Original Paper

Grassland Animal Husbandry Ecological Efficiency in Karst Rocky Desertification Areas: Spatiotemporal Dynamics and Differential Drivers

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Abstract

Maintaining and improving the health of grassland ecosystems is the key to promoting the sustainable development of grassland animal husbandry. This study selected three representative karst regions exhibiting varying degrees of rock desertification. EE of grassland animal husbandry in these three areas was calculated using the Super-SBM model. The spatio-temporal variation characteristics were analyzed by kernel density estimation, and the influencing factors were explored by the geographical detector. We found that: (1) The spatial heterogeneity of EE in grassland livestock farming within rock desertification areas is pronounced, diminishing with increasing desertification severity: Areas with potential-light KDC show the highest average efficiency (1.01), while those with medium-severe KDC have the lowest (0.51). (2) Villages with relatively high or high EE are scattered across the three study areas. (3) In areas with potential-light and light-medium KDC, human factors have a clear impact on EE, while in medium-severe KDC affected areas, natural factors play a more significant role. The findings of this study serve as a reference for decision-making regarding the restoration and security of grassland ecosystems in ecologically vulnerable regions worldwide.

Keywords

Grassland, ecological efficiency, Super-SBM, karst desertification control

1. Introduction

Grasslands play an essential role in maintaining ecological balance and supporting regional economic growth (Scurlock & Hall, 1997). However, grasslands are now facing serious threats from continuous degradation,, which directly undermines their capacity to support biodiversity, provide ecosystem services, and safeguard human wellbeing (Yan et al., 2023). Despite supporting 70% of global agricultural land, grasslands are experiencing worsening degradation due to inappropriate human land use (Török et al., 2021). Consequently, in recent years, measuring EE of grassland animal husbandry has gradually become an important indicator for ecological restoration. As a result, in recent years, measuring EE of grassland animal husbandry has gradually become an important indicator for ecological restoration. This indicator plays a key role in reducing the impact of animal husbandry on grassland health, improving EE, and balancing grassland sustainability with livestock-based livelihoods (Huang et al., 2016).

The KDC in South China, centered on the Yunnan-Guizhou Plateau, has the world's most concentrated and continuous distribution of carbonate rocks. It is estimated that this area supports the survival and development of millions of people in China (Ford & Williams, 2007). However, with the intensification of global climate change, the depletion of non-renewable resources, population explosions, and food shortages, these issues have collectively led to worsening rocky desertification in karst regions (Wu et al., 2021). Therefore, to support the survival and development of local residents, the Chinese government has been persistently implementing the KDC project since the 1990s (Zhang et al., 2024). Within this effort, establishing grasslands and developing herbivore-based animal husbandry serve as a typical approach under the "comprehensive management" project for rocky desertification. Grassland animal husbandry has gradually become an important industry in KDC areas, playing a central role in both ecological restoration and economic growth (Song et al., 2024).

EE was first proposed in 1990, referring to the ratio of increased value to increased environmental impact, which seeks to achieve a balance between the economy and the environment. Since then, it has been widely applied in the field of agricultural evaluation (D'Amato et al., 2017). Currently, research on EE mainly focuses on measuring EE levels and analyzing influencing factors (Song et al., 2020). In terms of measuring EE levels, for instance, Chen et al. (2020) used the Super-CCR model to assess the forest ecological security and forestry management efficiency across various provinces in China, concluding that EE generally shows an upward trend in terms of forest ecological security, while the efficiency values in northern forest areas have decreased. Sun et al. (2023) used the Data Envelopment Analysis model to study the overall green EE of agriculture in China. They found that agricultural green EE increased from 0.7340 in 2002 to 0.8205 in 2021, representing an increase of 11.78%. Additionally, to explore the main factors affecting EE, Tang et al. (2022) found that market incentives and environmental regulation have a significant positive impact on agricultural EE and food balance regions in China. Zhang et al. (2023) using the Quadratic Assignment Procedure regression method, found that total water consumption and maize cultivation positively influence the agricultural EE

91

network in China's Han River Basin.

This study examines grassland livestock farming across 22 villages in three karst regions with varying degrees of KDC, specifically examining the grassland livestock farming in a total of 22 villages. Integrating the concept of EE, it employs the Super-SBM model and Geo-detector methodology to assess EE in KDC areas from 2013 to 2023 and investigate its influencing factors. The technical roadmap of this paper is shown in Figure 1 below. The technical flow of this study is illustrated in Figure. 1. The main research contents are: (1) Quantifying regional differences in EE of grassland animal husbandry across areas with varying degrees of KDC. (2) Analysis of influencing factors on EE of grassland animal husbandry in KDC areas based on spatial heterogeneity. (3) Proposed policy recommendations for optimizing the grassland animal husbandry industry and improving grassland management in KDC areas. This study aims to advance the high-quality development of grassland-livestock industries and strengthen grassland ecological conservation, providing theoretical and policy recommendations for grassland restoration and ecological management in KDC.
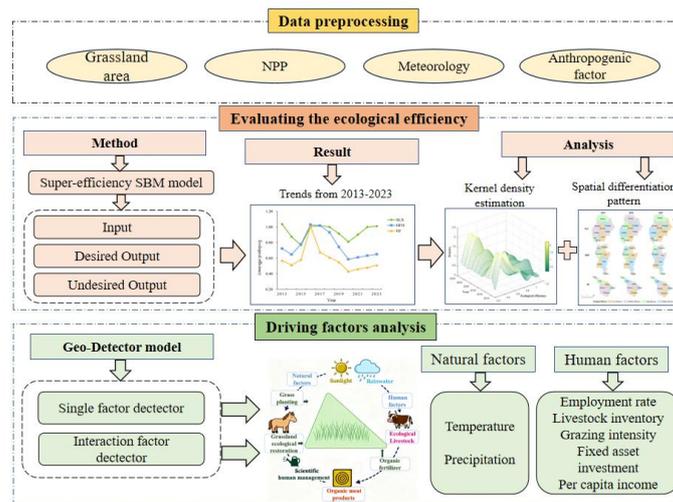

Figure 1. Technical Flow Chart

2. Materials and Methods

2.1 Study Area

Located in Guizhou Province, the center of the SCK, it is one of the regions with the most concentrated karst landforms. It spans between 103°~110°E and 24°~30°N, belonging to a subtropical humid monsoon climate, with higher terrain in the west and lower in the east (Cheng et al., 2017). The region is rich in grassland resources, with an area of 1.15×10^4 to 3.17×10^4 km²; however, the spatial distribution of grasslands is uneven, and the degree of fragmentation is high (He et al., 2023). Regarding the classification standards for the intensity of stoniness, the Chinese Forestry Administration has established the "Monitoring Technical Specifications for Stoniness in Karst

92

Regions", categorizing stoniness into five levels: non desertification, potential desertification, light desertification, medium desertification, and severe desertification (Sheng et al., 2018).

This study selected three core KDC areas located in Guizhou Province, running from north to south (Figure 2). The Salaxi research area (SLX) is located in the northern central part of Guizhou Province, specifically in Salaxi Town and Yejiao Township of Bijie City (105°1′12″-105°8′38″E, 27°11′09″-27°17′28″N), where the proportion of karst land is 74.25%. This area is classified as a potential-light KDC, with desertification management mainly relying on artificially planted grasslands, supplemented by natural grasslands(Wang et al., 2023)[18]. The Hongfenghu research area (HFH) is situated in the central part of Guizhou Province, in Qingzhen City (106°18′14″-106°23′24″E, 26°27′08″-26°34′15″N). The proportion of karst land here is 94.59%, classified as a light-medium KDC, primarily consisting of artificially planted pastures and natural shrub-grasslands, presenting a typical karst patchy landscape (Wang et al., 2017). The Huajiang research area (HJ) is located on both sides of the Beipan River Huajiang Canyon at the junction of Guanyin County and Zhenfeng County in the southwestern part of Guizhou Provinc (105°35′11″-105°43′18″E, 25°37′07″-25°42′25″N), with a karst land proportion of 87.92%. This area is classified as a medium-severe KDC, with a low planting rate of pastures and high ecological sensitivity (Chen et al., 2023).
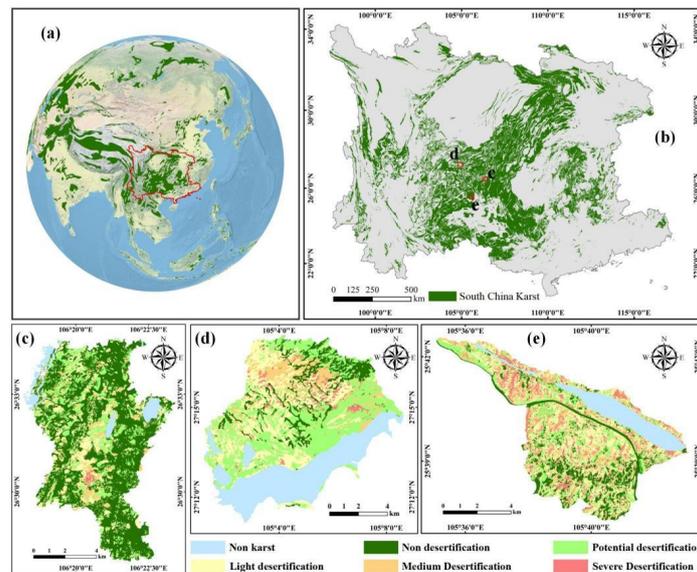

Figure 2. The Study Area. a. Represents the Location of the Southern Karst of China in the World; b. Shows the Location of the Research Area within the Southern Karst of China; c-e. Represent the Degree of Stoniness and the Locations of SLX, HFH, and HJ

2.2 Data Sources

2.2.1 Evaluation Indicators for EE

According to the connotation of EE first proposed by Schaltegger and Sturm (1990), the fundamental idea for constructing the EE evaluation system is the input and output of "resources, economy, and

93

ecology." At the same time, referencing the evaluation index system of EE research on the ecological quality development of grassland animal husbandry by Zhao et al. (2023). To facilitate subsequent accounting and analysis, ArcGis was used to standardize the data on land input and natural input into a raster format, and the EE evaluation index system for the grassland animal husbandry industry in the KDC was established (Table 1).

Table 1. Input-output Indicators of Ecological Efficiency in Grassland Animal Husbandry

Type	Component	Indicator	source
Input indicator	Land input	Grassland area(hm^2)	Resource and Environmental Science Data Platform(https://www.resdc.cn/),Resolution 30m
	Natural input	Net Primary Productivity(NPP)(reflect the quantity and quality of grassland)	United States Geological Survey(https://www.usgs.gov/),Resolution 500m
	Labor input	Number of livestock industry practitioners(per 10,000 persons)	Regional Statistical Bulletin
	Fixed asset investment	Investment in fixed assets of the livestock industry(per 10,000 yuan)	Regional Statistical Bulletin
	Agricultural inputs	Fertilizers and seeds(t)	Regional Statistical Bulletin
Expected indicator	Livestock industry output value	Total output value of animal husbandry(per 10,000 yuan)	Regional Statistical Bulletin
Unexpected output indicator	Carbon emissions from livestock farming	Calculation of CO_2 emissions in animal husbandry using the emission factor method(t·head^{-1}·a^{-1})	The number of livestock and poultry raised (year-end stock) is sourced from the regional statistical bulletin.
	Livestock manure pollution	Estimation of pollutant content in livestock manure based on pollution emission coefficients(t·head^{-1}·a^{-1})	The number of livestock and poultry raised (year-end stock) is sourced from the regional statistical bulletin.

94

2.2.2 Factors Affecting EE

In the development of grassland animal husbandry, the productive function of grasslands is ultimately reflected through the value of animal products, supported by forage grass cultivation (Han et al., 2020). Therefore, in identifying the factors affecting the ecological efficiency of grassland animal husbandry, based on the research findings of Du et al.(2017)[24], we selected indicators such as annual precipitation, annual average temperature, proportion of the livestock industry workforce, livestock inventory, grazing intensity, fixed asset investment, and per capita disposable income (Table 2). The data for annual precipitation and annual average temperature were spatially interpolated using the inverse distance weighting method to obtain temperature and precipitation data for each region.

Table 2. Indicator for Factors Influencing the Ecological Efficiency of Grassland Animal Husbandry

Type	Factor	Explaination	Source
Natural factor	Annual average precipitation	Average precipitation at the end of the year(mm)	National Qinghai–Tibet Plateau Scientific Data Center (https://www.tpdc.ac.cn)
	Annual average temperature	Average temperature at year-end (°C)	National Centers for Environmental Information (https://www.ncei.noaa.gov/)
Human factor	Proportion of employment in animal husbandry	The proportion of people engaged in animal husbandry to the total rural workforce(%)	Regional Statistical Bulletin
	Livestock inventory	Livestock numbers at year-end (per heads)	Regional Statistical Bulletin
	Grazing intensity	Grazing density per unit area of grassland (head/hm²)	Regional Statistical Bulletin
	Fixed asset investment	Fixed asset investment in animal husbandry(per 10,000 yuan)	Regional Statistical Bulletin
	Per capita disposable income	Per capita disposable income in animal husbandry (per 10,000 yuan)	Regional Statistical Bulletin

2.3 Research Methods

2.3.1 Calculation of Carbon Emission in Animal Husbandry

Referring to the emission factor calculation method by Gu et al. (2023), the data acquisition involved in this method is relatively easy and can accurately reflect the greenhouse gas emissions from the livestock sector. The emission coefficients for greenhouse gas sources in livestock farming mainly reference the recommended values from the '2006 Guidelines for National Greenhouse Gas Inventories(https://www.ipcc-nggip.iges.or.jp/public/2006gl/chinese/index.html).   The calculation formula for carbon emissions in the livestock sector is as follows:

$$I=\sum I_i=\sum AD_i \times EF_i \tag{1}$$

In the formula, I represents the total CO_{2e} emissions from livestock (t·head^{-1}·a^{-1}); I_i is the CO_{2e} emissions from the i-th greenhouse gas emission source (t·head^{-1}·a^{-1}); AD_i is the activity level of the i-th greenhouse gas emission source, which refers to the livestock population in various regions (10,000 heads); and EF_i is the CO_{2e} emission factor for the i-th greenhouse gas emission source (kg·head^{-1}·a^{-1}).

2.3.2 Calculation of Pollution Emission from Livestock

The calculation of this indicator refers to the method used by Zhang et al. (2020), which calculates the concentrations of pollutants such as Chemical Oxygen Demand (COD), Total Phosphorus (TP), and Total Nitrogen (TN) generated from livestock manure. Then, using the mean method, the three types of pollutants are combined into a single livestock manure pollution index. The calculation formulas for the generation amounts of pollutants from various types of livestock and poultry manure are as follows:

$$X=N \times T \times G/1000 \tag{2}$$

In this formula, X represents the generation amount of various types of livestock manure (t·a^{-1}); N represents the feeding quantity (10,000 heads); T represents the feeding period (d); and G represents the daily excretion coefficient of various types of manure (kg·head^{-1}·a^{-11}).

The calculation formula for the total amount of pollutants generated from livestock and poultry manure is as follows:

$$P=X \times g/1000 \tag{3}$$

In the equation, P represents the pollutant content in livestock manure (t); X represents the amount of manure generated from various types of livestock (t·a^{-1}); g represents the pollutant parameters for various types of manure (kg·a^{-1}).

2.3.3 Super-efficiency SBM

Efficiency evaluation mainly includes parametric methods and non-parametric methods (Sueyoshi et al., 2017). To overcome the shortcomings of traditional models, Tone proposed a measure model based on super-efficiency slack, the SBM-DEA model, which incorporates slack variables into the objective function and effectively addresses the slackness issue of input-output variables, allowing for a more accurate measurement of efficiency levels in the presence of undesirable outputs (Du et al., 2010). The computational formula for the super-efficiency SBM model is as follows:

$$\rho=min\frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{q_1+q_2}(\sum_{r=1}^{q1}\frac{s_r^+}{y_{rk}}+\sum_{t=1}^{q2}\frac{s_t^{b-}}{b_{tk}})} \tag{4}$$

96

$$s.t. \begin{cases} & \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik} \\ & \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j + s_r^+ \geq y_{rk} \\ & \sum_{j=1,j\neq k}^{n} b_{tj}\lambda_j - s_t^{b-} \leq b_{tk} \\ & 1 - \frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1} \frac{s_r^+}{y_{rk}} + \sum_{t=1}^{q_2} \frac{s_t^{b-}}{b_{tk}}\right) > 0 \\ & s^- \geq 0, s^+ \geq 0, \lambda \geq 0 \\ & i=1,2,\ldots,m; r=1,2,\ldots,n(j\neq k) \end{cases} \tag{5}$$

In the equation, ρ represents the ecological efficiency value of grassland livestock farming; the inputs, expected outputs, and undesirable outputs of grass and livestock farming for decision units j and k are m, q_1, q_2; the input factor serial number is i, the expected output serial number is r, the redundant amount of input is s^-, the redundant amount of undesirable output is s_t^{b-}, the slack amount of expected output is s^+ the input indicators are x, the expected output indicators are y, the undesirable output indicators are b, and the weight vector of the decision unit is λ.

2.3.4 Kernel Density Estimation

The kernel density estimation is a non-parametric statistical method used to estimate the probability density function of a random variable (Silverman, 1986). This method allows for an intuitive analysis of the clustering degree of land use spatial distribution. The calculation formula is as follows:

$$f_n(x) = \frac{1}{nh} \sum_{i=1}^{n} k\left(\frac{x-X_i}{h}\right) \tag{6}$$

In the formula, $k\left(\frac{x-X_i}{h}\right)$ is referred to as the kernel function, $h > 0$ is the bandwidth, and $x-X_i$ is the distance from point x to the sample point X_i. Additionally, the quality of the kernel density estimation depends on the kernel function and is influenced by the choice of bandwidth h. When the selected point is closer to the sample, the kernel function approaches zero, indicating that the density value is larger.

2.3.5 Geographical Detector

Geographical detectors can detect the spatial differentiation characteristics of individual variables as well as the heterogeneity of the spatial distribution of two variables, thereby uncovering potential causal relationships between the two variables(Huo and Sun, 2021)[30]. Its calculation formula is as follows:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{h=1}^{L} N_h \sigma_h^2 \tag{7}$$

In the formula, q represents the explanatory power of the influencing factors on ecological efficiency, with a range of 0-1. The larger the value of m, the greater the explanatory power. N and N_h denotes the number of units in the entire area and layers, respectively. L is the stratification of variables, while σ^2 and σ_h^2 are the variances of layer h and the entire area.

3. Results

3.1 Evaluation of EE

The EE values of grassland animal husbandry in KDC from 2013 to 2023 were measured using the Super-SBM model (Figure 3). Overall, the EE in the three study areas showed a fluctuating upward trend. By 2023, the average EE in the SLX area was 1.01, indicating good EE. The ecological efficiency of the HFH area and the HJ area was 0.65 and 0.51, respectively, indicating a low efficiency level. The HFH and the HJ area exhibited substantial fluctuations, characterized by three phases: 2013 to 2014, 2015 to 2020, and 2021 to 2023. In 2013 to 2014, the EE of grassland animal husbandry showed an overall declining trend. From 2015 to 2020, the EE in these areas initially increased, followed by fluctuating declines. In the period from 2021 to 2023, The overall ecological efficiency of grassland animal husbandry first increased and then fluctuated downward. From 2013 to 2023, the SLX study area showed relatively stable and high ecological efficiency. Although there were some fluctuations, it remained in the range of 0.8 to 1.0 or above, with an upward trend in the later period.
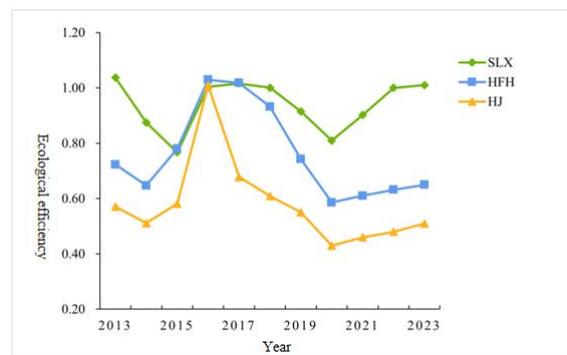

Figure 3. Trend of Grassland Animal Husbandry Ecological Efficiency Changes in the Study Area from 2013 to 2023

3.2 Spatio-temporal Dynamic Changes of EE

To more clearly observe the overall spatiotemporal dynamic evolution of grassland animal husbandry EE in the KDC, this paper utilizes Matlab to create a three-dimensional dynamic Kernel density map of the EE of grassland animal husbandry from 2013 to 2023 (Figure 4). Overall, the findings are as follows: First, the distribution center of EE in the study area has a directional shift to the right, indicating that the overall EE is showing a gradual upward trend. Second, the distribution of EE in grassland animal husbandry exhibits a right-tailed state, which suggests that certain villages within the KDC have EE that are significantly higher than the average level. Third, the peaks of animal husbandry EE from 2013 to 2023 primarily present a "unimodal" distribution, indicating that although the differences in EE between different levels of KDC have increased, the distribution remains relatively concentrated without obvious segmentation or multiple concentrated areas.
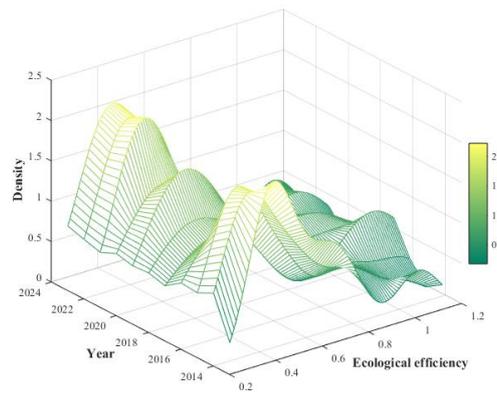
Figure 4. Kernel Density of Grassland Animal Husbandry in the Study Area

3.3 Spatial differentiation pattern of EE

Starting from 2013, typical years were selected every five years, namely 2013, 2018, and 2023. This selection is combined with the EE characteristics of grassland animal husbandry under the management of KDC and references related research on efficiency classification. To ensure the stability and reliability of the results, the default Natural Breaks classification method in ArcGIS software was used to categorize the EE of grassland animal husbandry in the 22 villages across the three study areas (9 villages in SLX, 7 villages in HFH, and 6 villages in HJ) into four types: high-efficiency areas, medium-efficiency areas, low-efficiency areas, and relatively high-efficiency areas, and their spatiotemporal differentiation patterns were visualized (Figure 5).
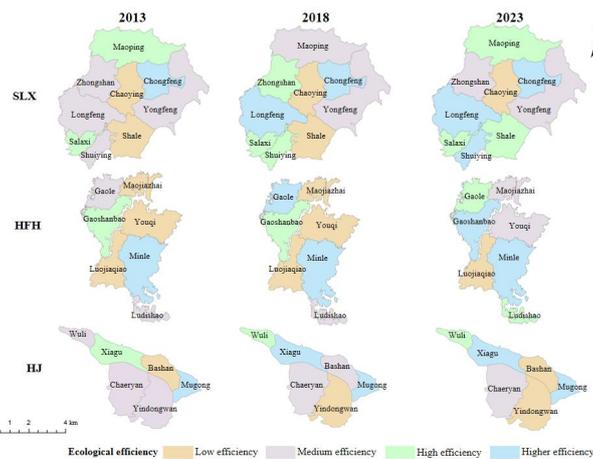

Figure 5. Spatial Distribution Pattern of Ecological Efficiency in Grassland Animal Husbandry

In 2013, looking at the 22 villages as a whole, there were 7 villages classified as higher efficiency and high efficiency, 9 villages classified as medium efficiency, and 6 villages classified as low efficiency. The proportion of higher efficiency and high efficiency villages was highest in SLX (33.33%) and HJ

99

(33.33%), while it was lowest in HFH (28.57%).

In 2018, there were a total of 11 villages classified as higher efficiency and high efficiency, with SLX having the highest proportion at 55.56%. This included Zhongshan village, Longfeng village, Shuiying village, Salaxi village, and Chongfeng village in SLX; Gaole village, Gaoshanbao village, and Minle village in HFH; and Wuli village, Xiagu village, and Mugong village in HJ. There were 6 villages classified as low efficiency, which included Chaoying village and Shale village in Salaxi study area, Maojiashan village, Youqi village, and Luojiaqiao village in HFH, and Yindongwan village in HJ.

In 2023, there were a total of 13 villages classified as higher efficiency and high efficiency, 5 villages classified as medium efficiency, and 4 villages classified as low efficiency. In the Salaxi study area, the proportion of villages with relatively high ecological efficiency was also the highest at 46.15%, while in the Hongfeng Lake study area, this proportion rose to 30.77%.

3.4 Analysis of Influencing Factors on EE

3.4.1 Factor Detection

Using the geographic detector, a single-factor analysis of EE in KDC was conducted, yielding *q* statistical values for each factor, which were then ranked. Meanwhile, the variance inflation factor (VIF) was used to test all factors, ensuring that the VIF values for all factors in each year were less than 10 (Table 3), thereby meeting the model requirements.

Table 3. Results of the Influence Factor VIF Test

Influencing factor	VIF(2013)	VIF(2018)	VIF(2023)
Annual precipitation(X1)	1.580	1.659	1.422
Annual average temperature(X2)	1.554	1.205	1.447
Percentage of agricultural and pastoral employment population(X3)	1.724	1.510	1.410
Livestock inventory(X4)	2.614	3.004	1.715
Grazing intensity(X5)	1.732	1.640	1.093
Fixed asset investment(X6)	2.878	2.623	2.366
Per capita disposable income(X7)	1.404	1.357	1.410

The results indicate that the factors influencing the EE levels in the three study areas are different, as shown in the table (Table 4). The top three dominant driving factors in SLX are fixed capital investment (X6), average annual temperature (X2), and the proportion of the livestock employment population (X3). In HJ, the top three dominant driving factors are average annual precipitation (X1), livestock stocking rate (X4), and average annual temperature (X2). In HFH, the top three dominant driving factors are average annual precipitation (X1), the proportion of the livestock employment population (X3), and grazing intensity (X5). Among these, natural factors such as precipitation and

temperature significantly impact the EE of all three study areas and are key natural climate factors. Notably, in areas with medium-severe KDC, the effects of temperature and precipitation are more pronounced due to the more vulnerable ecological environment. Due to differences in the development of grassland animal husbandry and the effects of human management across the three study areas, the influence of human factors also varies.

Table 4. Results of Ecological Efficiency Factor Detection in the Study Area from 2013 to 2023

Impact Factor	SLX	HJ	HFH
Annual precipitation(X1)	0.195**	0.432***	0.304***
Annual average temperature(X2)	0.394**	0.342**	0.061**
Percentage of agricultural and pastoral employment population(X3)	0.389**	0.186*	0.197**
Livestock inventory(X4)	0.386**	0.412**	0.082*
Grazing intensity(X5)	0.096*	0.018*	0.107**
Fixed asset investment(X6)	0.563**	0.342**	0.073*
Per capita disposable income(X7)	0.088*	0.346**	0.105***

Note. ***,**,*indicate that the variable is significant at 1%,5%,and 10%level respectively.

3.4.2 Interaction Detection

From the interaction detection results (Figure 6), it can be seen that the interaction among factors in the three study areas exhibits two types: dual-factor enhancement and nonlinear enhancement. The driving force of dual-factor interactions is stronger than that of individual factors. This indicates that the EE of grassland animal husbandry in KDC is not solely influenced by a single factor, confirming that changes in grassland EE result from a complex interplay of factors. Specifically: ①In SLX, the interaction effects of the proportion of employment in animal husbandry (X3)∩livestock stock(X4), average annual precipitation(X1)∩proportion of employment in agriculture and animal husbandry(X3), and proportion of employment in animal husbandry(X3)∩fixed asset investment(X6) had explanatory powers of 0.582, 0.578, and 0.543, respectively. It can be seen that the interaction between human factors has stronger explanatory power than the interaction between natural and human factors. ②In HFH, the interaction effects of average annual precipitation(X1)∩fixed asset investment(X6), fixed asset investment(X6)∩per capita disposable income(X7), and fixed asset investment(X6)∩livestock stock(X4) had strong explanatory powers of 0.850, 0.798, and 0.777, respectively. This indicates that the role of natural factors in the ecological efficiency of grassland animal husbandry is not independent, but rather highly dependent on the conversion of fixed asset investment(X6) driven by human factors. ③In HJ, the interactions of annual precipitation(X1)∩per capita disposable income(X7), annual precipitation(X1)∩fixed asset investment(X6), and annual precipitation (X1)∩livestock stock(X4)

ranked among the top three explanatory powers, with values of 0.887, 0.885, and 0.882, respectively. Natural factors have become the core precondition that dominates various interactions and affects ecological efficiency in the HJ area.
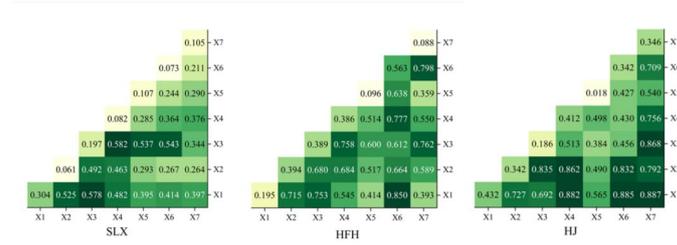

Figure 6. Interaction Factor Detection Results of Ecological Efficiency in the Study Area

4. Discussion

4.1 Spatio-temporal Characteristics of EE of Grassland Animal Husbandry in KDC

In studies on agricultural EE in karst areas, researchers commonly find that the level of rocky desertification is a key factor limiting production efficiency (Li et al., 2023). This study further extends this pattern to grassland animal husbandry, confirming that the negative relationship between rocky desertification levels and EE also applies in livestock production. This study finds that the EE of grassland animal husbandry in KDC areas showed significant spatial variation, and it decreased as the level of rocky desertification increased. This is consistent with the trends identified by Wen et al.(2024)[32]. This indicates that rocky desertification, as a deep-seated geographical factor, exerts a long-term and stable influence on EE of grassland animal husbandry (Zhao et al., 2021). Moreover, the finding of differing EE gradients from potential-light to moderate-severe KDC further substantiates the notion that rock desertification is not merely a consequence of ecological degradation. It itself exacerbates the vicious cycle between ecological and economic development by constraining EE (Wu et al., 2022).

At the research scale, studying the EE of grassland livestock farming at the village level in karst regions, which are characterized by "ecological fragmentation" and "socio-economic micro-levels," fills a gap in micro-scale research (Wang et al., 2022). At the same time, it reveals that in promoting the ecological development of grassland animal husbandry in KDC areas, relying solely on macro-level desertification control policies is insufficient to achieve overall improvements in EE. It is essential to focus on small-scale differences at the village level and implement targeted interventions. This aligns with Huang et al.(2021), who proposed different ecological protection patterns for the grasslands in North China, distinguishing between various protection zones, pastoral areas, agro-pastoral interface zones, and agricultural areas. Similarly, grassland protection efforts in Inner Mongolia should also adopt tailored ecological restoration policies for specific areas, rather than implementing uniform measures across the board (Lu et al., 2024).

102

4.2 Factors Influencing EE of Grassland Animal Husbandry in KDC

The EE of grassland livestock farming in KDC is limited by natural environmental constraints and disturbed by human activities. Factors such as precipitation and temperature show a positive correlation with the growth of grassland vegetation (Dai et al., 2023). Temperature, precipitation, and solar radiation dominate changes in grassland NPP. These climatic factors play a vital role in carbon cycling, ecological conservation, and environmental security in grassland ecosystems (Hua et al., 2025). Grazing is the main human factor controlling variations in grassland productivity (Chen et al., 2020). Human activities have led to nearly 60% of vegetation degradation in karst areas. Natural factors influencing the enhancement of grassland ecosystem services are the primary determinants in the initial stages, subsequently transitioning to human-related factors as the dominant influence (Li et al., 2025).

It is noteworthy that we further discovered spatial variability in the intensity of factors influencing EE of grassland livestock farming across different levels of rock desertification. Human factors significantly influence EE in potential-light and light-medium KDC, while natural factors have a more pronounced effect in medium-severe KDC regions (Tang et al., 2023). Chen et al. (2024) found significant spatial heterogeneity in the natural, human, and integrated factors driving rock desertification and soil erosion in the karst region of Chongqing. Due to the spatial heterogeneity of karst topography in southwestern China, the contributions of climate change and human activities to soil moisture trends also exhibit regional variations (Wei et al., 2022). These findings all support the conclusions of this study. In areas with potential-light or light-moderate KDC，human factors not only individually have a strong influence on EE of grassland animal husbandry, but their interactions also serve as the key driving force determining the level of EE (Li et al., 2024). This indicates that, before grassland ecosystems undergo irreversible degradation, EE can be enhanced through human interventions such as promoting artificial grassland establishment, implementing stall feeding, and optimising livestock herd composition. Conversely, in medium-severe KDC, natural constraints exert a greater influence than human factors, thereby dominating the situation. Natural factors constrain human activities. Differences in the degree of rock desertification have led to a shift in the relationship between natural and human influences (Peng et al., 2020)[46]. Therefore, the development of grassland animal husbandry in this region must strictly adhere to natural principles. The focus of human intervention should be on ecological restoration of grasslands rather than pursuing increased production efficiency.

4.3 Limitations and Future Insights

Although this study has achieved certain results, it still has the following limitations: In data acquisition, due to the difficulties in obtaining data from the karst region and the relatively short research period, we were unable to fully clarify the long-term trends in EE. Future research could establish long-term field monitoring stations. In the analysis of influencing factors, the geo-detector primarily identified the independent effects of factors, with insufficient depth in examining interactions between them, making it difficult to reveal the complexity of the influencing mechanisms.Future research could use farmer

surveys to include more variables, such as environmental awareness and risk. This approach could better reveal the underlying reasons for differences in EE.

5. Conclusion

This study focused on three areas with different levels of rocky desertification in the karst region. Systematically measured EE of grassland animal husbandry, analyzed its spatiotemporal characteristics, and identified influencing factors. The main research conclusions are as follows: (1) The EE of grassland livestock farming remains generally low overall, exhibiting a significant negative correlation with the degree of rock desertification. Areas with potential-light KDC demonstrate the highest average EE, approaching ideal levels; conversely, regions with medium-severe KDC exhibit the lowest average EE, indicating a state of imbalance. (2) In the three study areas, villages with relatively high EE do not form contiguous clusters but are scattered in a dotted pattern, showing significant spatial heterogeneity and fragmentation in their distribution. (3) Factors influencing EE of grassland livestock farming exhibit distinct spatial variation across different levels of rock desertification. Human factors predominate in areas with potential-light and light-medium KDC; whereas in areas with medium-severe KDC, natural factors become the dominant influence. This study provides a reference for decision-making on grassland ecosystem restoration and sustainable grassland development.

Acknowledgments

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106

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