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Effects of climate change and grazing intensity on grassland productivity—A case study of Inner Mongolia, China

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ABSTRACT

In the last 30 years, grassland productivity has declined seriously due to climate variations and unreasonable human activities. Therefore, to analyze the impact of different factors on grassland productivity, we selected three grassland stations of the Typical Steppe from west to east and collected 38 years of data. The Pearson Correlation and Fixed Effect Model were used to analyze the impact of precipitation, temperature, and grazing intensity on grassland productivity. The empirical results show that precipitation positively and significantly affected grassland productivity. The effects of climate change are more significant than human activities, but the impact of temperature is greater than precipitation. The synergy between precipitation and temperature was greater than between precipitation and temperature separately. In addition, the effects of climate change and human activities on grassland productivity have evident regional heterogeneity. The variation trend gradually increases from west to east in factors that affect grassland productivity. Therefore, we suggest some implications for grassland risk management, such as utilizing some financial products for climate risk and focusing on the synergy index to design financial products, such as design weather derivatives. Lastly, we should strengthen the research on the relationship between climate change and grassland productivity to provide a scientific basis for revealing the intrinsic relationship between climate, human activities, and grassland productivity.

1. Introduction

Grassland is an important national ecological security barrier with a strong capacity to sequester carbon and cope with climate change. At the same time, grassland is also an important resource for grassland animal husbandry, which is crucial to social and economic development [1]. In China, the grassland area covers approximately 400 million hectares, and Inner Mongolian grassland

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1 Grassland productivity refers to the capacity of grassland to generate various products, encompassing both plant-based products (such as forage) and animal-based products.

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ranks 2nd [2]. Grassland productivity is the primary indicator reflecting complete ecological services [3]. In the last 30 years, grassland productivity[1] has been declining; however, the trend is changing in recent years, and there has been a partial recovery [4]. The vast expanse of grassland and its unique geographical distribution highlights the crucial strategic significance of national ecological security. Moreover, they underscore the importance and irreplaceability of grasslands in addressing climate change. Therefore, it holds immense value for grassland management to clarify the laws governing the impact of climate change and other factors on grassland productivity.

A decrease in grassland productivity indicates a decline in grassland vegetation coverage and an increase in soil exposure, aggravating grassland degradation. On the other hand, the reduction of grassland productivity affects livestock supply, directly affecting livestock quantity and quality and indirectly affecting herders' income levels. Consequently, affecting the stability and sustainability of the entire livestock production. Changes in grassland productivity are because of natural conditions and socioeconomic environment. Studies have shown that direct factors such as climate variations, landforms, soil type, and human activities cause a decrease in grassland productivity [5–9].

Previously published research revealed that precipitation positively correlates with grassland productivity [10–14], and in different seasons precipitation's impact varies on grassland productivity for different grassland types [15,16]. Second, there is controversy in the research on the effects of temperature on grassland productivity. Some scholars think temperature and grassland productivity have a positive relationship [13,17] , but some believe there is a negative relationship [18,19]. Therefore, the relationship between temperature and productivity is uncertain, and the temperature affects differently on grassland in different seasons [20,21]. Thirdly, among human activities, grazing intensity is the main factor affecting grassland productivity [22–29], which has a negative relationship with grassland productivity, but recently gradually turned to a positive relationship [30,31].

Previous research is extensive and fruitful, but still, there are gaps. First, few scholars have studied the impact of climate change and grazing intensity on grassland productivity; identifying the importance between climate change and grazing intensity for grassland would help us adopt a more reasonable way to protect the grassland. Second, previous studies focused on the different grassland types in the same region, but there is a lack of reflection on the same grassland in different areas under different conditions; studying the same type of grassland in various areas is conducive to grassland management. Thirdly, the previous studies focused on the effects of temperature and precipitation on grassland productivity but rarely discussed the synergistic effect of both factors. Finally, statistical analysis methods such as comparative analysis, mathematical statistics, model simulation, etc., only consider the correlation relationship between climate change and grassland productivity in previous studies. However, these studies ignore that there is a complex many-to-one relationship but not a simple correlation relationship, so building a causal relationship model can help further identify the relationship between grassland productivity and its influencing factors.

The Typical Steppe is the main body of the Chinese grassland, which plays a vital role in ecological protection and climate regulation. It is also the base for the survival of herders in Inner Mongolia, China [25]. Therefore, the Typical Steppe is taken as an example to identify the influence of climate change and grazing intensity on grassland productivity. Three typical steppe sites have been selected to collect data on grassland productivity, corresponding meteorological observation, and socioeconomic statistics. Based on the research gaps, we have three research objectives: firstly, to identify which factor is more critical to grassland productivity, natural factors or human activity factors [32,33]; secondly, to identify the synergistic effect of temperature and precipitation on grassland productivity. Thirdly, under the same grassland type, whether there is regional heterogeneity in the impact of climate change

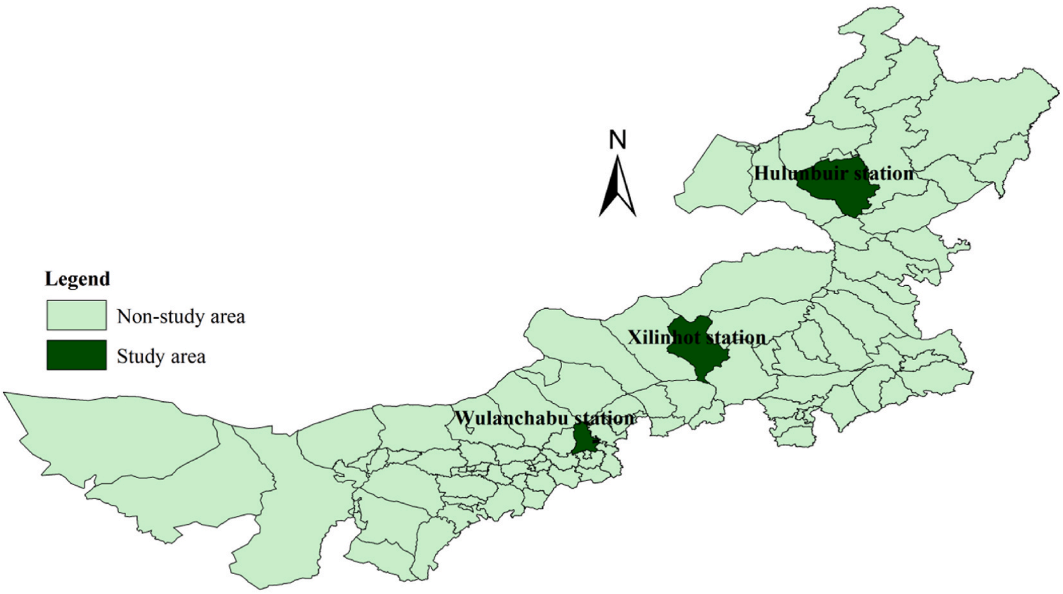

Fig. 1. Distribution of sample in the study area of Typical Steppe in Inner Mongolia.

and grazing intensity on grassland productivity. This research can provide a scientific reference to formulate management strategies for grassland ecosystems. It would play an essential, instructive role for animal husbandry producers to cope with extreme climate changes and unreasonable human activities.

2. Method and material

2.1. Study area

Inner Mongolia is located in the north of China (see Fig. 1), at 97°10′∼126°02′ east longitude and 37°30′∼53°20′ north latitude, and mainly has a temperate continental climate. The annual average temperature of the whole region is −5∼10 °C, increasing from northeast to southwest. The yearly precipitation rate is 35∼530 mm, decreasing from southeast to northwest. This paper selects the Typical Steppes of Inner Mongolia as the research area. Three representative national grassland monitoring stations were chosen from east to west; namely, Menggen Chulu Monitoring Station (48°48′N, 119°49′E) in Hulunbuir City (named Hulunbuir station), located in No. 2 Caokulun, Bayantuohai Town, Ewenki Banner West, at an altitude of 653.5 m. The soil is mainly composed of dark chestnut calcium. The plants mainly include *Leymus Chinensis*, *Eriophorum*, *Stipa capillata Linn*, *Poa annua Linn*, etc. the Maodeng Monitoring Station (named Xilinhot station) in Xilinhot City (43°57′N, 116°07′E) is located 12 km east of the Maodeng Ranch, at an altitude of 1003 m. The soil is 0–30 cm light loam. The 30∼100 cm medium loam soil is dominant. The plants are mainly *Stipa krylovii Roshev.*, *Leymus Chinensis,* and *Artemisia frigida Willd.*; Wulanchabu city, Chahaer monitoring station (41°27′N, 113°11′E) is in the Baiyinchagan Commune (named Wulanchabu station), with an altitude of 1423.5 m. The soil is mainly dark chestnut calcium, and the plants are mainly *Leymus Chinensis Artemisia argyi Levl. Et Vant.* and *Stipa krylovii Roshev* [34].

2.2. Data

(1) The grassland productivity data is taken from the national grassland fixed monitoring sites in the grassland areas. Hulunbuir station, Xilinhot station, and Wulanchabu station were selected in the eastern, central, and western parts of Inner Mongolia. From 1983 to 2020, the monthly grassland productivity data of three stations from April to September is taken as the overall grassland productivity of the whole of the banner county (Fig. 2).

(2) The meteorological data is obtained from the China Meteorological Science Data Sharing Service Network (http://data.cma.cn). From 1983 to 2020, the daily data sets of China's surface climate are selected. There is a national meteorological station distributed across the sample points. Due to outliers and missing values, this data is processed through time outlier inspection, spatial outlier inspection, high and low outlier inspection, missing value replacement, etc., and through essential data quality control such as data homogeneity inspection. Monthly average precipitation and monthly average temperature data were obtained statistically.

(3) The data on grazing intensity is taken from the "Inner Mongolia Statistical Yearbook." from 1989 to 2020, comprsing three banners, due to the limited available data. The data included information on the number of livestock and the area of regional grassland. We used these data to calculate the grazing intensity, which is determined by the ratio of the number of livestock to the grassland area.

2.3. Method

2.3.1. Pearson correlation analysis

Pearson correlation analysis method is one of the most common methods to analyze the correlation between two variables. This method investigated the relationship between grassland productivity, precipitation, and temperature. According to previous research, there is a lag in the impact of precipitation on grassland productivity. Therefore, this study conducts a correlation analysis between grassland productivity and temperature from January to December and its lag.

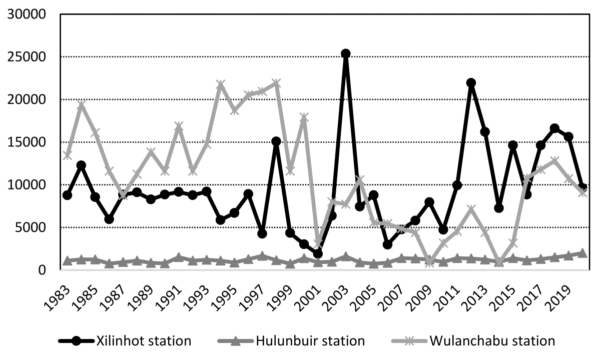

Fig. 2. Changes of grassland productivity in three study areas of Typical Steppe in Inner Mongolia from 1983 to 2020.

2.3.2. Fixed effects model

Adopting the fixed-effect model in this study offers several benefits. It controls for individual-specific characteristics, mitigates omitted variable bias, addresses endogeneity concerns, improves efficiency, and contributes to a more accurate analysis of the panel data [35]. The fixed-effect model addresses heteroskedasticity that cannot be captured directly through the model [36]. Since this study utilizes panel data, which contains more and larger amounts of information, it is necessary to identify the potential variability among individuals in the data and consequently select the fixed-effect model.

(1) Pearson correlation analysis results showed a correlation between grassland productivity and climate change. This paper defines growing and non-growing seasons based on existing empirical research. April to September is the growing season, and the rest are the non-growing seasons (Wang 2019). According to the growing season, the non-growing season is divided into the early non-growing season (January to March) and the late non-growing season (October to December). Accordingly, explained variable is the monthly average grassland productivity. The explanatory variables include monthly average precipitation (April to September), previous monthly average precipitation, the average monthly temperature in the early non-growing season (average temperature from January to March), and the average monthly temperature in the last non-growing season (average temperature from October to December), grazing intensity is calculated based on the number of livestock and the area of the regional grassland [37]. Based on the above variables, the following panel data model is constructed to analyze the impact of climate change and human activities on grassland productivity [38–41], and the functional relationship is shown in Equation (1):

$$Yield_{it} = \beta_0 + \beta_1 p_{it} + \beta_2 p_{it-1} + \beta_3 pt_{it} + \beta_4 lt_{it} + \beta_5 hu_{it} + \beta_{6-8}\, pr_i + \beta_9 T_t + \mu_{it} \tag{1}$$

Among them, Yield_it is the monthly average grassland productivity of the i-th region and the t-th year; p_it is the monthly average precipitation of the i-th region and the t-th year; p_{it-1} is the i-th region and the t-1th year, which is the precipitation in the previous period; pt_{it} is the average temperature from January to May in the i-th region and the t-th year, that is, the temperature in the early non-growing season; lt_{it} is the i-th region and the t-th year. The average temperature from September to December is the temperature of the last non-growing season, hu_{it} is the grazing intensity in the i-th region and the t-th year; pr_i is the regional dummy variable; T is the time variable; μ_{it} is the random term; $\beta_0, \beta_1 \ldots \beta_9$ are the parameters.

(2) Temperature and precipitation's synergy is introduced in the model further to study the synergy effect of precipitation and temperature. So, the form of Equation (2) is set as follows:

$$Yield_{it} = \beta_0 + \beta_1 p_{it} + \beta_2 p_{it-1} + \beta_3 pt_{it} + \beta_4 lt_{it} + \beta_5 hu_{it} + \beta_6 jh1 + \beta_7 jh2 + \beta_{8-10}\, pr_i + \beta_{11} T_t + \mu_{it} \tag{2}$$

Among them, $jh1$ is the intersection of precipitation and temperature of the early non-growing season, $jh2$ is the intersection of precipitation and temperature of the last non-growing season, and $\beta_0, \beta_1, \cdots \beta_{11}$ are parameters.

(3) To further observe the regional heterogeneity of the three stations in the east, middle, and west of Inner Mongolia, the following Equation (3) was constructed:

$$Yield_t(pr_i) = \beta_0 + \beta_1 p_t + \beta_2 p_{t-1} + \beta_3 pt_t + \beta_4 lt_t + \beta_5 hu_{it} + \beta_6 jh1 + \beta_7 jh2 + \beta_8 T_t + \mu_t \tag{3}$$

Among them, $\mathrm{Yield_t(i)}$ is the monthly average grassland productivity, where $\mathrm{pr_i} = 1$, is the monthly average grassland productivity of Wulanchabu station, and $\mathrm{pr_i} = 2$, is the monthly average grassland productivity of t Hulunbuir station, $\mathrm{pr_i} = 3$ is the monthly average grassland productivity of Xilinhot station, and $\beta_0, \beta_1, \cdots \beta_8$ are parameters.

3. Results

3.1. The results of the correlation analysis

The results of the Pearson correlation analysis show that there is a correlation between precipitation and grassland productivity. In May and July, the precipitation significantly correlated with grassland productivity. While the correlation between the precipitation in June and the grassland productivity in July was positively significant, and the correlation between precipitation in July and the

Table 1
Correlation analysis between precipitation and grassland productivity in the Typical Steppe region.

Grassland Productivity	Precipitation					
	Apr.	May	Jun.	Jul.	Aug.	Sep.
May	0.103	0.338**				
Jun.	0.059	0.203	0.105			
Jul.	−0.01	0.153	0.242*	0.314**		
Aug.	0.094	0.189	0.127	0.313**	0.008	
Average	0.053	.207*	0.164	0.330**	−0.079	−0.009

Note: ** was significant at 0.01 and * was significant at 0.05.

grassland productivity in August was positively significant (Table 1). Overall, in the current period, the correlation coefficient between precipitation and grassland productivity is greater than in the previous period.

The temperature from April to September negatively correlates with grassland productivity. The temperature in the non-growing season (from January to March and October to December) positively and significantly correlates with grassland productivity (Table 2). And January and December have higher correlation coefficients (0.54 and 0.58, respectively) than May and September, which is only 0.3.

3.2. The results of fixed effects estimation for long panel data models

Based on the data type: n = 3, t = 38, t > n, First, the LSDV method determines whether the data have an individual fixed effect or a time-fixed effect (without considering the autocorrelation first). Second, the Wald and Breusch-Pagan LM test was used to check the groups' autocorrelation, contemporaneous correlation, and heteroscedasticity. Robust standard errors were used to address the problem of heteroskedasticity between groups (see Table 3).

3.2.1. Analysis of the impact of climate change and human activities on grassland productivity

First, precipitation has a positive and significant impact on grassland productivity, a 1% increase in precipitation would increase grassland productivity by 0.76%. Second, a 1% increase in precipitation would increase grassland productivity by 0.2%. Third, the temperature of the early and last non-growing seasons had a negative impact on grassland productivity, and the temperature in the last non-growing season contributes more to grassland productivity than in the early non-growing season.

Fourth, the synergy of temperature and precipitation positively affects grassland productivity. The contribution of the synergy of temperature and precipitation in the early non-growing season is greater than in the last non-growing season, which indicated that precipitation moderated the grassland productivity early. The positive moderation indicates that increased precipitation and temperature could improve grassland productivity in the previous non-growing season. After precipitation reaches a certain level, the increase in temperature will increase grassland productivity.

Fifth, human activities negatively affect grassland productivity. An increase in grazing intensity would decrease grassland productivity. Sixth, the analysis of the contribution of independent variables reveals that climate change critically influences grassland productivity. The contribution of climate variation is ranked as follows: the intersection of temperature and precipitation in the early non-growing season > precipitation > grazing intensity. It shows that the contribution of precipitation is more significant than human activities to grassland productivity. Still, the impact of precipitation on grassland productivity is more significant than temperature (see Table 3).

3.2.2. Regional heterogeneity analysis on the typical steppe

The fixed-effect regression results show that the model has individual fixed effects. There is regional heterogeneity of influencing factors to grassland productivity in the Typical Steppes. That proved that regional heterogeneity analysis is correct, as shown in Table 3. For the Typical Steppe in Wulanchabu, precipitation is the main factor affecting grassland productivity. At the same time, precipitation has a positive and significant effect on the temperature in the early non-growing season; for the Typical Steppe in Xilinhot, precipitation had a positive and significant impact on the temperature in the early non-growing season. In addition, grazing intensity has a negative and significant impact; for the Hulunbuir Typical Steppe, the synergy of precipitation, temperature, and precipitation in the early non-growing season significantly impacts grassland productivity. Results indicate that the number of factors that significantly affect the grassland productivity of the Typical Steppes gradually increases from west to east. While the grassland productivity of the Typical Steppes in the west is only affected by precipitation, the effect of precipitation and temperature gradually increases from west to east. For example, the contribution of precipitation was 0.72, 0.74, and 0.76, respectively, and temperature contribution in the early non-growing season was −0.61, −0.82, and −1.1 (Table 3).

The regional heterogeneity analysis revealed that the Typical Steppes in the east had more apparent heterogeneity than those in the west and central regions. The results of the Typical Steppes in the central and western regions are not much different from the baseline model. Only the adjustment term of precipitation on the temperature in the early non-growing season is more significant. The influence and the significance of other variables have not changed significantly. In addition, the grazing intensity only considerably impacted the

Table 2
Correlation analysis between temperature and grassland productivity in the Typical Steppe region.

Grass-land Productivity	Temperature											
	The temperature in the early growing season					The temperature in the growing season			The temperature in the later growing season			
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
May	.477**	.486**	.421**	.378**	.224*	0.059	−0.06	0.013	.326**	.369**	.434**	.518**
Jun.	.540**	.472**	.438**	.377**	.255*	−0.11	−0.15	−0.02	.264*	.415**	.501**	.597**
Jul.	.496**	.445**	.434**	.380**	.342**	−0.17	−0.19	0.015	.282**	.404**	.469**	.533**
Aug.	.583**	.516**	.497**	.458**	.319**	−0.11	−0.17	−0.09	.308**	.497**	.570**	.631**
Average	.586**	.524**	.499**	.445**	.337**	−0.13	−0.18	−0.03	.317**	.477**	.557**	.635**

Note: ** was significant at 0.01 and * was significant at 0.05.

Table 3
Estimated results of the fixed-effect model estimation.

Variables	Benchmark model	Synergy analysis	Heterogeneity analysis		
			Wulanchabu station (West)	Xilinhot station (Middle)	Hulunbuir station (East)
precipitation	0.412*** (0.091)	0.761*** (0.185)	0.723*** (0.117)	0.743*** (0.123)	0.761*** (0.148)
Precipitation in the early	0.199** (0.093)	0.197* (0.090)	0.192* (0.088)	0.225** (0.072)	0.202*** (0.052)
Temperature in the early growing season	−0.337 (0.229)	−1.070 (0.612)	−0.612 (0.563)	−0.815 (0.462)	−1.062** (0.370)
Temperature in the later growing season	−0.061 (0.234)	−0.278 (0.612)	0.321 (0.607)	0.152 (0.628)	−0.252 (0.426)
Synergy of temperature in the early growing season and precipitation	–	1.037 (0.772)	1.035* (0.494)	1.052* (0.411)	1.040*** (0.216)
Synergy of temperature in the later growing season and precipitation	–	0.140 (0.672)	0.041 (0.582)	0.009 (0.538)	0.126 (0.393)
Grazing intensity	−0.316 (0.225)	−0.108 (0.227)	−0.255 (0.166)	−0.354** (0.118)	−0.137 (0.143)
Wulanchabu station	0.074 (0.390)	0.077 (0.377)	−0.644*** (0.054)		
Xilinhot station	0.000 (.)	0.000 (.)		0.719*** (0.060)	
Hulunbuir station	−1.792*** (0.528)	−1.889*** (0.505)			−1.837*** (0.092)
T	0.003 (0.014)	0.004 (0.013)	0.007 (0.045)	0.006 (0.043)	0.004 (0.039)
Constant	0.532* (0.311)	0.484 (0.297)	0.006 (0.776)	−0.429 (0.825)	0.487 (0.735)

Note: ***, ** and * represent significant at 1%, 5% and 10% levels respectively; (.) is standard error.

grassland productivity of the Typical Steppes in the central region, and the effects in the other areas were insignificant.

4. Conclusion and discussion

This paper focuses on the significant impact of climate change and human activities on the Typical Steppes' productivity. Three representative grasslands in the eastern, central, and western parts of Inner Mongolia were selected based on the meteorological, socioeconomic, and yield information. The Pearson Correlation Analysis and the Long-panel Fixed Effect Model empirically analyzed the precipitation, temperature, and grazing intensity on grassland productivity. This study concluded that precipitation was significantly positively correlated with grassland productivity. This finding aligns with previous studies conducted in the field [10,12]. There was a significant positive correlation between temperature and grassland productivity in the non-growing season.

Secondly, the result of the Long-Panel Fixed Effect Model reveals that, in the early non-grassland growing season, the temperature, the synergy of the temperature, and precipitation are the most critical factors affecting the grassland productivity of the Typical Steppes. Precipitation is a vital factor that positively and significantly impacts grassland productivity. This finding addresses the limitations identified in previous studies [8,9]. In the meantime, precipitation positively adjusts the temperature in the early non-growth season. The temperature negatively affects grassland productivity. Each influence factor's contribution is ranked as follows: The synergy of precipitation and temperature > precipitation > precipitation in the previous period > grazing intensity.

Finally, due to differences in geographical environment and climatic conditions, the response laws of climate change and human activities of the Typical Steppes in different regions are different. The number of factors significantly affecting grassland productivity gradually increases from west to east, and the degree of response factors continues to improve. We discovered varying results across different study areas and types of grassland [15,16]. In addition, the effect of grazing intensity on grassland productivity was significant only in the middle Typical Steppes.

5. Management implications and limitations

5.1. Based on the conclusions of this paper, we put forward the following management implications

First, the study found that the impact of climate change on grassland productivity is more significant than the impact of human activity. Therefore, we should focus on the Typical Steppes risk management in tackling climate change. In addition to constructing more comprehensive disaster prevention and mitigation measures, we should pay attention to some market risk management tools, such as financial products for climate risk. Second, the study found that climate change is an important factor that affects grassland productivity; among them, the synergy of temperature and precipitation on grassland productivity is the largest. Besides focusing on a single climate factor's influence on the grassland, focus on more synergy between climate factors, for example, in designing financial products for climate risk, selecting a comprehensive consideration of multiple climate factors as the product index. Third, we found that the factors that affect grassland productivity are different even under the same type of grassland. In the three selected areas, the eastern area of the Typical Steppes is the most sensitive area to climate change, the second sensitive area to climate change is the Typical Steppe in the central, and the Typical Western Steppes are not sensitive to climate change. Therefore, we should choose risk management methods according to local conditions under the same type of grassland. For example, for the Typical Steppes in the eastern region, which is most sensitive to climate change, weather derivatives are suitable for this place. We can choose appropriate weather indicators to design grassland weather derivatives.

This study has certain limitations. Firstly, grazing intensity data were available only for 33 years, while we collected the grassland productivity data for 37 years, which makes the unbalanced panel dataset. Although we aimed to examine the effects of climate change and grazing intensity on grassland productivity, data availability was limited. As a result, we could only establish a relationship between grazing intensity and grassland yield over a broader spatial scale, which may not fully correspond to the specific locations of the grassland yield data. Therefore, there may be some deviation in the findings. In future studies, it is crucial to investigate the impact of various climatic factors, such as, solar radiation, and humidity, on grassland productivity. For instance, exploring how humidity levels influence the rate of evapotranspiration and water retention in grasslands can shed light on the water balance. Understanding this relationships between these climatic factors and grassland productivity will aid in developing effective strategies for sustainable land management and conservation.

Author contribution statement

Xinya GUO, Muhammad Umer Arshad, Yuanfeng ZHAO: Conceived and designed the experiments.
Xinya GUO, Muhammad Umer Arshad: Performed the experiments.
Muhammad Umer Arshad, Xinya GUO, Yuanfeng ZHAO: Analyzed and interpreted the data.
Yufei GONG, and Hongyu LI: Contributed reagents, materials, analysis tools or data.
Xinya GUO, Muhammad Umer Arshad: Wrote the paper.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

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.

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