Analysis of Influencing Factors on Land Use Patterns in Huailai County (Postprint)

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Abstract

As an important ecological barrier for the capital Beijing and northern China, the land use pattern of Huailai County, Hebei Province, is not only directly related to county-level land resource utilization, but also has certain impacts on the sustainable development of surrounding land ecology. In land use change research, the driving mechanism is the focus, and the key to revealing this mechanism lies in correctly understanding the relationship between land use landscape patterns and influencing factors. This paper takes Huailai County as the study area, interprets land use data for 1994, 2004, and 2014 with the support of remote sensing technology, and selects eight factors from socioeconomic and natural factors including average elevation, terrain relief, annual average precipitation, temperature seasonality, distance from roads, distance from town centers, GDP density, and population aggregation. Combined with landscape pattern gradient analysis and Canonical Correspondence Analysis (CCA) methods, the relationship between land use landscape patterns and influencing factors is studied. The conclusions are as follows: In 2014, the contagion index, interspersion and juxtaposition index, and Shannon diversity index of land use landscape in Huailai County showed obvious spatial differences, all exhibiting certain gradient characteristics in both east-west and north-south directions; along the east-west and north-south axes, the contagion index showed a trend of being high at both ends and low in the middle, while the interspersion and juxtaposition index, Shannon diversity, and Shannon evenness showed the opposite trend. Average elevation and population aggregation have relatively large influences on the distribution of land use landscape types in the study area, while GDP density has a relatively small influence. In 1994, 2004, and 2014, the cumulative explanatory power of land use type data and influencing factors on the four ordination axes was 99.1%, 99.3%, and 99.3%, respectively, with total eigenvalues of 0.780, 0.720, and 0.853, respectively. Based on the explanatory power values, the eigenvalue in 2014 was significantly higher than in the pre-

vious two periods, demonstrating its superiority in describing the relationship between land use types and influencing factors. Among the influencing factors, terrain relief, temperature seasonality, annual average precipitation, distance from roads, and distance from towns have relatively strong correlations with the distribution of land use landscape types in the study area, with relatively high correlation coefficients. As the study period progressed, the correlation of terrain relief gradually decreased, while the correlations of the other four influencing factors gradually increased. Through this study, the causes of land use change in Huailai County are revealed, and theoretical basis is provided for the sustainable development of land use.

Full Text

Preamble

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Analysis of Influencing Factors on Land Use Patterns in Huailai County*

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Abstract
As an important ecological barrier protecting Beijing and northern China, Huailai County in Hebei Province exhibits land use patterns that directly affect local land resource utilization and influence the sustainable development of surrounding ecosystems. Understanding the driving mechanisms of land use change requires correctly identifying relationships between landscape patterns and their influencing factors. This study interpreted land use data for 1994, 2004, and 2014 using remote sensing technology, selecting eight factors from socioeconomic and natural domains: average elevation, relief, annual precipitation, temperature seasonality, distance from roads, distance from urban centers, GDP density, and population aggregation. Combining landscape pattern gradient analysis with Canonical Correspondence Analysis (CCA), we examined relationships between land use landscape patterns and these factors. Results revealed significant spatial variation in contagion index, interspersion-juxtaposition index, and Shannon' s diversity index across east-west and north-south gradients in 2014. The contagion index showed higher values at both ends and lower values in the middle along both axes, while the other three indices exhibited opposite trends. Average elevation and

population aggregation strongly influenced land use type distribution, whereas GDP density had minimal impact. The cumulative explanatory power of the first four ordination axes for land use type data and influencing factors was 99.1%, 99.3%, and 99.3% for 1994, 2004, and 2014, respectively, with total eigenvalues of 0.780, 0.720, and 0.853. The 2014 eigenvalue was notably higher than previous periods, demonstrating superior explanatory capacity. Relief, temperature seasonality, annual precipitation, distance from roads, and distance from urban centers showed strong correlations with land use landscape patterns, with correlation coefficients gradually decreasing for relief and increasing for the other four factors over time. This study reveals the causes of land use change in Huailai County and provides a theoretical basis for sustainable land use development.

Keywords
Landscape pattern; Land use; Driving mechanism; Social factor; Natural factor; Huailai County

Introduction

Land, as a fundamental resource, provides the essential material basis for human production and livelihood. However, with continuous economic development, human interference has led to irrational land use, dramatically altering land cover patterns. These changes not only affect terrestrial biodiversity but also profoundly influence global biochemical and atmospheric cycles. Land ecosystems are inherently constrained by natural conditions, and anthropogenic destruction and irrational utilization during socioeconomic development have generated increasingly frequent problems that directly impact ecosystem service functions. The proportion, intensity, and rate of change in land resource types constitute important drivers of ecosystem area, type, and pattern transformations, significantly affecting material cycling, energy flow, and biodiversity while determining ecosystem health indices and development levels.

Since the International Geosphere-Biosphere Programme (IGBP) and International Human Dimensions Programme on Global Environmental Change (IHDP) jointly proposed the Land-Use and Land-Cover Change (LUCC) research initiative, GIS and RS technologies have become the latest international trend in land use change research. Remote sensing provides robust support for temporal land use studies, offering comparable frameworks for revealing spatiotemporal patterns of land use change. GIS technology integrates temporal dynamic simulation with spatial pattern analysis, combining multiple statistical and spatial analytical methods that play crucial roles in regional LUCC process simulation and spatial pattern analysis. Domestic landscape pattern analysis research, which began in the early 1990s under the influence of the North American school, has achieved significant results across different regions and scales using advanced methods like landscape indices, GIS, and statistical models. Wang et al. introduced American landscape ecological analysis methods to study suburban landscapes in Shenyang' s western suburbs, proposing a framework for spatial landscape analysis. Wang Siyuan et al. analyzed China' s land use patterns and evolution over the past decade using a 1:100,000 land use database. Tian Guangjin et al. investigated rural settlement landscape characteristics in Hebei Province using TM imagery and GIS technology. The application of remote sensing technology to land use analysis has not only filled methodological gaps but also substantially improved analytical accuracy.

With advances in satellite remote sensing and spatial information systems, geoscience research on terrestrial surface characteristics and modern processes has entered a quantitative stage supported by comprehensive data. However, most studies combining statistical analysis with GIS have yielded results with insufficient depth and precision, failing to effectively address practical land use problems. This study employs canonical correspondence analysis and fractal theory supported by remote sensing technology to explore land landscape structure and evolution characteristics, quantitatively examining relationships between land use landscape patterns and influencing factors in Huailai County, Hebei Province, and assessing the impact degree of different factors. The findings can guide targeted protection and efficient, rational utilization of precious land resources.

1.1 Study Area

Huailai County is located in northwestern Hebei Province, southeast of Zhangjiakou City, between 115°16 -115°58 E and 40°4 -40°35 N [Figure 1: see original paper]. The county covers a total area of 1,782 km^2 and administers 11 towns (Shacheng, Tumu, Xinbao' an, Beixinbu, Dahuangzhuang, Guanting, Sangyuan, Xiaonanxinbu, Cunrui, Xibali, and Donghuayuan), 6 townships (Wangjialou, Ruiyunguan, Sunzhuangzi, Langshan, Jimingyi, and Dongbali), and 279 administrative villages. The topography consists primarily of plains, hills, and mountains, with continuous mountain ranges in both northern and southern regions forming a "V"-shaped basin between them. The climate is significantly affected by cold air masses, characterized by variable weather, abundant summer rainfall, and ample sunshine suitable for crop growth. The county exhibits diverse and continuously strengthening economic growth patterns, with total regional GDP reaching 865,000 million yuan in 2010, representing a 15.7% increase from the previous year. The primary, secondary, and tertiary industries contributed 116,335 million yuan (13.8% growth), 280,945 million yuan (19.8% growth), and 467,720 million yuan (14.1% growth), respectively.

1.2 Data Sources and Processing

All data were obtained from the Chinese Academy of Sciences International Data Center. Based on literature review and image analysis, TM bands 5, 4, and 3 were selected from the seven TM bands as they provide complete vegetation information. Three periods of Landsat-TM satellite imagery were used, acquired in September 1994, September 2004, and August 2014. After interpreting climatic and transportation data from the three periods and applying GIS spatial statistics and analysis functions, land use type area changes were obtained (Table 1), along with corresponding landscape index variations (Table 2). Quantitative analysis methods and fractal theory were then applied to derive land landscape structure and evolution characteristics.

1.3.1 Selection of Impact Factors

As natural and socioeconomic composite systems continuously evolve through human-land interactions, land landscape patterns undergo complex changes. Understanding these driving factors is crucial for predicting landscape pattern changes and developing optimization strategies. Driving factors can be categorized as natural or anthropogenic. Natural factors are geographical elements that influence regional landscape pattern gradients, including hydrological, climatic, meteorological, and geomorphological components. Anthropogenic factors derive from socioeconomic activities such as population changes, agricultural production improvements, natural resource exploitation, and urban development, which affect regional land and water resources differently across time and space, causing spatial distribution changes in land landscape patterns.

Based on research objectives and Huailai County' s actual conditions, considering data availability and representativeness, four natural impact indicators were selected: temperature seasonality, annual precipitation, average elevation, and relief. Four anthropogenic indicators were also chosen: distance from roads, population density, economic density, and distance from urban centers. After processing the factor data, ordination analysis was conducted on landscape patterns using 3 km × 3 km grid cells to standardize the resolution. Since factor data varied in resolution, data type, storage structure, and spatial resolution, different conversion methods were required.

Natural Impact Factors
DEM data for Huailai County were extracted from the land use/cover information database and masked using the county boundary in ArcGIS. Spatial analysis functions converted 30 m resolution DEM data to 3 km × 3 km elevation data, with each grid cell representing the average of all 30 m × 30 m pixels within it. Relief, defined as the elevation difference between the highest and lowest points in a region, serves as a basic descriptor of surface conditions and was calculated using the raster calculator [Figure 2: see original paper].

Climate is the most significant factor affecting vegetation distribution, with influence varying by spatial scale and temporal duration. Temperature and precipitation changes have the most obvious impacts, while human activities can alter local environments and create disturbances affecting landscape pattern distribution. Therefore, annual precipitation and temperature seasonality were selected to reflect Huailai County' s climate conditions.

The temperature seasonality formula is:

$$\text{Temperature Seasonality} = \frac{\sum_{i=1}^{12} |\text{MMT}_i - \text{MAT}|}{12}$$

where MAT is mean annual temperature and MMT is mean monthly temperature. ArcGIS raster calculator processed original meteorological data to obtain temperature seasonality at the appropriate scale. Annual precipitation data were extracted directly from processed meteorological data using ArcGIS [Figure 3: see original paper].

Anthropogenic Impact Factors
Urban centers and major transportation corridors represent important locational characteristics with strong attractive forces that influence land landscape patterns and serve as crucial drivers of change. Areas near urban centers and with good transportation access experience greater human impact, leading to more significant changes in land use types and landscape patterns. Data from the Huailai County land use/cover information database were used to calculate distances from each grid cell center to the nearest urban center and road using ArcGIS analysis tools [Figure 4: see original paper].

Population aggregation is a critical anthropogenic factor affecting regional land use/cover status and landscape patterns. Following Xie Hualin et al., population aggregation degree was calculated as:

$$\text{PGI}_j = \frac{P_j}{\sum_{j=1}^{n} P_j} \times \lambda$$

where PGI represents the estimated population value for settlement j, P is the total population of statistical area j, and is a weighting factor based on inverse distance weighting from urban centers and roads. A Kriging model interpolated population aggregation surface models [Figure 5: see original paper].

Local economic development represents another major factor driving land landscape pattern changes. GDP density was selected as a key economic indicator. Since GDP data are typically discrete, interpolation methods were used to estimate values for unknown areas. Spline interpolation was chosen based on previous research demonstrating its superior accuracy for GDP density and its ability to produce relatively smooth surfaces [Figure 6: see original paper].

1.3.2 Land Use Landscape Pattern Gradient Analysis Method

Landscape patterns within a given spatial range exhibit obvious differences due to variations in landscape type composition, quantity, shape, and spatial distribution. Analyzing these differences often reveals directional characteristics, namely landscape pattern gradients. Using ArcGIS and previously calculated landscape indices, trend lines for Huailai County' s 2014 landscape-level indices were plotted [Figure 7: see original paper]. The results show significant spatial variation and gradient characteristics in contagion index, interspersion-juxtaposition index, and Shannon' s diversity and evenness indices along both east-west and north-south axes. The contagion index displayed a concave curve with higher values at both ends and lower values in the middle, while the other three indices showed the opposite convex trend, though with varying curvature magnitudes.

This gradient distribution, while possessing unique attributes, forms through the same processes as other geographical phenomena. Landscape pattern spatial distribution and gradient changes originate from multiple factors, including internal and external, direct and indirect influences, with external factors generally comprising natural and anthropogenic categories.

Ordination, first defined by Soviet scientists in the early 1930s and refined by Ranensky two decades later, has evolved to arrange not only sample plots but also plant species and environmental factors. This method applies to complex studies of community relationships, community-environment interactions, and community-member associations. Ordination arranges samples or species in space so that ordination axes reflect ecological gradients, revealing relationships between vegetation distribution and environmental factors.

Numerous ordination methods exist, including simple ordination techniques such as weighted averaging, polar ordination, and gradient analysis, as well as principal component analysis, correspondence analysis, and their derivatives. This study employed the internationally recognized Canoco software for gradient analysis. Response variables (equivalent to dependent variables) and explanatory variables (equivalent to independent variables) were converted to recognizable data types, after which response variable distribution types were analyzed to determine appropriate models (primarily linear or unimodal). Based on data characteristics and research objectives, suitable ordination methods were selected and applied. If results were unsatisfactory, alternative methods were tested for comparison. Final results were imported to generate ordination diagrams for interpretation, revealing how natural and anthropogenic factors influence landscape pattern gradient characteristics in Huailai County.

2 Results and Analysis

Remote sensing interpretation data for 1994, 2004, and 2014 were divided using a grid method, with cells numbered from left to right and top to bottom, yielding 205 land use sample plots for each period. In Excel, matrices of land use type area proportions and impact factors were constructed for each year. The WcanoImp module in Canoco 4.5 software converted these matrices into formats recognizable by the analysis software.

Detrended Correspondence Analysis (DCA) was performed to eliminate arch effects and reduce the influence of first-axis arrangement on second-axis positioning. The longest gradient length in four axes determines model selection: CCA is suitable when the first axis gradient exceeds 4.0, RDA when below 3.0, and either method when between 3.0 and 4.0. As shown in Table 3, all three periods exhibited first-axis gradient lengths greater than 4.0, making Canonical Correspondence Analysis (CCA) the appropriate choice.

Eigenvalues are crucial indicators for ordination axes, enabling calculation of land use type data variance and explanatory power of relationships between land use types and impact factors. Table 4 demonstrates strong correlations between land use type ordination axes and impact factor axes across all three years. The cumulative explanatory power of the first four ordination axes for land use type data and impact factors was 99.1%, 99.3%, and 99.3% for 1994, 2004, and 2014, respectively, with total eigenvalues of 0.780, 0.720, and 0.853. The 2014 eigenvalue was significantly higher than previous periods, indicating superior explanatory capacity.

2.1 Correlation Analysis Between Land Use Types and Impact Factors Across Periods

Analysis of the 1994 CCA ordination diagram [Figure 8a: see original paper] and correlation coefficients between impact factors and ordination axes revealed that the first axis primarily reflected average elevation (0.8041), relief (0.6133), annual precipitation (0.7641), temperature seasonality (0.6177), distance from roads (0.6424), and distance from urban centers (0.6705). Population aggregation and GDP density showed relatively weaker correlations (-0.3969 and -0.3150, respectively). Moving left to right along Axis 1, average elevation, relief, annual precipitation, and temperature seasonality increased, while distances from urban centers and major roads also increased. Axis 2 primarily reflected average elevation (0.1885), population aggregation (0.4852), and GDP density (0.1190), with elevation, population aggregation, and GDP increasing from bottom to top. Axes 3 and 4 reflected different factors, with relief (-0.2443) correlating strongly with Axis 3 and population aggregation (0.1404) and GDP density (0.1201) with Axis 4.

Axis 1 represented elevation changes, showing positive correlations between elevation and woodland/unused land area, and negative correlations with cultivated land, construction land, garden plots, and water areas. Axis 2 reflected relationships between population aggregation and land use types, with cultivated and construction land increasing with population aggregation (positive correlation), while garden plots, woodland, water areas, and unused land decreased (negative correlation). Land use types with similar spatial distributions in the ordination diagram indicate similar environmental conditions; cultivated and construction land showed the smallest distance, reflecting their close spatial distribution due to proximity to settlements for convenient farming and food supply.

For 2004 [Figure 8b: see original paper], Axis 1 correlations were similar: average elevation (0.8030), relief (0.6012), annual precipitation (0.7703), temperature seasonality (0.6227), distance from roads (0.6492), and distance from urban centers (0.6772). Population aggregation and GDP density remained relatively weak (-0.3985 and -0.3191). Axis 2 reflected average elevation (0.1664), population aggregation (0.4571), and GDP density (0.1463). Relief, GDP density, distance from roads, and distance from urban centers correlated with Axis 3, while relief showed the strongest correlation with Axis 4 (-0.1536). The relationships between land use types and elevation/population aggregation remained consistent with 1994 patterns.

For 2014 [Figure 8c: see original paper], Axis 1 correlations increased for several factors: average elevation (0.8518), relief (0.5878), annual precipitation (0.7693), temperature seasonality (0.7029), distance from roads (0.6890), and distance from urban centers (0.7124). Axis 2 reflected relief (-0.1998), annual precipitation (0.1071), temperature seasonality (0.1106), population aggregation (0.6054), and GDP density (0.2338). Relief and population aggregation correlated with Axis 3, while relief showed the strongest correlation with Axis 4 (-0.1793). Axis 1 continued to represent elevation changes with consistent positive correlations for woodland/unused land and negative correlations for other types. Axis 2 reflected population aggregation relationships, with cultivated land, water areas, and woodland showing positive correlations, while garden plots, construction land, and unused land showed negative correlations.

2.2 Temporal Changes in Relationships Between Land Use Landscape Types and Impact Factors

The analysis revealed temporal variations in relationships between land use types and impact factors. Average elevation showed the strongest influence on landscape patterns, with correlation coefficients of 0.8041, 0.8030, and 0.8518 across the three periods. Population aggregation demonstrated the strongest correlation with Axis 2 (0.4852, 0.4571, and 0.6054). Relief, temperature seasonality, annual precipitation, distance from roads, and distance from urban centers also showed relatively strong correlations. Over time, relief's correlation gradually decreased, while the other four factors' correlations increased. GDP density exhibited minimal influence, with correlation coefficients of -0.3150, -0.3191, and -0.1567, showing no significant relationship with land use landscape types across study periods.

Conclusion

Land, bearing the foundation of human life, has use patterns that directly affect regional ecological security. For Huailai County, experiencing rapid urbanization and industrialization, rational and effective land use faces unprecedented challenges. Based on remote sensing data, digital elevation data, and other sources, this study analyzed land use data to examine dynamic landscape pattern evolution and response analysis of selected impact factors, yielding the following conclusions:

CCA ordination for 1994, 2004, and 2014 showed cumulative explanatory powers of 99.1%, 99.3%, and 99.3% on the first four axes, with total eigenvalues of 0.780, 0.720, and 0.853. The 2004 and 2014 results outperformed 1994, with 2014's eigenvalue significantly higher than previous periods, demonstrating superior explanatory capacity. The eight selected impact factors explained between 99.1% (1994) and 99.3% (2014) of the overall land use landscape pattern, indicating excellent explanatory performance. Factors showed clear differentiation along Axes 1 and 2, with natural factors primarily influencing Axis 1 and anthropogenic factors more significantly affecting Axis 2. Average elevation and population aggregation notably impacted landscape patterns on Axes 1 and 2, respectively, while relief, temperature seasonality, annual precipitation, distance from roads, and distance from urban centers also exerted substantial influence. Therefore, land use planning should prioritize these high-impact factors and implement appropriate measures to promote rational land use and stable land resource development.

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Note: Figure translations are in progress. See original paper for figures.