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Spatial Pattern and Driving Mechanisms of Settlements in the Agro-Pastoral Ecotone of Northern China: A Case Study of Eastern Inner Mongolia

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Abstract: Rural settlements in agro-pastoral ecotones reflect the complex interplay between natural constraints and human land use, particularly in ecologically sensitive and climatically transitional regions. This study investigated the agro-pastoral ecotone of eastern Inner Mongolia, a representative region characterized by environmental heterogeneity and competing land use functions. Landscape pattern indices, ordinary least squares (OLS) regression, and geographically weighted regression (GWR) were employed to analyze settlement morphology and its environmental determinants. The results reveal a distinct east–west spatial gradient: settlements are larger and more concentrated in low-elevation plains with favorable hydrothermal conditions, whereas those in mountainous and pastoral areas are smaller, sparser, and more fragmented. OLS regression revealed a strong positive correlation between arable land and settlement density ($r > 0.8$), whereas elevation and slope were significantly negatively correlated. GWR results further highlight spatial non-stationarity in the influence of key environmental factors. Average annual temperature generally shows a positive influence on settlement density, particularly in the central and eastern agricultural areas. In contrast, forest cover is predominantly negative, especially in the Greater Khingan Mountains. Proximity to water resources consistently enhances settlement density, although the magnitude of this effect varies across regions. Based on spatial characteristics and land use structure, rural settlements were categorized into four types: alpine pastoral, agro-pastoral transitional, river valley agricultural, and forest ecological. This study provides empirical evidence that natural factors (topography, climate, and hydrology) and land use variables (farmland, pasture, and woodland) collectively shape rural settlement patterns in transitional landscapes. The findings offer methodological and practical insights for targeted land management and sustainable rural development in agro-pastoral regions under ecological and socioeconomic pressures.

Keywords: rural settlements; agro-pastoral ecotone; spatial pattern; landscape indices; cluster analysis; geographically weighted regression; eastern Inner Mongolia

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Academic Editors: Yilun Liu, Xiaocong Xu, Guohua Hu and Mateus Batistella

Received: 19 April 2025
Revised: 31 May 2025
Accepted: 10 June 2025
Published: 12 June 2025

Citation: Zhang, Z.; Wu, X.; Chen, S.; Jia, L.; Wang, Q.; Zhang, Z.; Li, M.; Jia, R.; Lin, Q. Spatial Pattern and Driving Mechanisms of Settlements in the Agro-Pastoral Ecotone of Northern China: A Case Study of Eastern Inner Mongolia. *Land* **2025**, *14*, 1268. https://doi.org/10.3390/land14061268

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1. Introduction

The agro-pastoral ecotone, a transitional zone between agricultural and pastoral production systems, exhibits pronounced ecological fragility and sensitivity in human–environment relationships. According to the Food and Agriculture Organization of the

United Nations (FAO), the agro-pastoral ecotone, a crucial component of global terrestrial ecosystems, accounts for approximately 40% of the Earth's land surface and plays vital ecological roles, including biodiversity conservation and carbon sequestration. However, the distinctive natural conditions and the intertwined nature of agricultural and pastoral production systems pose significant challenges to settlement development in these regions. On the one hand, settlements must accommodate the dual demands of farming and livestock husbandry [1]; on the other hand, ecological fragility imposes strict constraints on settlement expansion [2,3]. These characteristics result in settlement spatial patterns within the agro-pastoral ecotone that are markedly different from those in purely agricultural or purely pastoral regions [4]. Therefore, investigating the spatial patterns of settlements in the agro-pastoral ecotone is of great significance, as it contributes to a deeper understanding of the operational mechanisms of coupled human–environment systems and offers a scientific foundation for regional ecological conservation, rational resource management, and the formulation of sustainable development policies [5].

In recent decades, research on rural settlements has undergone significant methodological advancements. Early studies primarily relied on fieldwork, typological classifications, and qualitative morphological assessments to examine the relationship between settlements and their environment. However, with the advancement of remote sensing (RS) and geographic information systems (GISs) [6,7], quantitative spatial analysis has become increasingly prominent [8]. Scholars widely employ landscape pattern indices—such as patch density (PD), mean patch size (MPS), splitting index (SPLIT), and landscape shape index (LSI)—to characterize settlement distribution, fragmentation, and complexity [9–13]. Fan et al. integrated landscape ecology, fractal geometry, and mathematical statistics to develop an indicator system for settlement fractal characteristics, quantifying settlement spatial complexity and evolutionary trends [14,15]. Spatial econometric methods, including ordinary least squares (OLS), geographically weighted regression (GWR), and Geodetector, have further enabled researchers to unravel the impacts of environmental and socioeconomic drivers on rural settlement dynamics [15–17]. Moreover, the application of clustering techniques such as K-means and hierarchical clustering has improved the classification of rural settlements based on morphological, functional, and locational attributes. Mi et al. further classified settlements in eastern Inner Mongolia by size (micro, small, medium, large), providing a model for integrated classification based on ecological, production, and residential types [18]. These methodological improvements have fostered a more precise and multidimensional understanding of rural settlement patterns, particularly in ecologically sensitive areas such as the agro-pastoral ecotone.

Despite the abundant research achievements mentioned above, there are still gaps in settlement studies within large-scale agro-pastoral ecotones, especially in the context of extensive agro-pastoral transitional zones. Most existing studies focus on the relationship between settlements and a single land use type (e.g., farmland or pasture), without adequately quantifying the spatial associations among multiple critical elements. Furthermore, effective integration between point-based (settlement centers) and area-based (grid landscape indicators) multi-scale analyses is lacking, which hinders efforts to bridge micro-scale morphology with macro-scale spatial patterns. Existing research often analyzes settlements in agricultural or pastoral environments, overlooking the complex and transitional nature of settlements in mixed-use landscapes.

The eastern Inner Mongolia agro-pastoral ecotone represents a crucial transitional zone between the fertile black soil region and the expansive grasslands of Northern China [19–21]. This region uniquely integrates high-quality arable land with natural pastures, representing a quintessential semi-humid to semi-arid ecological transition belt [22]. It exhibits distinct vegetation zonation, characterized by a fragile and sensitive ecosystem with a

significant risk of soil and water loss, alongside diverse climatic conditions and land use practices [23–25]. Traditional agriculture and pastoralism coexist with the rapid emergence of new industries such as rural tourism, resulting in a distinctive spatial settlement pattern characterized by "broad dispersion and localized concentration," where productive and residential functions are closely intertwined [26,27]. The dynamic evolution of this complex human–environment system closely parallels that of other major agro-pastoral transitional zones globally, including the Sahel in Africa [28,29], the Pampas of South America [30,31], and the Eurasian Steppe Belt [32]. These parallels highlight the adaptive evolution of settlement patterns in response to ecological conditions. Consequently, the eastern Inner Mongolia agro-pastoral ecotone serves as a representative model of human–environment interactions in Northern China's agro-pastoral areas and an ideal case study for comparative research on global agro-pastoral ecotones.

To address this research gap, this study focuses on the eastern Inner Mongolia agro-pastoral ecotone as a representative case. It employs a multi-scale analytical approach using a "settlement point + grid cell" framework. Specifically, it quantifies the spatial distribution characteristics of settlements through landscape pattern indices, identifying key driving factors and their mechanisms influencing settlement distribution and evolution with a geographically weighted regression model, finally establishing a settlement classification system that integrates ecological, productive, and residential functions through cluster analysis. This research aims to provide a scientific basis for regional sustainable development and to offer valuable insights for settlement research and management in similar ecologically fragile regions worldwide.

2. Materials and Methods

2.1. Study Area

Eastern Inner Mongolia Autonomous Region, herein referred to as eastern Inner Mongolia, is situated within the agro-pastoral ecotone of Northern China. Geographically, eastern Inner Mongolia lies between 115°21′–126°04′ E and 41°17′–53°20′ N, with an approximate east–west span of 750 km and a north–south extent of 1330 km. It covers a total land area of approximately 452,300 km^2, accounting for 39.1% of Inner Mongolia's total area. Administratively, eastern Inner Mongolia comprises four prefecture-level jurisdictions: Hulunbuir, Hinggan League, Tongliao, and Chifeng [18].

Eastern Inner Mongolia is one of Inner Mongolia's more economically advanced subregions and plays a strategic role in both the Northeast China Revitalization Strategy and the Western Development Strategy [33]. The region's rural landscape is characterized by a mixed agro-pastoral production system. From an economic geography perspective, eastern Inner Mongolia maintains strong spatial and socioeconomic linkages with China's three northeastern provinces, sharing similar industrial structures, historical trajectories, and resource endowments. Collectively, these areas form a relatively integrated regional economic zone [34]. In terms of industrial development, county-level data reveal a pronounced spatial gradient in the proportions of secondary and tertiary sectors, displaying a "higher in the south, lower in the north" distribution pattern [18]. Key industries such as mining, processing, and agro-pastoral product development have experienced rapid growth. Demographic patterns also exhibit spatial heterogeneity: urban centers display concentrated population growth, while peripheral counties and banners experience dispersed and often declining populations. These spatial patterns have demonstrated temporal stability in recent years.

Environmentally, eastern Inner Mongolia has a temperate continental climate characterized by high solar radiation, low humidity, marked seasonality, and significant diurnal temperature variation. Summer precipitation increases toward the coastal margins, con-

tributing to pronounced seasonal hydrological variation. The region lies on the eastern margin of the Mongolian Plateau, with topography descending from southwest to northeast. Landforms include mountains, low hills, plains, high plateaus, and intermontane basins. River systems originate mainly from the flanks of the Greater Khingan Mountains, with limited exorheic drainage. Soils in the region are diverse, consisting of both zonal soils, such as gray forest soils, chernozems, and chestnut soils; and azonal soils, including meadow, alluvial, aeolian sandy, saline, and alkaline soils. Vegetation transitions spatially from sandy grasslands and typical steppe in the southwest to meadow steppe, temperate deciduous broadleaf forest, and cold–temperate coniferous forest in the northeast [4].

The specific study area is located in the central section of eastern Inner Mongolia's agro-pastoral ecotone, between 117°06′–123°42′ E and 42°14′–47°39′ N (Figure 1). It spans approximately 600 km east–west and 610 km north–south, covering a total area of 178,230 km^2—equivalent to 15.06% of Inner Mongolia's total territory. This study focuses on the spatial characteristics of rural settlements within this transitional zone.

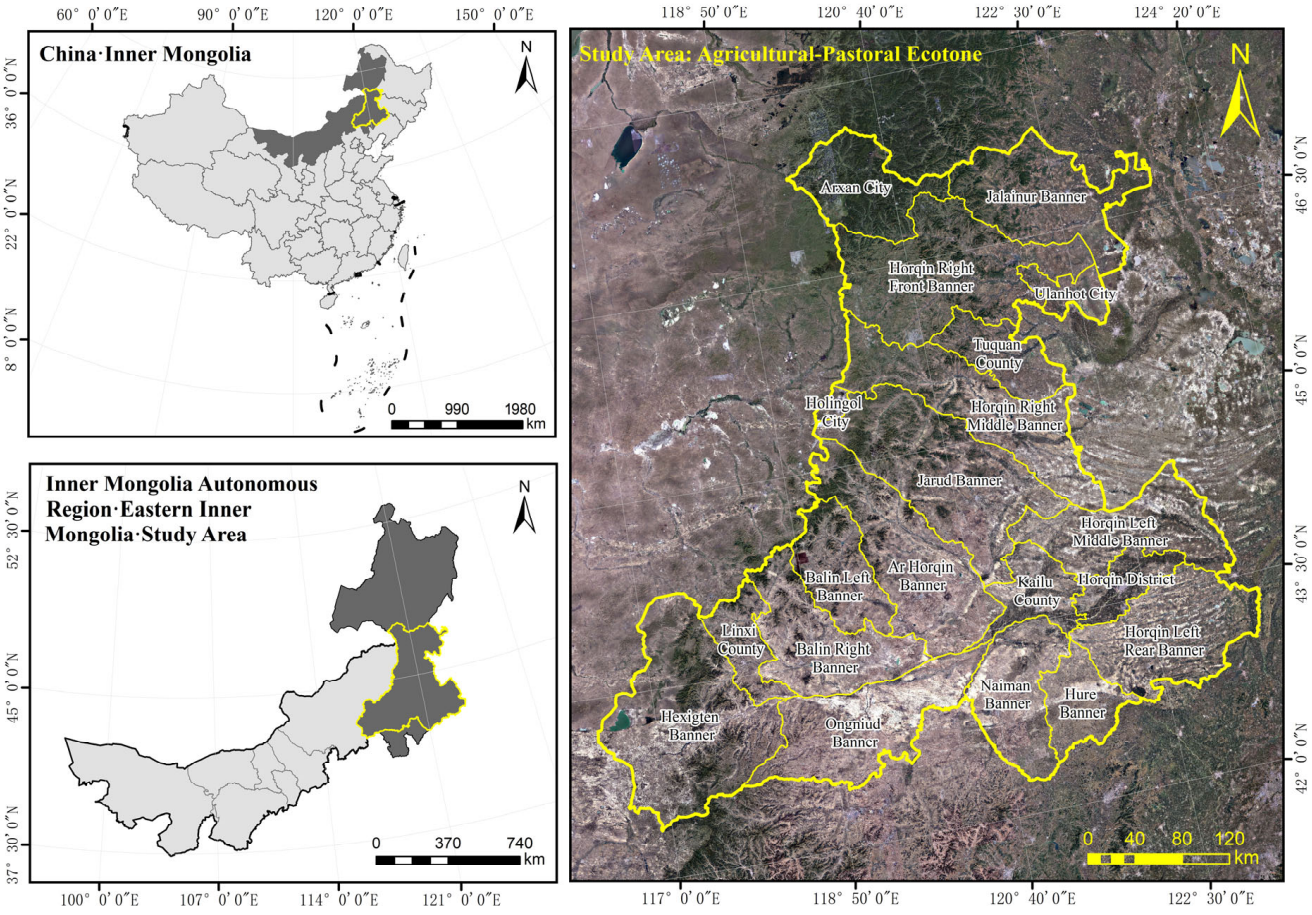


Figure 1. Study area. Source: The administrative boundaries were downloaded from the Chinese Standard Administrative Division Data, with the map review number GS (2024) 0650. The satellite base map was downloaded from Google Earth (https://earth.google.com/ (accessed on 20 February 2025)).

2.2. Data Sources

The spatial formation and evolution of rural settlements are influenced by a range of interacting factors, typically classified into biophysical and socioeconomic domains [35]. To capture these complex dynamics within the agro-pastoral ecotone of eastern Inner Mongolia, this study integrates diverse geospatial datasets, which are categorized into two principal types: natural environmental variables (e.g., elevation, slope, and precipitation)

and socioeconomic indicators (e.g., population distribution and GDP). This study systematically collected and synthesized diverse rural landscape data from the eastern Inner Mongolia agro-pastoral zone, encompassing geospatial datasets, photographic surveys, and contextual textual materials. The primary data sources for this research are detailed in Table 1.

Table 1. Data sources for the study area.

Data Category	Data Name	Data Source	Specification (Resolution/Scale)	Processing Tools
Natural Environment	Elevation (m)	Geospatial Data Cloud (https://www.gscloud.cn/search (accessed on 20 September 2024))	30 m, 5 m	GIS
	Slope (°)	Geospatial Data Cloud	30 m	Derived from DEM using GIS
	Aspect	Geospatial Data Cloud	30 m	Derived from DEM using GIS
	Annual Precipitation (mm)	Resource and Environment Science & Data Center (https://www.resdc.cn/ (accessed on 18 September 2024))	30 m	GIS
	Lakes	Geofabrik Download Server (https://download.geofabrik.de/ (accessed on 24 September 2024))	—	GIS
	River Networks	Geospatial Data Cloud	30 m	Derived from DEM using GIS
	High-resolution Imagery	Google Earth	0.5–2.5 m	GIS
	Road Network	Geofabrik Download Server	30 m	GIS
Socio-Economic	Population Distribution	WorldPop (https://hub.worldpop.org/ (accessed on 5 October 2024))	100 m	GIS
	Built-up Areas (2020)	Resource and Environment Science & Data Center (https://www.resdc.cn/ (accessed on 27 September 2024))	30 m	GIS
	Settlement patch (2023)	Sentinel-2 Land Cover Explorer (https://livingatlas.arcgis.com/landcoverexplorer (accessed on 24 February 2025))	10 m	GIS
	GDP	National Tibetan Plateau Science Data Center (http://data.tpdc.ac.cn/zh-hans/ (accessed on 6 January 2025))	—	GIS
	Land Use (2020)	Resource and Environment Science & Data Center	30 m	GIS

2.3. Methods

In this study, a structured three-stage research framework is adopted to investigate the spatial patterns and underlying drivers of rural settlements in the agro-pastoral ecotone of eastern Inner Mongolia. As depicted in Figure 2, at stage 1, considering the characteristics of the agro-pastoral ecotone in eastern Inner Mongolia, we collected two categories of baseline data: natural environmental variables and socioeconomic indicators (Table 1). These data were processed using ArcGIS 10.8 to derive spatial variables, such as patch area, density, and proximity, along with elevation, slope, aspect, farmland area, forest area, pasture area, mean annual temperature, distance to roads, and distance to rivers. These variables were then categorized according to their relevance to settlement formation. At stage 2, grid cell sizes were determined based on previous studies and data resolution. All variables were spatially aggregated and assigned to the corresponding grid cells. The final stage encompassed a suite of spatial analytical techniques: (1) Using FRAGSTATS 4.2, a set of landscape pattern indices, including PD, MPS, LSI, SPLIT, and MNN, were computed. These metrics were visualized and interpreted in ArcGIS 10.8 to determine spatial pattern characteristics and distribution factors. (2) Pearson's correlation analysis and GWR analysis were conducted to screen and verify three categories of factors potentially influencing settlement spatial patterns. (3) IBM SPSS Statistics 27 was used to process influence factors within each grid cell, serving as the basis for classifying settlement types via K-means clustering. The SSE criterion was applied as a validation metric.

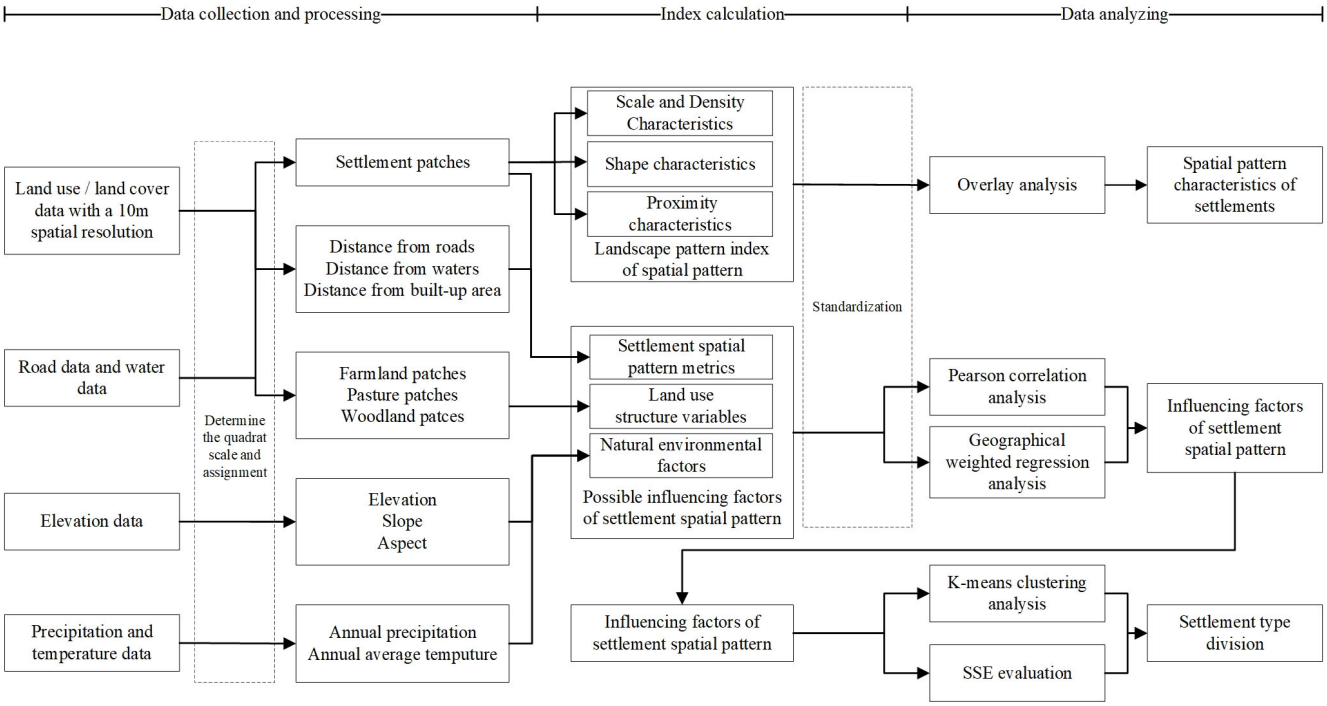


Figure 2. Research framework.

2.3.1. Quadrat-Based Spatial Analysis

All datasets were georeferenced to the WGS84 coordinate system. A grid-based (quadrat) framework was adopted to aggregate spatial data. Grid cell size was determined by considering the dataset resolution, the vast extent, and the low population density of the study area, and analytical precedents [36]. Given the spatial resolution of the core datasets (1 km) and the regional context of eastern Inner Mongolia, a 10 km × 10 km grid was selected as the basic spatial analysis unit. This grid system generated 1968 cells across the study area, of which 1842 contained valid rural settlement data.

2.3.2. Landscape Pattern Indices

Patch settlements were derived by subtracting urban areas from built-up areas. The built-up area data were obtained from the Sentinel-2 Land Cover Explorer (https://livingatlas.arcgis.com/landcoverexplorer (accessed on 24 February 2025)), while urban area data were sourced from the Resource and Environment Science & Data Center (https://www.resdc.cn/ (accessed on 27 September 2024)); see Table 1 for details. Under the theoretical framework of landscape ecology, a suite of landscape metrics was employed in this study to characterize the spatial structure of rural settlements in terms of density, shape complexity, and spatial configuration [37]. These indices were computed using FRAGSTATS 4.2, enabling the quantitative assessment of five selected metrics: landscape shape index (LSI; a measure of patch boundary complexity), splitting index (SPLIT; a measure of the degree of spatial dispersion), mean patch size (MPS) and patch density (PD) (measures of the spatial intensity and settlement scale), and mean nearest neighbor distance (MNN; a measure of spatial proximity) (Table 2). Together, these metrics provided an integrated perspective on settlement scale, regularity, and fragmentation across the study region.

Table 2. Landscape metrics are used to characterize settlement spatial patterns.

Spatial Pattern Feature	Landscape Metric	Description
Scale and Density	Patch Density (PD)	Number of patches per 100 km^2
	Mean Patch Size (MPS)	Average patch area within each grid cell (km^2)
Shape Complexity	Splitting Index (SPLIT)	Indicates degree of fragmentation; higher values denote greater dispersion
	Landscape Shape Index (LSI)	Measures patch boundary complexity relative to a square baseline
Spatial Proximity	Mean Nearest Neighbor Distance (MNN)	Average Euclidean distance between patches (km)

2.3.3. Correlation Analysis

To preliminarily assess linear relationships between settlement characteristics and potential explanatory variables, Pearson's correlation coefficient was employed. This measure evaluates the strength and direction of linear associations between continuous variables [38]. The correlation coefficient r is calculated as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \quad (1)$$

where $r \in [-1,1]$. Higher absolute values denote stronger correlations. Statistical significance was tested at the $\alpha = 0.05$ level, facilitating the identification of key drivers and reducing the influence of spurious correlations.

2.3.4. GWR Analysis

Geographically weighted regression (GWR) is a local spatial regression technique that addresses spatial non-stationarity issues. By constructing a variable–parameter model driven by geographical spatial heterogeneity, it effectively reveals the spatial differentiation patterns and complex mechanisms of geographical elements. This model breaks through the homogeneity assumption of traditional global regression and employs a spatially local weighting strategy to achieve location-dependent parameter estimation.

The mathematical model can be expressed as

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i) x_{ik} + \varepsilon_i \quad (2)$$

where (u_i,v_i) represents the spatial coordinates of the sample point i, β_k(u_i,v_i) denotes the regression coefficients that vary with spatial location, and ε_i is the random error term. Based on a systematic research framework for geographical spatial analysis, this study comprehensively considers the continuity of historical research findings, data availability, and the quantifiability of indicators to systematically construct a multi-dimensional driver factor system. A total of 11 explanatory variables are selected as factors influencing spatial heterogeneity, including topographic factors (elevation, slope, aspect), climatic elements (temperature, precipitation), locational characteristics (distance to water systems, distance to adjacent roads, accessibility to urban areas), and land use types (areas of arable land, farmland, and pastures). The spatial form of settlements is deconstructed into three-dimensional response variables: size attributes (settlement patch area), shape attributes (shape index), and proximity attributes (nearest neighbor distance index). Through geographically weighted correlation analysis, the spatial association mechanisms between these response variables and the influencing factors are revealed.

2.3.5. K-Means Clustering

To classify spatial units based on settlement characteristics and environmental conditions, K-means clustering was implemented. The algorithm partitions data into k clusters by minimizing intra-cluster variance through iterative reassignment based on Euclidean distance:

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \quad (3)$$

Cluster centroids are iteratively updated according to the mean of points within each cluster:

$$C_i' = \frac{1}{|S_i|}\sum_{x \in S_i} x \quad (4)$$

Model convergence was defined by a centroid movement threshold of 1×10^{-5} or a maximum of 300 iterations. The Elbow Method was used to determine the optimal number of clusters by identifying the inflection point in the sum of squared errors (SSE) [39]. Indicators associated with patch-level settlement spatial patterns, as well as key settlement pattern factors, were selected as input variables for the analysis. Clustering was performed using IBM SPSS Statistics 27.

3. Results

3.1. Spatial Characteristics of Rural Settlement Patterns

This section employs landscape ecological metrics within a standardized grid framework to assess the spatial configuration of rural settlements in the agro-pastoral ecotone of eastern Inner Mongolia. The analysis focuses on three key spatial dimensions—scale and density, shape complexity, and spatial proximity—to comprehensively characterize settlement morphology and spatial heterogeneity across the region.

3.1.1. Scale and Density Characteristics

To capture the spatial distribution and clustering intensity of rural settlements, kernel density estimation was utilized (Figure 3). Based on established classification standards and regional characteristics [18], settlements were categorized into five density levels. The

results indicate that high-density settlement clusters are predominantly concentrated in the southeastern section of the Liaohe Plain. Additionally, a continuous belt of moderately high-density settlements extends along the eastern foothills of the Greater Khingan Mountains, forming a linear axis from the central region to the northeast. Areas of moderate density are primarily distributed around high-density zones, particularly in the southeastern portion of the study area, forming relatively contiguous settlement belts. In contrast, the northwestern and southwestern margins are characterized by dispersed and low-density settlement patterns, with only isolated instances of clustering.

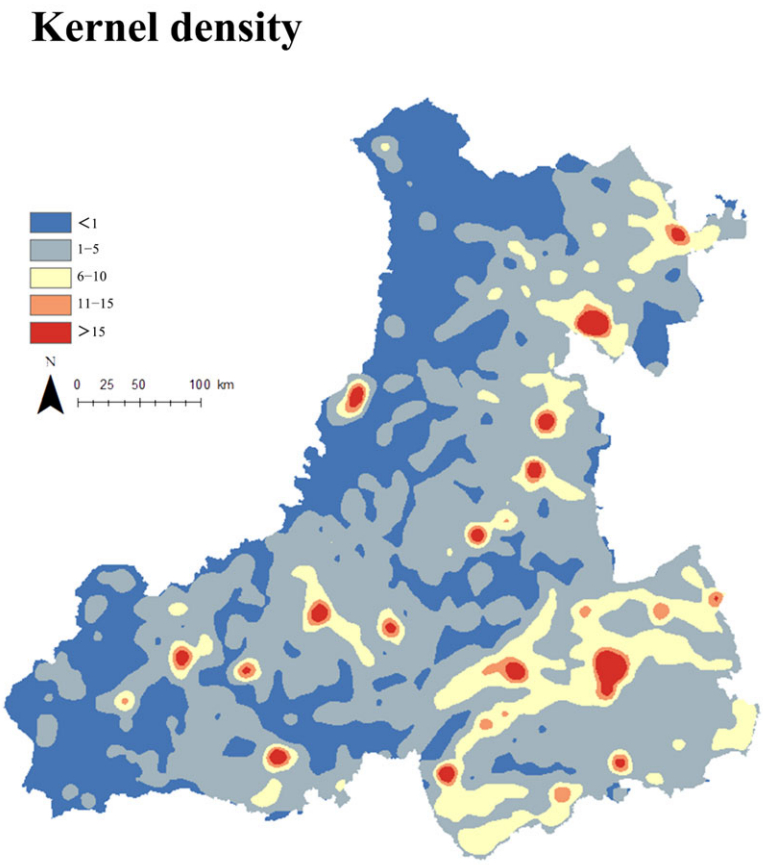


Figure 3. Settlement kernel density analysis.

The analysis of PD further supports these observations (Figure 4a). Aside from an anomalous concentration in Holingol City, areas exhibiting high PD are primarily located along the southern flank of the Greater Khingan Mountains and in the southeastern Liaohe Plain. The number of settlement patches per grid cell varies widely, with a maximum of 142 patches observed in eastern Zhalute Banner (Tongliao City, Inner Mongolia, China) and a regional average of 24.9 patches per cell. The spatial distribution of the patch area partially overlaps with that of PD but reveals distinct characteristics. Larger settlement patches are mainly distributed in the southeastern region, especially southeast of the Greater Khingan Mountains. Notably, some low-density areas in the southeast exhibit relatively large patch sizes, indicating a pattern of spatial aggregation. In contrast, the western region is characterized by both low PD and small average patch size. The MPS across the study region is 0.10 km^2, slightly below the national average of 0.13 km^2 for rural settlements (Figure 4b) [40].

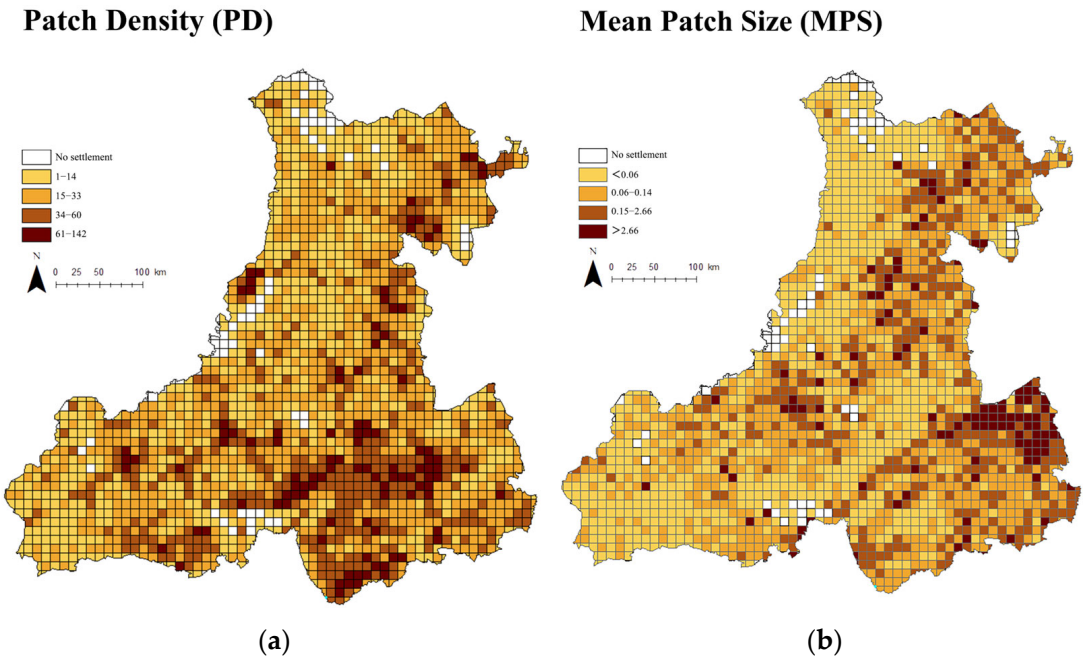


Figure 4. Spatial distribution of settlement scale and density characteristics. (**a**) Patch Density (PD). (**b**) Mean Patch Size (MPS).

3.1.2. Shape Characteristics

The SPLIT values indicate that the highest degrees of fragmentation occur in parts of the northeastern and southern study areas (Figure 5a). In contrast, central regions exhibit lower SPLIT values, reflecting more spatially cohesive settlement configurations. The average LSI value across the study area is 1.32. Only three grid cells exhibit LSI values exceeding 2.0, which are indicative of greater morphological complexity (Figure 5b). These irregular settlement forms are primarily located in the western foothills of the Greater Khingan Mountains and along the northeastern and southeastern peripheries.

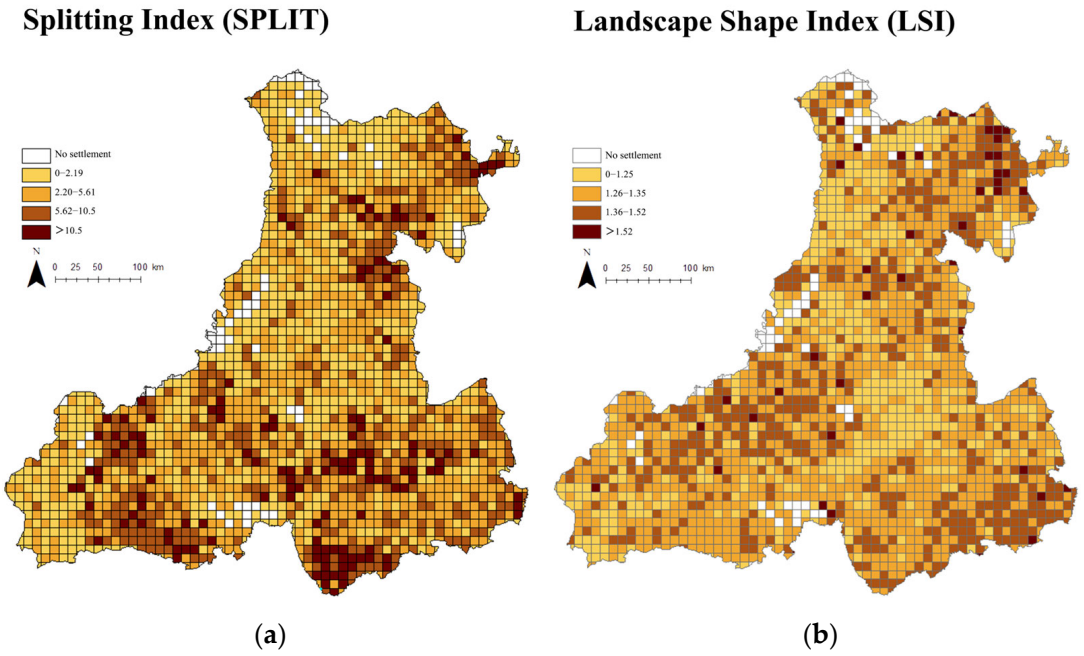


Figure 5. Spatial distribution of settlement shape characteristics. (**a**) Splitting Index (SPLIT). (**b**) Landscape Shape Index (LSI).

3.1.3. Proximity Characteristics

As illustrated in Figure 6, the spatial distribution of the MNN reveals clear variation across the region. The majority of settlement patches are separated by distances of less than 2.1 km, with a regional MNN of 0.83 km. This relatively short inter-patch distance aligns with the general pattern of small, scattered rural settlements in Inner Mongolia's low-density areas. Larger inter-patch distances are predominantly found in the northern portions of the study area. Grid cells exhibiting MNN values exceeding 5 km are mainly located along the northern and southern edges of the region. In certain cases, the maximum inter-patch distances exceed 12 km.

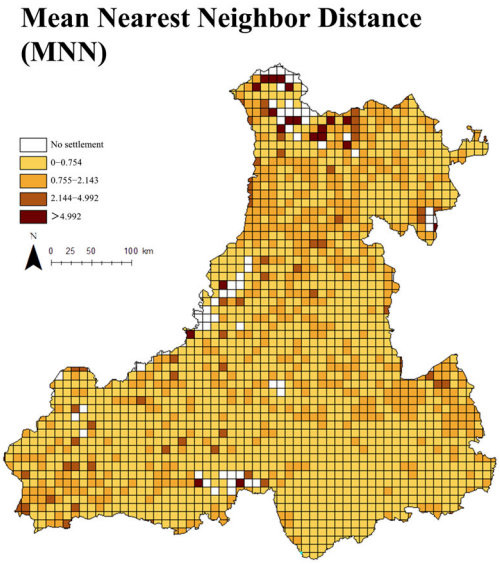


Figure 6. Spatial distribution of settlement proximity characteristics.

3.2. Analysis of Influencing Factors on Settlement Spatial Patterns

3.2.1. Selection and Correlation Analysis of Influencing Factors

To systematically identify the key drivers influencing rural settlement patterns in the agro-pastoral ecotone of eastern Inner Mongolia, 17 candidate variables were selected based on a synthesis of previous empirical studies. These variables were classified into three categories: (1) natural environmental factors, (2) land use structure variables, and (3) settlement spatial pattern metrics. Pearson's correlation analysis was conducted to examine inter-variable relationships and to filter out those with weak or statistically insignificant associations with settlement spatial patterns. The results are shown in Figure 7.

The correlation matrix (Figure 7) reveals several notable intra- and inter-category relationships. For instance, elevation shows a significant positive correlation with slope, indicating substantial topographical variation in the Inner Mongolia agro-pastoral zone—higher elevations are typically associated with steeper terrain. Additionally, farmland areas exhibit a strong negative correlation with pasture areas, suggesting a spatial trade-off between farmland expansion and grazing land. Within the settlement metrics, the number of settlement patches shows a positive correlation with both MPS and SPLIT, and a negative correlation with MNN, indicating a pattern in which settlements are locally clustered, yet fragmented and composed of larger and closely spaced patches.

Significant inter-group correlations also emerge. For example, elevation is negatively correlated with settlement size, indicating that larger settlements are predominantly situated in lower-elevation plains. In terms of land use, farmland areas exhibit a strong positive correlation with most settlement pattern factors (excluding MNN), suggesting that agricultural zones support denser, more fragmented settlement structures. Conversely, pasture

areas show strong negative correlations with these same metrics, reflecting a spatial pattern characterized by dispersed, loosely organized settlements typical of pastoral settlements in the agro-pastoral transitional zone.

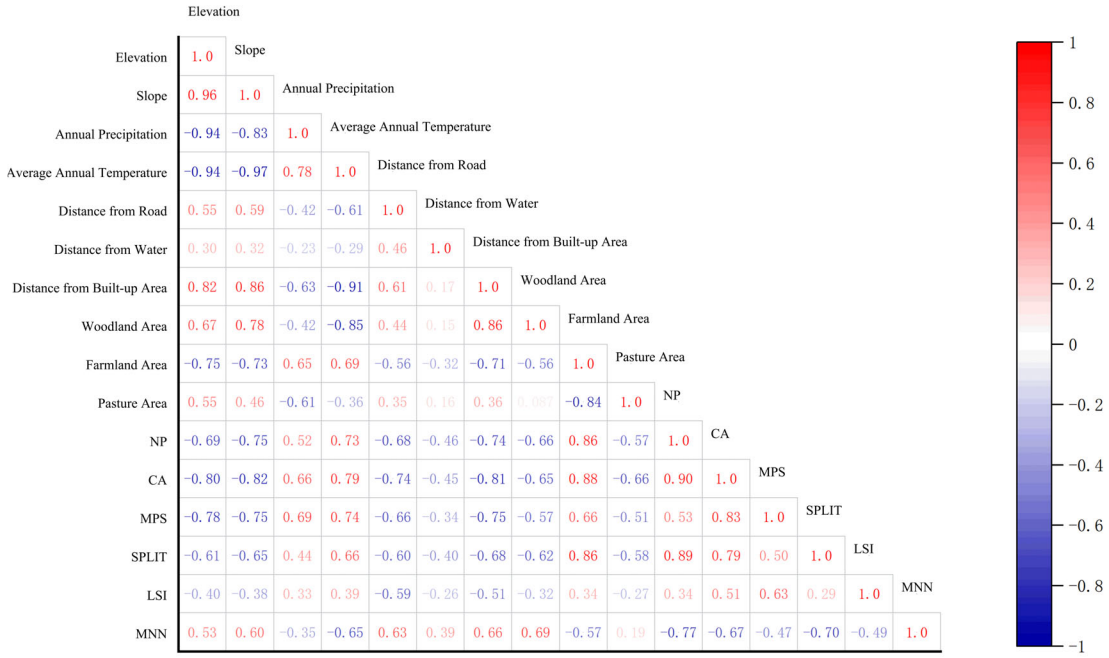


Figure 7. Pearson's correlation coefficients. Note: Correlation coefficients approaching +1 indicate a strong positive correlation, while those approaching −1 indicate a strong negative correlation.

3.2.2. Influencing Factors on Settlement Patterns

The spatially variable relationships between settlement spatial patterns and the most significant influencing factors were further explored using a GWR model. Prior to the GWR analysis, an ordinary least squares (OLS) regression was conducted (Table 3). Only variables with statistical significance at the $p < 0.01$ level were retained. In Figure 8, the spatial distribution of GWR coefficients between some representative factors with higher correlation coefficients was selected from all of the results for display.

Table 3. Ordinary least squares (OLS) results. * Indicates that $p < 0.05$ (significant at the 5% significance level).

Driving Factor	STD	Robust_SE	Robust_t	*p*	VIF
Distance from Built-up Area	6.848154	7.452350	1.839169	0.066054	---
Elevation	0.002422	0.002172	5.316906	0.000000 *	7.337293
Slope	0.146924	0.109742	−7.134488	0.000000 *	2.553408
Aspect	0.026538	0.035446	0.552522	0.580666	1.007989
Annual Precipitation	0.007222	0.007048	−0.724715	0.468712	3.401655
Average Annual Temperature	0.281337	0.283416	8.085078	0.000000 *	4.019192
Woodland Area	0.566052	0.402226	4.223385	0.000030 *	2.551190
Farmland Area	0.561533	0.531298	20.156815	0.000000 *	2.508411
Pasture Area	0.568564	0.512372	2.980651	0.002925 *	2.571708
Distance from Road	0.000095	0.000072	−7.634840	0.000000 *	1.200317
Distance from Water	0.000190	0.000161	−7.077612	0.000000 *	1.130285

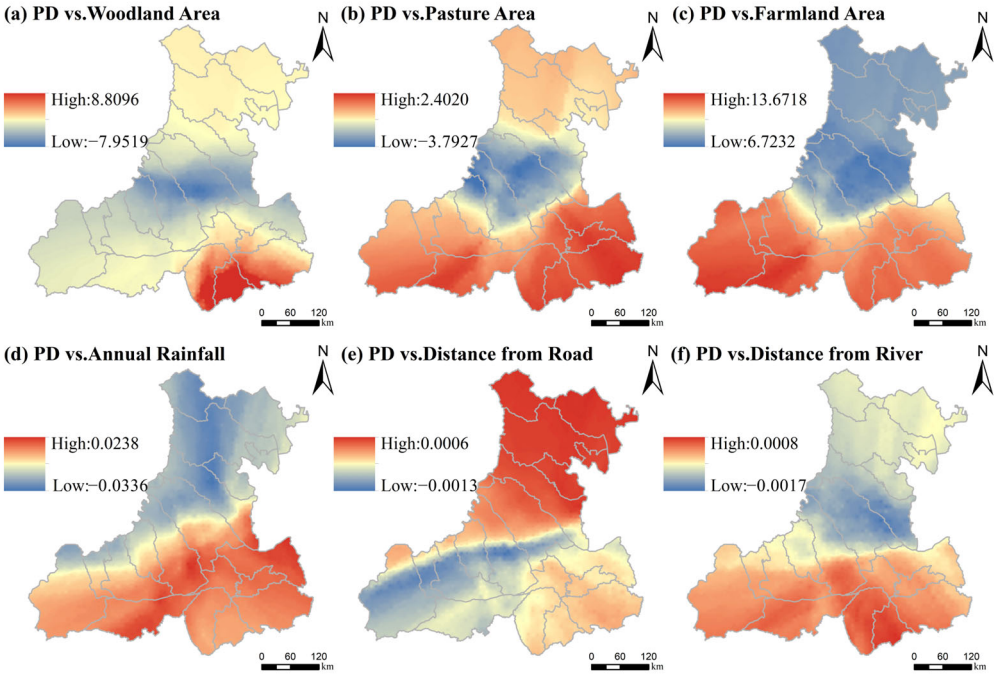


Figure 8. Spatial distribution of GWR coefficients for highly correlated influence factors.

The ordinary least squares (OLS) regression results presented in Table 3 offer crucial insights into the global relationships between various environmental and socioeconomic factors and rural settlement patterns in eastern Inner Mongolia's agro-pastoral ecotone. The statistical significance of several variables ($p < 0.01$) highlights their prominent roles as key drivers of settlement distribution and morphology within this unique transitional zone. These include elevation, slope, average annual temperature, woodland area, farmland area, pasture area, distance from road, and distance from water. Among these, elevation has a VIF of 7.337293, indicating a moderate level of multicollinearity. Distance from built-up area ($p = 0.066054$), annual precipitation ($p = 0.468712$), and aspect ($p = 0.580666$) were not found to be statistically significant at the $p < 0.01$ level in this OLS model. These OLS results provide an understanding of the global relationships between the influencing factors and settlement spatial patterns.

To further dissect these relationships and capture spatial non-stationarity, geographically weighted regression (GWR) was applied. In Figure 8, the GWR results demonstrate the following spatial heterogeneity in the relationships between environmental and socioeconomic factors and settlement. PD vs. woodland area: The coefficients for woodland area show a general negative relationship with PD across most of the study area. This negative correlation is particularly strong in the central and northeastern mountainous regions, such as the core of the Greater Khingan Range, where extensive forest cover and ecological constraints limit settlement development and density. Conversely, some areas, possibly at the forest–grassland interface or where forest patches are smaller, show a weaker negative or even slightly positive relationship, suggesting complex interactions or specific local adaptations.

The relationship between pasture area and settlement is predominantly negative across the study area, particularly in the western and northern pastoral zones. This indicates that as pasture areas increase, settlement density tends to decrease, reflecting the dispersed nature of pastoral settlements. However, in some localized areas, notably in the eastern parts of the study region, the coefficients become less negative or even slightly positive, possibly indicating areas where intensive livestock farming occurs near more established settlements, or where agricultural activities are interspersed with grazing.

Farmland area exhibits a strong and widely positive correlation with settlement across much of the study area, especially prominent in the southeastern Liaohe Plain and river valley agricultural areas. This suggests that higher concentrations of farmland lead to greater settlement density and more compact settlement patterns, consistent with the requirements for intensive agricultural production. The intensity of this positive relationship varies spatially, with the strongest positive effects observed in the most fertile and accessible agricultural zones.

The GWR coefficients for annual rainfall demonstrate a spatially varied influence on settlement. In the wetter southeastern parts of the study area, a positive correlation may be observed, indicating that higher rainfall supports agricultural activities that encourage denser settlements. Conversely, in the drier northwestern and central regions, the relationship might turn negative or become less pronounced, as excessive rainfall could lead to issues such as waterlogging or limited agricultural productivity, thereby impacting settlement density. This highlights a non-linear or threshold-dependent influence of precipitation.

The relationship between distance from road and settlement generally shows a negative correlation across the entire region. This signifies that as the distance from roads increases, settlement density tends to decrease, underscoring the critical role of transportation accessibility in facilitating settlement development and aggregation. The strength of this negative relationship can vary, potentially being stronger in more developed or economically active areas where connectivity is paramount, and weaker in remote areas where settlements are less dependent on formal road networks.

Distance from water: Similarly to distance from roads, distance from water typically exhibits a negative relationship with settlement, indicating that settlements tend to be denser closer to water sources. This pattern is particularly strong along major river systems and areas with abundant water bodies, reflecting the fundamental human need for water for both domestic use and agricultural production. In areas with less reliable water sources or where alternative water supply methods are prevalent, this relationship might be less pronounced or even shift slightly.

3.3. Settlement Landscape Cluster Analysis

Based on the outcomes of correlation and regression analyses and informed by the specific environmental and socioeconomic context of the study area, a selection of representative settlement pattern factors and highly correlated natural environmental and land use factors was incorporated in K-means clustering. The SSE method was employed to determine the optimal number of clusters, resulting in the identification of four rural settlement landscape types: alpine pastoral settlements (Type I), agro-pastoral transitional settlements (Type II), river valley agricultural settlements (Type III), and highland forested settlements (Type IV) (Table 4).

As illustrated in Figure 9, the eastern foothills of the Greater Khingan Mountains, characterized by moderate elevation and gentle slopes, are predominantly composed of Type II and Type III settlements. Type II settlements are commonly found along river valleys and agricultural zones. In comparison, the western mountainous zones of the Greater Khingan Mountains are primarily associated with Type I and Type II settlements. In terms of frequency, the first three types (Types I–III) appear in relatively similar proportions, while Type IV settlements are notably fewer (Table 5).

Table 4. The average values of the factors of the four categories.

Cluster Type	Annual Precipitation	Woodland Area	Farmland Area	Pasture Area	Distance from Road	Distance from Water	PD	MPS	SPLIT	LSI	MNN
Type I	467.3	1,355,978.0	24,599,066.97	62,433,027.07	1894.03	2106.75	28.15	0.093	5.09	1.32	677.85
Type II	448.79	1,345,129.41	30,563,112.4	60,979,527.4	2317.24	2160.43	26.77	0.12	4.31	1.31	728.56
Type III	490.05	7,063,550.10	37,372,565.86	44,784,305.79	4601.37	2466.31	21.69	0.09	3.86	1.31	917.87
Type IV	485.32	41,676,498.4	16,862,602.98	21,358,811.19	3500.34	1971.17	10.31	0.06	1.94	1.32	1843.83

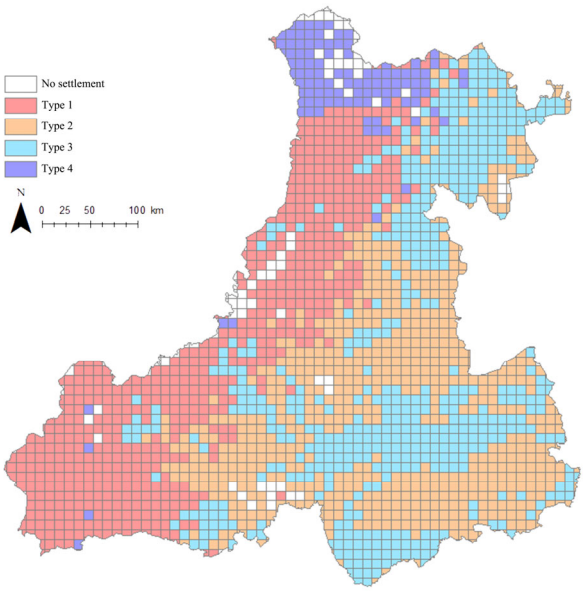


Figure 9. Classification of rural settlement spatial patterns.

Table 5. Spatial pattern characteristics of rural settlements in eastern Inner Mongolia's agro-pastoral zone.

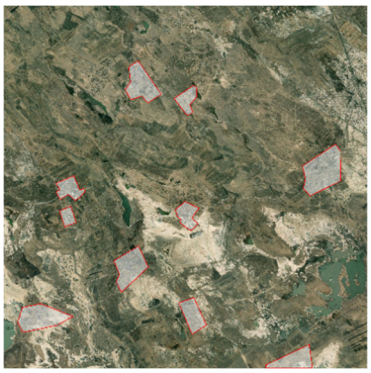
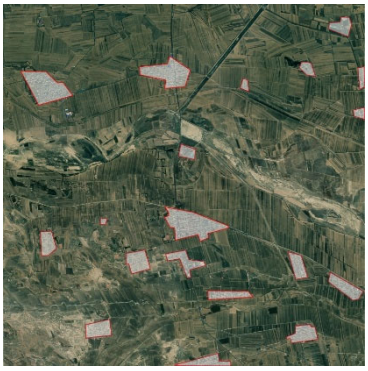
Cluster Type	Dominant Landscape Context	Spatial Distribution Characteristics	Illustration (per 100 km^2)
Type I	Alpine Pastoral Zones	Predominantly distributed in mountainous areas with steep slopes and limited arable land; settlements are aligned with ecological edges, roads, and waterways.	
Type II	Agro-Pastoral Transitional Zones	Located in ecotonal foothills and transitional belts where farming and herding intersect; moderate terrain constraints and mixed land potential.	

Table 5. *Cont.*

Cluster Type	Dominant Landscape Context	Spatial Distribution Characteristics	Illustration (per 100 km^2)
Type III	River Valley and Agricultural Zones	Concentrated in fertile river valleys and alluvial plains; favorable topography supports intensive agriculture and infrastructural accessibility.	
Type IV	Highland Forested Regions	Confined to high-altitude, densely forested zones with strong ecological restrictions and poor development conditions.	

4. Discussion

4.1. Settlement Landscape Characteristics in Agro-Pastoral Zones

4.1.1. Moderate Overall Settlement Scale with a Prevalence of Small Settlements

Rural settlements within the agro-pastoral ecotone of eastern Inner Mongolia reflect the broader demographic and territorial characteristics of the Inner Mongolia Autonomous Region—an extensive area of land with low population density. Settlement patterns in this ecotone are defined by a moderate overall scale and a predominance of small, spatially fragmented settlements [40], a configuration that aligns with typical patterns observed in Northeastern China. Quantitative analysis reveals that in 57.5% of the grid cells (Figure 10), the average patch area of rural settlements is less than 0.1 km^2. Furthermore, the mean landscape shape index across all grid cells is 1.32. Compared with other subregions of eastern Inner Mongolia, settlements within the agro-pastoral ecotone tend to be more numerous but smaller in size [18]. The average area of individual settlements is relatively small, indicating a highly dispersed spatial distribution pattern. This "multi-point, small-patch" structure results not only from natural constraints such as topography and climatic conditions limiting the scale of arable land, but is also closely associated with human settlement preferences, historical spatial patterns, and the capacity of infrastructure provision.

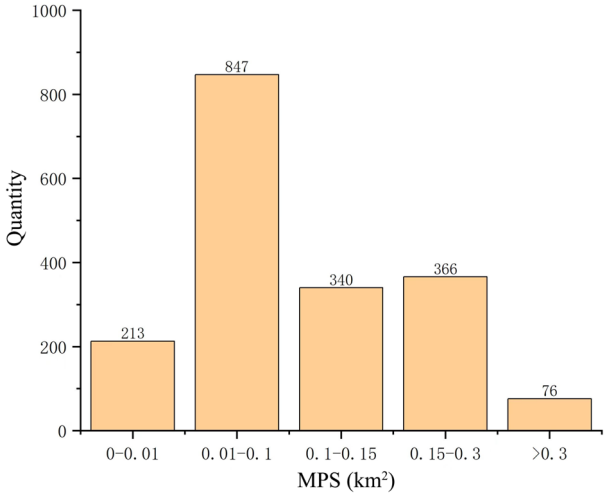


Figure 10. Statistical distribution of MPS per grid cell. (Source: self-drawn.).

4.1.2. Distinct East–West Spatial Differentiation Shaped by Greater Khingan Mountains

The Greater Khingan Mountains [41] serve as a geomorphological boundary that exerts a significant influence on settlement distribution. A clear east–west gradient is observed, with denser and more cohesive settlement patterns concentrated on its eastern foothills and sparsely distributed, smaller-scale settlements characterizing the western mountainous region. The eastern zone benefits from relatively flat terrain, favorable hydrothermal conditions, fertile soils, and extended frost-free periods. These conditions support intensive agricultural production. Furthermore, proximity to the Northeast China Economic Zone has further stimulated settlement consolidation and spatial densification. In contrast, the western flank of the Greater Khingan Mountains is marked by elevated terrain, complex topography, and harsher hydrothermal conditions. Extensive forest coverage, lower soil fertility, and limited growing seasons constrain cultivation. While certain flat grassland areas are suitable for grazing, most settlements in the highland zone are small, scattered, and aligned along ecological corridors such as riverbanks and transport routes. As a result, most settlements are small in scale and spatially dispersed, typically arranged in linear patterns along ecological corridors such as rivers and transportation routes. This spatial differentiation pattern clearly reflects the combined influence of natural geographic constraints and anthropogenic interventions. In the eastern plains, favorable resource endowments coupled with historical policy support have fostered high-density, clustered settlement patterns. In contrast, the elevated western regions exhibit sparse and fragmented settlement forms, constrained by limited ecological carrying capacity and underdeveloped infrastructure.

4.2. Driving Mechanisms of Settlements

A multi-scale analytical framework is proposed in this study that integrates "settlement points and grid cells" with landscape pattern indices, K-means clustering, and geographically weighted regression (GWR), promoting progress in rural settlement research within complex ecological zones such as the agro-pastoral ecotone. Traditional studies often focus on either agricultural or pastoral settlements separately, neglecting their composite nature, or lack effective coupling of micro- and macro-scale analyses, making it difficult to link microscopic morphology with macroscopic patterns. By effectively bridging the gap between micro-level settlement morphology and macro-level regional patterns, this integration allows for a more nuanced quantification of internal settlement structure (e.g., shape complexity via LSI, fragmentation via SPLIT) while simultaneously analyzing their regional distribution and density (via kernel density estimation and PD). This enhanced

spatial characterization improves the reliability of our findings by providing a more robust representation of complex settlement landscapes.

Elevation exhibits a highly significant negative correlation with settlement size, indicating that larger settlements are predominantly concentrated in low-altitude plains [42]. This finding aligns with the widely accepted principle that low-elevation areas generally offer more favorable conditions for human habitation and agricultural development, such as gentler slopes, deeper soils, and greater access to water resources. Although the variance inflation factor (VIF) for elevation is 7.337, suggesting moderate multicollinearity, its strong statistical significance underscores its fundamental role in shaping settlement distribution. This effect is particularly evident in mountainous regions, where higher elevations clearly constrain both the number and size of settlements. Similarly to elevation, slope is another critical topographic factor. Steeper gradients often limit agricultural potential and construction feasibility, thereby inhibiting the formation of dense settlement clusters. The observed significant negative correlation ($p < 0.01$) supports this notion, indicating that areas with steeper slopes tend to have fewer and smaller settlements—reflecting a human preference for flatter terrain in residential and productive land use decisions. Temperature, as a key hydrothermal variable, directly influences both agricultural productivity and human livability [43].

More favorable thermal conditions generally support larger and more concentrated settlements by enhancing crop growth and overall habitability. The strong statistical significance of this variable confirms that warmer areas within the study region are more conducive to settlement development and expansion. Forest cover, particularly in areas of dense woodland, is typically associated with ecological conservation zones or regions with limited agricultural potential and poor accessibility. The significant negative association ($p < 0.01$) likely reflects the combined effects of environmental constraints and land use regulations, where extensive forested areas limit the expansion of rural settlements—as observed in the core zones of the Greater Khingan Mountains. Arable land shows a strong positive correlation with most settlement pattern indicators, suggesting that agricultural zones support denser and more fragmented settlement structures [44]. This is intuitive, as rural settlements in agrarian societies are inherently linked to farming activities. Fertile soils and irrigation potential, especially in river valley areas, tend to attract and sustain higher population densities. In contrast, the pasture area is significantly negatively correlated with settlement density and scale [45]. This reflects the spatial characteristics of pastoral settlements, which are typically scattered, point-like, and loosely organized. These settlements require large tracts of grazing land and tend to be less spatially concentrated than agricultural settlements. Distance to roads is a fundamental determinant of accessibility and connectivity [42], facilitating economic activities, access to services, and transportation. Its high statistical significance ($p < 0.01$) indicates a strong tendency for settlements to cluster near transportation networks, highlighting the critical role of infrastructure in shaping spatial settlement patterns. Water availability is essential for both human consumption and agricultural activities. The strong statistical significance of this variable ($p < 0.01$) underscores the historical and ongoing dependence of rural settlements on stable water sources, resulting in higher settlement densities near rivers and other water bodies.

In contrast, distance to built-up areas, aspect, and annual precipitation did not exhibit statistical significance at the global scale, with *p*-values of 0.066054, 0.580666, and 0.468712, respectively. The lack of significance for distance to built-up areas suggests that, within the agro-pastoral ecotone, existing urban centers may exert less of a direct influence on rural settlement patterns than natural or land-use-related factors, at least when evaluated using a global linear model. Although there is a traditional preference in Northern China for south-facing dwellings, aspect appears to have negligible influence on the macro-

scale distribution of settlements across the study area. This may be attributed to the inability of global models such as OLS to capture localized microclimatic preferences through a single average coefficient. Similarly, despite the well-established ecological and agricultural importance of annual precipitation, its lack of global statistical significance may be explained by pronounced seasonal hydrological variability in the region. Specifically, total annual precipitation may be less critical for settlement siting decisions than more stable water sources (e.g., perennial rivers) or land use suitability. Alternatively, this result may reflect spatially non-stationary relationships that are not adequately captured by global regression models.

4.3. Formation Mechanisms and Development Strategies for Different Settlement Types

The spatial patterns of rural settlements in eastern Inner Mongolia's agro-pastoral ecotone are a result of complex interactions between natural geographical factors and human activities [46]. The distinct environmental conditions across the region have led to varied settlement morphologies and distributions, reflecting long-term adaptive strategies by local residents. Understanding these formation mechanisms is crucial for developing targeted and sustainable development strategies.

4.3.1. Alpine Pastoral Settlements

Alpine pastoral areas are predominantly located in high-altitude, ecologically fragile mountainous regions characterized by steep terrain, harsh hydrothermal conditions, extensive forest cover, low soil fertility, and shortened growing seasons. Such natural limitations severely constrain agricultural activities and limit the land's capacity to support dense populations [47]. Consequently, traditional nomadic or semi-nomadic pastoralism has emerged as the dominant livelihood strategy, giving rise to sparse, small-scale settlements [48]. These settlements are typically dispersed and tend to cluster along ecological corridors such as river valleys and transportation routes, where accessibility and resource availability are relatively favorable. The development strategy in these areas is as follows: prioritize ecological protection and sustainable resource management; implement seasonal grazing regulations to prevent overgrazing and maintain grassland health; establish mobile service and supply nodes to cater to the dispersed population and enhance access to essential services [49]; and promote eco-cultural tourism that respects local traditions and the fragile environment, while conserving traditional settlement forms. This approach fosters a low-impact, sustainable economy that aligns with the ecological carrying capacity of these highland areas.

4.3.2. Agro-Pastoral Transitional Settlements

Located in the ecotonal foothills and transitional zones between agricultural and pastoral systems, agro-pastoral transitional zones are characterized by moderately favorable environmental conditions, including relatively flat terrain but limited water access and heterogeneous land use patterns. The mixed-use landscape supports both cultivation and grazing, though neither at high intensity due to constraints such as soil fertility and distance from river systems. Settlements in this zone adopt flexible, adaptive forms that are neither as compact as typical agricultural villages nor as dispersed as pastoral ones, reflecting a functional compromise. Sustainable development in these areas should prioritize integrated land use strategies, including rotational grazing–cropping systems to enhance soil productivity, the promotion of high-value agro-pastoral products to diversify livelihoods, and ecosystem-based infrastructure to strengthen resilience against environmental variability [46].

4.3.3. River Valley Agricultural Settlements

River valley agricultural areas are primarily located in low-lying areas characterized by flat terrain, fertile soils, abundant water resources, and favorable hydrothermal conditions, which collectively support intensive agricultural production and dense population concentrations. Proximity to urban centers enhances market access and infrastructure development, further promoting spatial consolidation along river systems. Historically shaped by migration and large-scale land reclamation, these areas have evolved into demographic and economic hubs. Development strategies should focus on advancing intensive and smart agriculture through technological innovation, including precision irrigation and mechanized farming, while encouraging settlement consolidation to optimize land use and public service delivery. Moreover, integrating agricultural zones with surrounding grazing areas can promote multifunctional landscape management and sustainable rural development.

4.3.4. Highland Forested Settlements

Located in high-altitude, densely forested regions typically designated as ecological protection zones, highland forested regions are characterized by limited accessibility, extensive forest cover, and strict regulatory constraints, all of which severely restrict traditional agricultural and pastoral activities. Settlement presence is minimal, shaped predominantly by conservation policies and the ecological sensitivity of the landscape. Development strategies should prioritize ecological function transformation, replacing extractive practices with low-impact under-forest economies such as medicinal plant cultivation and mushroom farming. The establishment of ecological research and monitoring facilities, along with the promotion of seasonal eco-tourism (e.g., environmental education and winter tourism), can offer sustainable livelihood alternatives while supporting long-term conservation objectives.

4.4. Limitations and Prospects

Despite the significant findings of this study, certain limitations warrant acknowledgment, which, in turn, inform avenues for future research. Firstly, the spatial resolution of the satellite imagery utilized in this study may have led to the underrepresentation of some smaller settlements, and minor boundary inconsistencies might exist within the grid cells. While these factors introduce a degree of uncertainty, they do not substantially impact the overall validity of the research conclusions. Secondly, inherent in any typological classification is a degree of simplification. Although our classification provides valuable insights for differentiated land use policies, it represents a generalized framework of complex realities. Future research could advance in two key directions to build upon the foundation laid by this study. First, integrating higher-resolution remote sensing data with detailed field surveys would enable a more refined and precise classification of settlements. This approach could potentially capture the nuances of smaller, more fragmented settlements and improve the accuracy of spatial analyses. Second, conducting in-depth case studies of representative settlement clusters could yield richer insights into the internal structure and dynamic processes of different settlement types.

5. Conclusions

This study explored the spatial distribution and underlying drivers of rural settlements in the agro-pastoral ecotone of eastern Inner Mongolia by combining settlement point data with grid-based landscape analysis and employing OLS and GWR models. The results reveal a pronounced east–west gradient: larger, more densely clustered settlements are predominantly located in low-altitude plains with favorable hydrothermal conditions and

abundant arable land, whereas smaller, more fragmented settlements are typically found in mountainous and pastoral regions with harsher environmental conditions. Settlement density and morphology are primarily influenced by topographic features, climatic conditions, and land use patterns. Arable land strongly promotes settlement concentration ($r > 0.8$), while elevation and slope impose substantial constraints. Warmer temperatures and greater water accessibility also contribute to higher settlement densities, whereas forest cover—especially in protected areas such as the Greater Khingan Mountains—restricts expansion. The GWR model reveals spatial non-stationarity in these relationships, emphasizing the importance of considering local environmental variability in rural planning. The influence of farmland is more pronounced in fertile valleys, whereas elevation imposes greater limitations on settlements in rugged terrain. Based on an integrated analysis of environmental conditions, land use structures, and settlement forms, four types of rural settlements were identified: alpine pastoral, agro-pastoral transitional, river valley agricultural, and forest ecological.

Overall, this research advances our understanding of human–environment interactions in agro-pastoral zones and offers a methodological framework for characterizing rural settlements within ecologically and spatially complex contexts. The findings can inform region-specific land use planning, rural revitalization strategies, and sustainable development initiatives in other ecologically sensitive transitional regions.

Author Contributions: Conceptualization, X.W., S.C. and L.J.; Methodology, Z.Z. (Ziqi Zhang), S.C., Q.W., Z.Z. (Zhiqing Zhang) and M.L.; Software, Z.Z. (Ziqi Zhang), X.W., Q.W., Z.Z. (Zhiqing Zhang), M.L. and R.J.; Formal analysis, Z.Z. (Ziqi Zhang), X.W., S.C., L.J., Q.W., Z.Z. (Zhiqing Zhang), M.L. and R.J.; Investigation, Z.Z. (Ziqi Zhang), X.W. and M.L.; Resources, X.W., Q.W. and M.L.; Data curation, Z.Z. (Ziqi Zhang), X.W., Q.W., Z.Z. (Zhiqing Zhang), M.L. and R.J.; Writing—original draft, Z.Z. (Ziqi Zhang), X.W., Q.W., Z.Z. (Zhiqing Zhang), M.L. and R.J.; Writing—review & editing, Z.Z. (Ziqi Zhang), X.W., S.C., L.J. and Q.W.; Visualization, Z.Z. (Ziqi Zhang), Z.Z. (Zhiqing Zhang), M.L. and R.J.; Supervision, Z.Z. (Ziqi Zhang) and L.J.; Project administration, Z.Z. (Ziqi Zhang) and L.J.; Funding acquisition, Q.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: We have additional analyses that we intend to conduct in our further study, therefore, we are refraining from releasing the database at this stage of our research.

Conflicts of Interest: The authors declare no conflict of interest.

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