity, and serving as the material basis for pastoralist survival (Petermann and Buzhdygan, 2021; He et al., 2023). Therefore, sustainable development of grassland ecosystems is crucial for ensuring global ecological balance and promoting sustainable livestock husbandry (Erb et al., 2018). However, the functional diversity and integrity of grassland ecosystems have been severely impacted by human activities (such as grazing, tillage, and mowing) and climate change (Zeng et al., 2014; Jordon et al., 2024), resulting in varying degrees of degradation. Among the factors contributing to grassland degradation, overgrazing is a critical driver of vegetation cover decline, topsoil structure destruction, and soil compaction (Romero-Ruiz et al., 2023; Guo and Chen, 2024). Overgrazing typically occurs when actual carrying capacity exceeds grassland carrying capacity (GCC) and seriously restricts sustainable utilization of grassland resources (Huang et al., 2021). Consequently, coordinated development of grassland ecosystems and livestock husbandry has become an important issue in grassland sustainable development research (Du et al., 2022; Li et al., 2022).

GCC refers to the ability of grassland resources in a given area to sustainably support the largest population, livestock numbers, and economic production (Guevara et al., 1997; Yan et al., 2023). As an indicator for quantifying grassland productivity, it is paramount in determining ecologically sustainable stocking rates that account for vegetation production, regional ecology, and livestock needs (Qian et al., 2012). Grassland degradation, land desertification, biodiversity loss, and other problems occur when actual carrying capacity exceeds GCC (Wei et al., 2022). Therefore, timely and accurate understanding of GCC is essential for formulating rational grassland grazing management policies. Net primary productivity (NPP) of vegetation, which accounts for plant growth, respiration, and nutrient utilization, is a direct factor of grassland productivity and can be used to assess potential food supply for livestock, thus helping determine GCC (De Leeuw et al., 2019; Yan et al., 2023). Researchers primarily estimate GCC at large regional scales based on remote sensing data (Ba et al., 2023; Wang et al., 2024b). For example, Du et al. (2024) used the Carnegie Ames Stanford Approach (CASA) model to estimate GCC and found that the theoretical carrying capacity of grasslands in the Qilian Mountains, China showed a significant increasing trend from 2000 to 2018. Another study evaluated GCC of Azerbaijani grasslands based on grass production and found that a reasonable GCC allowed only 65.00% of aboveground biomass to be consumed (De Leeuw et al., 2019). Li et al. (2024) examined GCC on the Eastern Mongolian Plateau based on remote sensing data and clarified influencing factors of GCC. The main factors driving GCC changes are receiving increasing attention from researchers. For instance, studies of GCC in Tajikistan and Kyrgyzstan have shown that human overgrazing and climate change are primary factors influencing GCC changes (Umuhoza et al., 2021). A study of the Xizang Plateau in China found synergistic effects of climate change and ecological conservation on GCC (Yan et al., 2024). These studies have confirmed the role of human activities and climate change in influencing GCC.

To quantitatively evaluate the balance between GCC and actual carrying capacity, scholars introduced the forage-livestock balance concept (Dong et al., 2002; Mai et al., 2013). The core of this concept is to evaluate the relationship between grass and livestock based on grass amount, GCC, and actual livestock load (Wang and Liu, 2017). Based on remote sensing data and ground surveys on forage-livestock balance, Xiong et al. (2025) found that Wensu County in northern China experienced serious overloading in the past 23 years, and Qu et al. (2021) found that the grassland area of Xilingol League in China was overloaded from 2000 to 2015, accounting for 50.00% of the study area. Clear equilibrium distribution and overloading patterns provide an important theoretical basis for sustainable development of regional animal husbandry. Researchers have also modeled and predicted future GCC trends (Zhang et al., 2023; Shi et al., 2024; Wang et al., 2024a), and simulation results can provide important theoretical support for optimization of regional grazing management policies.

As a typical ecologically fragile zone, the agro-pastoral transition zone of northern China is an important livestock production base and ecological barrier area

in the country (Yang et al., 2020; Guo et al., 2023; Dai et al., 2024; Yang et al., 2024). As a traditional and important economic activity, grazing exerts a determinant influence on regional ecosystem structure and function through its intensity and management practices. For the agro-pastoral transition zone of northern China, researchers have studied the effects of grazing on *Stipa baicalensis* Roshev. grasslands (Jin and Han, 2010), Hulunbuir grasslands (Zhu et al., 2022), and grasslands in Inner Mongolia (Su et al., 2017), finding that grazing overloads grasslands to varying degrees. However, most of these studies focused on grazing at small spatial scales and lacked comprehensive examination of the entire area. Furthermore, their results lacked predictive analysis of potential future GCC changes, which reduces their utility as references for prospective government decisions. Therefore, research on GCC, forage-livestock balance, and determinant factors in the agro-pastoral transition zone of northern China is essential to promote ecological protection and restoration of this area and its sustainable social and economic development. Studies on small areas showed that GCC increased (Song et al., 2018; Li et al., 2024) and most of these areas were overloaded (Su et al., 2017; Zhu et al., 2022). Hence, we hypothesized that GCC in the agro-pastoral transition zone of northern China followed a general upward trend from 2000 to 2022, and the forage-livestock balance was overloaded. Meanwhile, we explored the main factors influencing GCC and forecasted future GCC trends in the area.

2.1 Study Area

The study area is located between 35°30'–45°30' N and 105°55'–124°00' E, covering a total area of 813.4×10^3 km², which includes the Inner Mongolia Autonomous Region, Shaanxi Province, Liaoning Province, Shanxi Province, Gansu Province, Ningxia Hui Autonomous Region, and Hebei Province (Fenetahun et al., 2022). The agro-pastoral transition zone of northern China is situated in the temperate continental monsoon climate zone, characterized by high temperatures and rainfall in summer and cold, dry conditions in winter (Yang et al., 2024). Precipitation is concentrated in July and August, decreasing from southeast to northwest. Fluctuations between dry and wet conditions are evident, reflecting the unique characteristics of the East Asian monsoon climate (Bai et al., 2022). The annual average temperature ranges from 2°C to 8°C, and average annual precipitation ranges from 300 to 500 mm.

2.2.1 Remote Sensing Data

Surface solar radiation data were obtained from the National Tibetan Plateau Science Data Center (Table 1). Temperature data with a spatial resolution of 1 km were acquired from the China Regional Monthly Mean Temperature Dataset from 1901 to 2022. Precipitation data with a spatial resolution of 1 km were derived from the China Regional Monthly Precipitation Dataset from 1901 to 2022. Potential evapotranspiration (PET) data were sourced from the PET dataset for China from 1990 to 2022, which was calculated using the

Hargreaves formula based on monthly minimum, average, and maximum air temperature data. Normalized difference vegetation index (NDVI) data with a spatial resolution of 250 m were obtained from monthly NDVI products for China from 2000 to 2022. Land use data with a spatial resolution of 30 m were obtained from the annual China land cover dataset, which contains nine land cover classifications: cropland, woodland, shrubland, grassland, water body, permanent snow and glaciers, vacant land, impervious surface, and wetland. NPP data with a spatial resolution of 500 m were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra NPP gap-filled yearly L4 global 500 m Sinusoidal grid product, derived from the Terra sensor on the National Aeronautics and Space Administration (NASA) platform. Slope length data were derived from elevation data using the data analysis tool of ArcGIS v.10.4 software (Environmental Systems Research Institute Inc. (ESRI), Redlands, USA). Remote sensing data with various resolutions were resampled to a uniform resolution of 500 m for analysis using ArcGIS.

Annual livestock inventory data from cities and counties in the agro-pastoral transition zone of northern China from 2000 to 2022 were collected to quantitatively assess spatiotemporal characteristics of forage-livestock balance. In this study, livestock inventory was converted into standard sheep units (SHU) following the method outlined in the Agricultural Industry Standard of China, with conversion factors set at 4.0 for large livestock and 1.0 for sheep (Su et al., 2002).

2.2.2 Data for Future Scenario

The corrected NASA Earth Exchange Global Daily Scale Prediction dataset from the Coupled Model Intercomparison Project Phase 6 (CMIP6) was used for future scenario modeling. Future temperature and precipitation data from the shared socioeconomic pathway (SSP)2-4.5 and SSP5-8.5 scenarios were used to estimate NPP in the study area. Potential GCC was then predicted using the estimated NPP data (Table 2).

2.3.1 Grassland Yield

Grassland yield, defined as the total amount of dry matter produced in a given area over a specific period, is a key indicator for assessing grassland ecosystem production capacity (Jin et al., 2011). In this study, we extracted land use data for grasslands based on grassland land classes in the study area. NPP was then estimated using the Carnegie-Ames-Stanford Approach (CASA) model. The estimated NPP values were superimposed on grassland yield data to obtain actual NPP from 2000 to 2022. Actual NPP was further used to calculate grassland yield per unit area using the following formula (Zhu et al., 2022):

$$B_g = \frac{NPP \times S_{bn}}{S_{ug}}$$

where B_g is the total annual hay production per unit area ($\text{g}/(\text{m}^2 \cdot \text{a})$); NPP is the total annual net primary production of grasslands ($\text{g C}/(\text{m}^2 \cdot \text{a})$); S_{bn} is the conversion coefficient of grassland biomass converted into NPP (0.45 g/g C) (Zhu et al., 2022); and S_{ug} is the ratio coefficient of belowground to aboveground biomass for different grassland types (Chen et al., 2008; Zhang et al., 2016), shown in Table 3.

2.3.2 GCC

GCC was calculated by combining edible pasture yield with livestock daily consumption (Chen, 2005, 2008). The formula can be expressed as follows:

$$GCC = \frac{H_g \times K_1 \times K_2 \times K_3}{L_g \times d}$$

where GCC is the grassland carrying capacity (SHU); H_g is the annual grassland hay yield (g/m^2); K_1 is the utilization rate of different grassland types: 50.00% for grassland, 60.00% for meadow, 55.00% for irrigated grass bushes and swamps, and 40.00% for desert; K_2 is the utilization rate of grassland with a value of 85.00%; K_3 is the edible grass coefficient of grassland with a value of 80.00%; L_g is the daily feed intake of a sheep unit with a value of $2 \text{ kg}/(\text{SHU} \cdot \text{d})$; and d is the grazing period, calculated for 365 days of the year.

2.3.3 Forage-Livestock Balance Index

Grazing overload rate was used to measure forage-livestock balance in the study area and was calculated as follows (Xu and Yang, 2009; Xu et al., 2012):

$$C = \frac{C_s - C_h}{C_h} \times 100\%$$

where C is the grazing overload rate (%); C_s is the actual livestock load (SHU/hm^2); and C_h is the GCC per unit area (SHU/hm^2). The forage-livestock balance was categorized into five levels: insufficient GCC ($C \leq -10.00\%$), forage-livestock balance ($-10.00\% < C \leq 10.00\%$), critical overload ($10.00\% < C \leq 20.00\%$), overload ($20.00\% < C \leq 50.00\%$), and severe overload ($C > 50.00\%$) (Liu et al., 2018).

2.3.4 Supplementary Feeding

Supplementary feeding of agricultural by-products comprises two components: concentrate fodder and roughage. Concentrate fodder mainly includes bran and rapeseed oil cake, while roughage primarily includes straw. The daily feed intake for each standard sheep unit is 1.0 kg of concentrate fodder or 1.5 kg of roughage (Yang and Yang, 2000; Li et al., 2012). In this study, we calculated supplementary feeding amounts based on annual supplementation (365 days).

2.3.5 Simulation and Prediction of Grassland NPP

The model of Zhou et al. (1998) was adopted to estimate grassland NPP using vegetation CO₂ flux and water vapor flux equations. The model of Zhang et al. (2011) was used to calculate vegetation productivity and verify simulation results for Zalong Wetland, China (Yu et al., 2021). The calculation formulas are as follows:

$$NPP = RDI \times r$$

$$RDI = \frac{1 + a \times RDI + b \times RDI^2}{1 + c \times RDI + d \times RDI^2}$$

$$RDI = \frac{PER}{1 + 0.25 \times PER \times \left(1 - \frac{PET}{58.931 \times BT}\right)}$$

$$PER = \frac{PET}{r}$$

$$PET = \sum f \times BT$$

$$BT = \sum t$$

where *RDI* is the radiation dryness index; *r* is annual precipitation (mm); *a*, *b*, *c*, *d*, *e*, and *f* are constants with values of 9.87, 6.25, 0.629, 0.237, 0.00313, and 58.931, respectively; *PER* is the possible evaporation rate; *PET* is potential evapotranspiration (mm); *BT* is average annual biological temperature (°C); *t* is average daily temperature below 30°C and above 0°C; and *T* is average monthly temperature below 30°C and above 0°C.

2.3.6 Statistical Analysis

Pearson correlation analysis was used to quantify effects of precipitation and temperature on vegetation NPP. The correlation coefficient *R*² ranges from -1 to 1, where a larger absolute value indicates stronger correlation between vegetation NPP and influencing factors of precipitation or temperature (Sedgwick, 2012; Ma et al., 2023).

Geographical detector is a statistical tool proposed by Wang and Xu (2017) to explore spatial stratified heterogeneity of geographical elements and identify influencing factors. It quantifies effects of multiple independent variables on a dependent variable using significance testing. The *q*-value, representing the influence of independent variables on dependent variables, can be calculated as follows (Dai and Wang, 2020):

$$q = 1 - \frac{\sum_{k=1}^L N_k \sigma_k^2}{N \sigma^2}$$

where L is the classification or stratification of the independent variable; k is the stratification of livestock load or different driving factors; N_k is the number of hierarchical image elements of each data stratum; σ_k^2 is the variance of each level of image element of each data stratum; N is the number of all image elements; and σ^2 is the variance of all image metadata in the study area.

The q -value ranges from 0 to 1, indicating the degree of spatial stratified heterogeneity and contribution of driving factors to livestock load. A large q -value suggests substantial contribution of the driving factor to livestock load and significant spatial differences, while a small q -value indicates weak contribution.

Geographically weighted regression (GWR) models relationships between dependent and independent variables within localized areas. GWR provides insights into spatial heterogeneity, characterizing how variables such as GCC are influenced by explanatory variables including cumulative solar radiation, precipitation, and relative humidity. The model can be expressed as follows (Brunsdon et al., 1996):

$$Y_i = \beta_0(u_i, v_i) + \sum_{k=1}^K \beta_k(u_i, v_i) x_{ik} + \varepsilon_i$$

where Y_i is the satellite precipitation at position i ; u_i and v_i are horizontal and vertical coordinates of position i , respectively; $\beta_0(u_i, v_i)$ is the constant term of the model at the i th sample point; K is the number of independent variables; i is the number of samples; $\beta_k(u_i, v_i)$ is the regression coefficient for the k th independent variable at point i ; x_{ik} is the k th independent variable at the i th sample point; and ε_i is the random error term for sample point i . Given that GCC is characterized by spatial autocorrelation and spatial non-stationarity, we utilized a GWR model to explain the geospatial relationship between GCC and natural factors (cumulative solar radiation, precipitation, and relative humidity).

First, the ordinary least squares (OLS) method was used to conduct significance testing and linearity checks among these variables. The mean values of GCC, cumulative solar radiation, precipitation, and relative humidity from 2000 to 2022 in the agro-pastoral transition zone of northern China were used as gridded data to generate 11,140 grid points. At each grid point, corresponding values of GCC, cumulative solar radiation, precipitation, and relative humidity were available. GWR models were then employed to investigate local spatial correlations between GCC changes and each meteorological factor (cumulative solar radiation, precipitation, and relative humidity) to reveal spatial heterogeneity of interactions among these variables.

3.1 Spatiotemporal Variation of GCC

GCC in the agro-pastoral transition zone of northern China exhibited an overall upward trend (Fig. 1 [Figure 1: see original paper]). It reached its maximum in 2022, increasing by 66.31% compared with 2000. GCC also showed a fluctuating growth pattern over the past 23 years, with marked declines in 2007, 2009, 2015, 2017, and 2020, and notable increases in 2004, 2008, 2013, 2017, 2019, and 2022.

Spatial distribution of average GCC in the agro-pastoral transition zone of northern China varied greatly from 2000 to 2020, showing a “northeast-southwest” axis pattern. GCC values were higher in the south and east, and lower in the west and north (Fig. 2 [Figure 2: see original paper]). High GCC areas were found in Shaanxi and Hebei provinces. Medium GCC areas were located in southern Ningxia Hui Autonomous Region, Gansu Province, central Shaanxi Province, Shanxi Province, Hebei Province, Liaoning Province, and most parts of the Inner Mongolia Autonomous Region. Low GCC areas were distributed in northern Ningxia Hui Autonomous Region, northwestern Shanxi Province, and northwestern Inner Mongolia Autonomous Region.

3.2 Driving Factors of GCC

The selected natural and socio-economic factors, except for nighttime light, passed the significance test ($P < 0.05$), indicating their effects on GCC changes. The q -value of each factor for GCC spatial distribution from 2000 to 2022 was ranked as: accumulated solar radiation > relative humidity > precipitation > slope > population distribution > PET > terrain undulation > digital elevation model (DEM) > gross domestic product (GDP) > temperature > nighttime light (Fig. 3 [Figure 3: see original paper]). Among these, accumulated solar radiation and precipitation had strong interactions with other factors. In particular, the interactive driving interpretation of cumulative solar radiation relative humidity ($q = 0.62$) and accumulated solar radiation precipitation ($q = 0.56$) was strongest.

From 2000 to 2022, accumulated solar radiation and precipitation had the greatest effects on GCC in the agro-pastoral transition zone of northern China (Fig. 4 [Figure 4: see original paper]). Accumulated solar radiation mainly had a positive effect on GCC, with regression coefficients ranging from -0.19 to 0.17. Precipitation was strongly positively correlated with GCC, with regression coefficients ranging from -0.03 to 0.02. Positive effects were observed in areas with abundant precipitation and relatively high altitude, while negative effects were limited to a small area in Shaanxi Province. In contrast, relative humidity's impact on GCC was weaker than those of accumulated solar radiation and precipitation. Its effects were both positive and negative, with regression coefficients ranging from -0.03 to 0.28, though negative effects were slightly more pronounced and exhibited significant spatial variability. For most factor interactions, q -values of multi-factor combinations were higher than those of single factors, indicating stronger correlation with GCC.

3.3 Spatial and Temporal Distribution of Forage-Livestock Balance

The forage-livestock balance index in the agro-pastoral transition zone of northern China exhibited a fluctuating upward trend from 2000 to 2022, with grazing status predominantly characterized by overloaded and severely overloaded conditions (Fig. 5 [Figure 5: see original paper]). The years 2000, 2001, 2006, 2009, and 2015 were classified as severely overloaded, with the highest overload rate reaching 64.43% in 2009. In 2019, the value reached a critical overload level of 18.47%, while all other years experienced varying degrees of overload.

Spatially, insufficient GCC displayed a stepwise distribution pattern from southwest to northeast, primarily concentrated in Gansu Province, Shaanxi Province, and other areas (Fig. 6 [Figure 6: see original paper]). Severely overloaded areas were mainly distributed in the northwest, encompassing Ningxia Hui Autonomous Region, Gansu Province, northern Shaanxi Province, parts of Shanxi Province, and the Inner Mongolia Autonomous Region. Overloaded areas were scattered across the study area, extending from southwest to northeast. Critical overload areas were relatively limited and primarily located in Hebei Province, central Shaanxi Province, Inner Mongolia Autonomous Region, Liaoning Province, and parts of Gansu Province. Only a few areas, mainly in Shanxi Province, maintained forage-livestock balance.

3.4 Future Forecast of Potential GCC

Potential GCC in the agro-pastoral transition zone of northern China ($R^2 = 0.72$, $P < 0.05$) was calculated using CMIP6 future scenario data and a natural vegetation primary productivity model (Fig. 7a [Figure 7: see original paper]). The annual average value of historical potential GCC under the CMIP6 climate scenario was 1.46×10^7 SHU, showing no significant difference from existing GCC (1.37×10^7 SHU). This finding indicated that the CMIP6 model had high applicability for predicting potential GCC in the agro-pastoral transition zone of northern China under future climate scenarios. Under the SSP2-4.5 scenario, potential GCC ranged from 1.38×10^7 to 1.86×10^7 SHU with an annual average of 1.60×10^7 SHU. Under the SSP5-8.5 scenario, potential GCC ranged from 1.18×10^7 to 1.69×10^7 SHU with an average of 1.49×10^7 SHU. Potential GCC under both scenarios was expected to exhibit a fluctuating downward trend in the future, though potential GCC under the SSP2-4.5 scenario would be higher than that under the SSP5-8.5 scenario in 2028 (Fig. 7b).

Areas with high potential GCC were expected to be concentrated in Liaoning Province, eastern Hebei Province, and Shaanxi Province in the agro-pastoral transition zone of northern China, while areas with low potential GCC were located primarily in the north (Fig. 8 [Figure 8: see original paper]). Under the SSP2-4.5 scenario, a remarkable change in the spatial distribution of potential GCC would occur in 2028. In this year, areas with high potential GCC

would be mainly distributed in Shanxi Province, Hebei Province, and the Inner Mongolia Autonomous Region, exhibiting a northward movement trend. However, this trend might gradually revert to the previous pattern in 2029 (Fig. 8a-g). Under the SSP5-8.5 scenario, spatial distribution of potential GCC in the agro-pastoral transition zone of northern China was projected to follow a “northeast-southwest” axis, with high potential GCC in the east and south and low potential GCC in the west and north (Fig. 8h-n).

4.1 Spatiotemporal Variation of GCC

GCC in the agro-pastoral transition zone of northern China generally showed an upward trend over the study period, consistent with our hypothesis. In arid and semi-arid areas, precipitation is the main limiting factor for grassland vegetation growth (Zhang et al., 2022), and precipitation effects on vegetation are ultimately reflected in GCC (Chen et al., 2018; Huang et al., 2019; Wen et al., 2019; Chen et al., 2020). Our study also confirmed that increased precipitation led to increased GCC ($r = 0.641$, $P < 0.001$). However, uneven inter-annual precipitation distribution resulted in GCC decreases in some years. Researchers have found a strong lag effect of drought on grasslands, where drought-induced lag effects in the previous year reduce grass productivity and lead to GCC decreases in the following year (Fuchslueger et al., 2016; Hahn et al., 2021; Li et al., 2023). Thus, droughts in 2006, 2008, and 2019 resulted in low GCC in 2007, 2009, and 2020, respectively. However, the lag effects of drought in 2012 and 2016 did not cause GCC declines in 2013 and 2017. The main reason may be that grassland ecological subsidy and incentive policies, such as forage-livestock balance and audit approval for grassland requisition and occupation, introduced and implemented by the Chinese government in 2011 and 2015, contributed to grassland ecosystem restoration (Liu et al., 2021). Hence, GCC improved to a certain extent.

High GCC areas in the agro-pastoral transition zone of northern China were mainly distributed in eastern and southern areas, such as central Shaanxi Province and eastern and northern Hebei Province. Conversely, low GCC areas were primarily located in western and northern areas, including northern Ningxia Hui Autonomous Region, northwestern Shanxi Province, and northwestern Inner Mongolia Autonomous Region. Altitude in eastern and southern areas is low, and high temperatures in these areas can promote grassland vegetation regeneration by reducing cold stress and extending the growing season (Xu et al., 2020; Qi et al., 2024). High temperatures also increase photosynthetic efficiency, which favors grassland vegetation growth and consequently increases GCC (Dusenge et al., 2019). However, GCC is relatively small in low-altitude areas of northeastern Inner Mongolia, located in the northern agro-pastoral transition zone. This result can be attributed to low precipitation in the area, while higher temperatures lead to strong surface evaporation, which further reduces soil water content and is not conducive to vegetation growth, resulting in lower GCC (Erb et al., 2018; Jiang et al.,

2020). In the high altitude of northern Hebei Province, intense solar radiation promotes higher grass productivity, contributing to increased GCC in the area (Wen et al., 2019). However, this positive correlation is not absolute and is significantly regulated by precipitation (Umuhoza et al., 2021). Although solar radiation in northern and western areas of the agro-pastoral transition zone was relatively high, GCC in these areas did not increase with radiation due to low annual precipitation and intensified vegetation water stress. This finding further confirms the important role of precipitation and temperature on arid and semi-arid grasslands.

4.2 Temporal and Spatial Distribution of Forage-Livestock Balance

The agro-pastoral transition zone of northern China has been overloaded in most areas from 2000 to 2022, supporting our hypothesis. Although GCC showed an overall increasing trend, economic development has prompted herders to increase livestock numbers. As a result, the forage-livestock balance index remained in a relatively stable state. A small improvement in forage-livestock balance was observed after 2016. This phenomenon may be attributed to ecological conservation measures adopted by the government in 2015 (Liu et al., 2021). Achieving regional forage-livestock balance means maintaining a moderate number of livestock rather than simply reducing livestock numbers. Reasonable grazing is related to regional economic development and stability, requiring comprehensive consideration from multiple perspectives including society, economy, and technology (Chen et al., 2024; Guo and Chen, 2024). Therefore, reasonable grassland management policies (e.g., rotational grazing, grazing rest, and control of grazing intensity) should be formulated.

Spatially, overloaded and severely overloaded areas were mainly distributed in northern areas of the agro-pastoral transition zone, consistent with findings of Guo et al. (2021). These areas are characterized by typical arid and semi-arid climates with low and highly variable precipitation. Limited by scarce water resources and low above-ground biomass, these areas are highly vulnerable to overgrazing (Zhang et al., 2022). With global climate change, frequent extreme weather events further accelerate grassland degradation rates, increase pressure on grassland ecosystems, and ultimately exacerbate livestock overload in these areas (Cheng et al., 2014; Zhu et al., 2023; Xu, 2024). As population continues to grow and urbanization accelerates, human demand for livestock products continues to increase (Liu et al., 2006; Erdaw, 2023). This phenomenon prompts herders to further expand farming scale, rendering the regional forage-livestock balance overloaded.

4.3 Prediction of Potential GCC

Potential GCC would show a downward trend from 2024 to 2030, but would increase in 2028 under the SSP5-8.5 scenario. The main reason may be that el-

evated CO₂ concentration in this scenario promotes grass photosynthesis (Chai and Hu, 2024), which increases NPP and consequently potential GCC. In high latitudes of the agricultural and pastoral zones in northern China, warm temperatures lengthen the growing season (Zhang et al., 2022), which also indirectly increases potential GCC under this scenario. However, under the SSP2-4.5 scenario, potential GCC would decrease in 2028. The main reason may be that moderate warming under this scenario leads to increased evapotranspiration, and the increase in precipitation is insufficient to compensate for water loss (Xiang et al., 2021; Guo et al., 2023), resulting in water stress. Hence, potential GCC decreases under this scenario. In addition, increased frequency of drought events under this scenario (Li et al., 2020) is not conducive to high NPP, leading to decreased potential GCC in this area. Given that potential GCC in the future mainly shows a downward trend, reasonable livestock numbers should be controlled and effective management policies implemented to avoid further damage and degradation of grassland ecosystems caused by overgrazing. Prediction results indicated that future high-value areas of potential GCC are mainly distributed in southern areas of the agricultural and pastoral transition zone in northern China. Adequate precipitation and favorable temperatures in this area help increase potential GCC. Under the principle of coordinating economic development and environmental protection, grassland management policies should be optimized through spatial configuration of GCC, which is necessary for harmonizing economic and ecological development.

4.4 Limitations and Future Prospects

Analysis of spatiotemporal GCC variation in the agro-pastoral transition zone of northern China and its influencing factors provides a macro perspective on long-term GCC dynamics. However, the use of various data sources, such as meteorological and economic data, and the lack of field measurements for verification may lead to certain deviations in results. Strengthening verification tests in subsequent studies is necessary. In addition, this study utilized the CMIP6 dataset to predict potential GCC, considering effects of precipitation and temperature on GCC. However, in some areas, time series of temperature and precipitation distribution (whether rain and heat coincide), wind speed, and solar radiation are becoming increasingly significant factors affecting GCC. Owing to current difficulties in obtaining these data, improvements in collection and expansion of data sources are urgently needed to provide a solid foundation for in-depth and comprehensive research.

5 Conclusions

Multi-source remote sensing data were used to analyze GCC and forage-livestock balance in the agro-pastoral transition zone of northern China. Results showed an overall upward trend in GCC from 2000 to 2022, with high-value areas predominantly located in eastern and southern regions. These trends were primarily influenced by precipitation and temperature, supporting the conclusion that

precipitation is the most important factor affecting GCC in arid and semi-arid grasslands. High GCC areas in southern parts of the agro-pastoral transition zone might be related to high annual cumulative temperatures in these areas, further emphasizing temperature effects on GCC. The forage-livestock balance was overloaded in most parts of the study area. Future GCC estimation calculated by the selected model generally showed a downward trend, and areas with high GCC were mainly distributed in the south. These prediction results provide a theoretical basis for future optimization of grassland management policy.

Conflict of 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.

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