

Land Use Function Transformation and Its Eco-Environmental Effects: A Case Study of Gaochang District, Turpan City (Postprint)

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Abstract

Taking Gaochang District of Turpan City as an example, this study utilizes four periods of remote sensing imagery from 1990, 2000, 2010, and 2018 to interpret and obtain land use change data for the study area. Based on a grid scale and comprehensively employing methods such as land use transition matrix, kernel density estimation, ecological environment quality index, and ecological contribution rate, it quantitatively analyzes the spatiotemporal pattern characteristics and ecological environmental effects of land use transitions in three dominant functional zones—urbanization areas, major agricultural product production areas, and ecological functional zones—within Gaochang District during the study period. The results show that: (1) During 1990–2018, the spatial pattern of land use transitions in the three dominant functional zones of Gaochang District manifested as an overall increase in the area of major agricultural product production zones, fluctuating growth in urbanization areas, and a decreasing trend in ecological functional zones. During the study period, the spatial agglomeration of land use was higher in the central region than in the northern and southern regions, with the northern region's spatial agglomeration intensifying in 2018. (2) During 1990–2018, the areas of high-quality and low-quality ecological environment in Gaochang District decreased, while the areas of relatively high-quality and relatively low-quality ecological environment increased. The central region exhibited a trend of ecological environment quality improvement, whereas the northern and southwestern regions showed trends of ecological environment degradation. However, the overall degradation trend was slightly weaker than the improvement trend, indicating that the ecological environment quality is moving toward benign development. Through the quantitative analysis of land use transitions and their ecological environmental effects in Gaochang District during the study period, this paper aims to provide a reference for coordinating the sustainable utilization of land resources and ecological environmental protection in Gaochang District.

Full Text

Transformation of Land Use Function and Its Ecological Environmental Effects: A Case Study in Gaochang District, Turpan City

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Abstract: As an important node and transportation hub on the Silk Road Economic Belt, Gaochang District of Turpan City has experienced rapid economic development in recent years, with population continuously concentrating in the urban center and demand for construction land increasing persistently. Located in a desert oasis, Gaochang District represents a typical “ecologically fragile area with relatively backward economy.” This study utilizes four phases of remote sensing monitoring data (1990, 2000, 2010, and 2018) to interpret land use changes in the study area. Based on a 5 km × 5 km grid scale, we comprehensively apply land use transition matrix, kernel density estimation, eco-environmental quality index, and ecological contribution rate methods to quantitatively analyze the spatiotemporal patterns of land use transformation and their ecological environmental effects across three dominant functional zones—urbanized areas, main agricultural production areas, and ecological function areas—during the study period. The results indicate: (1) From 1990 to 2018, the land use area in urbanized zones showed fluctuating growth and was distributed in the central part; the area of main agricultural production zones generally increased, distributed in patches in the central region; while ecological function zones showed a decreasing trend, mainly distributed in the northern and southern parts. The growth of urbanized and agricultural production zones encroached upon ecological function zones. Spatial aggregation of land use was consistently higher in the central region than in the north and south throughout the study period. (2) From 1990 to 2018, high-quality and low-quality ecological environment zones in Gaochang District decreased, while higher-quality and lower-quality zones increased. Conversion of unused land to grassland was the primary driver of ecological environment improvement, while conversion of grassland to unused land was the main cause of ecological degradation in some areas. The central region showed a trend of ecological environment quality improvement, while the northern and southwestern regions exhibited degradation trends. However, the overall degradation trend was slightly smaller than the improvement trend, indicating that the ecological environment quality is developing favorably. This study provides a reference for coordinating sustainable land resource utilization and ecological environment protection in Gaochang District.

Key words: land use function transformation; ecological environment effect;

Gaochang District

Introduction

Land is the spatial carrier of major socio-economic activities and constitutes an important component of global environmental change and sustainable development research [1]. The concept of land use transition was proposed by British geographer Grainger [2], inspired by the forest transition hypothesis. Long Hualou introduced this concept into China in the early 21st century [3]. Land use transition refers to the transformation process of regional land use morphology corresponding to socio-economic development stage transitions, driven by socio-economic changes and innovation [4]. Current research on land use transition primarily focuses on theoretical frameworks [5], research frameworks [6], recessive land use morphology [7], ecological effects [8], and social effects [9] of land use transition. Among these, studies on the ecological environmental effects of land use transition mainly fall into two categories: (1) research on ecosystem service value assessment or landscape ecological patterns at provincial [10-12] and watershed scales [13-14]; and (2) studies on driving factors of land use transition in economically developed regions [15-16]. However, quantitative research on land use function transformation and its ecological environment quality changes in ecologically fragile areas remains scarce, with limited typicality and reference value of existing studies.

Turpan's Gaochang District has experienced rapid economic growth in recent years, with continuous population concentration in the urban center and persistent increase in construction land demand. Simultaneously, as a desert oasis, it belongs to a typical "ecologically fragile area with relatively backward economy." Therefore, this study utilizes four phases of land use remote sensing monitoring data (1990, 2000, 2010, and 2018) based on a $5 \text{ km} \times 5 \text{ km}$ grid scale. Starting from the three dominant functional zones—urbanized areas, main agricultural production areas, and ecological function areas—we employ land use transition matrix and kernel density estimation to investigate land use transformation characteristics in Gaochang District from 1990 to 2018. We also conduct a quantitative analysis of the ecological environmental effects of land use transformation using regional eco-environmental quality index and ecological contribution rate methods, aiming to provide a reference for coordinating sustainable land resource utilization and ecological environment protection in Gaochang District.

1.1 Study Area Overview

Gaochang District of Turpan City is located at the intersection of eastern, southern, and northern Xinjiang, serving as a transportation hub and important node on the Silk Road Economic Belt. The district covers a total area of 13,650.55 km^2 , governing seven townships, two towns, two farms, and one subdistrict office (excluding Bingtuan 221st Regiment). Primarily focused on crop cultivation, it is a main agricultural production area on the northern slope of the

Tianshan Mountains, famous for grapes, Hami melons, and cotton. It is also an important ecological function balance area for socio-economic development under the “Belt and Road” initiative, holding significant ecological strategic status [17]. Gaochang District represents a typical fragmented oasis in China’s arid regions, characterized by scarce water resources and harsh natural environments. In recent years, tourism and industrial development have exacerbated the imbalance between ecological environment and economic development, leading to a series of ecological problems. By the end of 2018, Gaochang District had a total population of 290,302 and a per capita GDP of 32,400 RMB.

1.2 Data Sources and Processing

This study employs land use data for 1990, 2000, 2010, and 2018 with a spatial resolution of 30 m $\times$ 30 m, derived from the multi-temporal land use/cover change remote sensing monitoring dataset published by the Resources and Environmental Science Data Center of the Chinese Academy of Sciences [18]. The integrated classification system includes 6 first-level land use types and 25 second-level types. Following the ecological environment indices for different second-level land use types proposed by Li Xiaowen et al. [19], we assign ecological environment indices to second-level land use types using area-weighted methods combined with field surveys in the study area (Table 1). Socio-economic data were obtained from the *Turpan Statistical Yearbook* [20] and field investigations.

Table 1 Classification of dominant land use functions and eco-environmental quality indices

Dominant Function Classification	Second-level Land Use Classification	Eco-environmental Index
Urbanized Area	Urban land, other construction land	0.20
Main Agricultural Production Area	Paddy field, dry land, rural residential land	0.30
Ecological Function Area	Dense forest, shrubland, sparse forest, other forest land	0.80
	High-coverage grassland, medium-coverage grassland, low-coverage grassland	0.60
	River channel, lake, reservoir/pit, permanent glacier/snow, beach, tidal flat	0.90
	Sandland, Gobi, saline-alkali land, swamp, bare land, bare rock land, other unused land	0.05

1.3.1 Land Use Transition Analysis

(1) Land Use Transition Matrix

The land use transition matrix intuitively presents the quantity and direction of mutual conversion among land use types, reflecting the structural characteristics of land use changes and transfer directions between types [21]. Its expression is:

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix}$$

where S_{ij} is the transition probability from land type i to j ; n is the number of land use types; i and j represent land use types before and after transition, respectively.

(2) Land Use Kernel Density Estimation Model

Kernel density estimation can intuitively characterize the spatial distribution pattern changes and agglomeration intensity of land use transition in Gaochang District. Higher kernel density values indicate greater spatial distribution density and stronger agglomeration [22]. The kernel density estimation expression is:

$$f(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right)$$

where $f(x)$ is the kernel density estimation at location x ; n is the number of data points; h is the bandwidth (search radius); K is the kernel function; and $x - x_i$ is the distance from estimation point x to event x_i .

(3) Regional Eco-environmental Quality Index

Considering the eco-environmental indices of the three dominant functional zones (urbanized areas, main agricultural production areas, and ecological function areas) in Gaochang District, the regional eco-environmental quality index quantitatively represents the overall ecological environment quality of a region [23]. Its expression is:

$$EV = \sum_{i=1}^N \frac{A_i}{TA} \times R_i$$

where EV is the eco-environmental quality index of the study area; A_i is the area of land use type i (km^2) in the region; TA is the total area of the region (km^2); R_i is the eco-environmental index of land use type i ; and N is the total number of land use types.

(4) Ecological Contribution Rate

The ecological contribution rate of land use transition refers to the change in regional eco-environmental quality caused by the transformation of a specific land use type. It quantifies the impact of mutual conversion among land types on regional eco-environmental quality, facilitating identification of dominant factors causing regional environmental changes [24]. Its expression is:

$$LEI = \frac{LE_1 - LE_0}{LA/TA}$$

where LEI is the ecological contribution rate of a specific land use change type; LE_0 and LE_1 are the eco-environmental quality indices assigned to a land type at the beginning and end of the change period, respectively; LA is the changed area of that land type (km^2); and TA is the total area of the study region (km^2).

1.3.2 Regional Eco-environmental Quality Analysis

The spatiotemporal differentiation of Gaochang District's eco-environmental quality index can be expressed through the eco-environmental quality index. Using ArcGIS 10.2 software, we conducted comparative analyses with grid sizes of $5 \text{ km} \times 5 \text{ km}$, $10 \text{ km} \times 10 \text{ km}$, $500 \text{ m} \times 500 \text{ m}$, and $50 \text{ m} \times 50 \text{ m}$. Considering the study area size, research requirements, and computational efficiency, we determined through repeated testing that the $5 \text{ km} \times 5 \text{ km}$ vector grid was the optimal research unit. Kriging interpolation was used to generate eco-environmental quality distribution maps, which were classified into five quality zones using natural breaks: low quality, relatively low quality, medium quality, relatively high quality, and high quality [25].

2.1.1 Spatial Pattern and Change Characteristics of Land Use Types

The ecological function area in Gaochang District has the largest area, followed by the main agricultural production area, with the urbanized area being the smallest (Table 2). From 1990 to 2018, the overall trend of land use transition showed fluctuating growth in urbanized areas, overall increase in main agricultural production areas, and rapid decrease in ecological function areas.

Table 2 Statistics of leading functional land area in Gaochang District during 1990–2018 (km^2)

Year	Urbanized Area	Main Agricultural Production Area	Ecological Function Area
1990	39.89	333.50	13,277.16
2000	40.05	537.91	13,072.59
2010	79.67	515.47	13,055.41
2018	120.56	515.47	13,014.52

From the temporal perspective: (1) Urbanized area showed an increasing trend, with urban land increasing year by year and industrial/mining land first decreasing then increasing significantly. From 2000 to 2010, industrial/mining land area increased by 39.89 km², 40.05 times the increment from 1990 to 2000, mainly due to the settlement of several well-known industrial and mining enterprises since 2000, leading to simultaneous growth in both industrial/mining and urban land. (2) Main agricultural production area experienced a process of substantial growth followed by slight reduction, primarily influenced by changes in agricultural land area, which grew from 333.50 km² to 537.91 km² then decreased to 515.47 km². These changes were mainly driven by agricultural industrial structure adjustments and closely related to reductions in grassland and unused land. During the study period, agricultural land increased by 181.97 km² and rural residential land increased by 2 km², showing an overall increasing trend. (3) In ecological function areas, water area increased annually while other land types decreased. Overall, ecological function area decreased by 267.31 km², including 52.80 km² reduction in forest land, 106.75 km² reduction in grassland, and 124.62 km² reduction in unused land, while water area increased by 2 km². Forest land reduction was mainly due to illegal reclamation/deforestation and partial conversion to agricultural land. Grassland increase from 2000 to 2010 primarily came from unused land and some land returned from cultivation to forest/grassland. Unused land showed a continuous decreasing trend overall. Water area changes were mainly attributed to substantial water conservancy facility construction and improvements since 2000, coupled with enhanced water-saving awareness among farmers. The expansion of Aiding Lake's surface area also contributed to increased water area [26].

Spatially (Fig. 2), ecological function areas were most widely distributed; main agricultural production areas were distributed in patches in central Gaochang District; urban land was mostly distributed in Gaochang Subdistrict; industrial/mining land was distributed in Qiquanhu Town, Putaogou Subdistrict, and Ya'er Town. From 1990 to 2000, land use transition changes were minor, mainly involving increased agricultural land in Sanbao Township and decreased grassland in Qiatkale Township (Fig. 2). The year 2000–2010 saw the most significant changes, with agricultural land increasing most substantially (194.45 km²), primarily in the southern part of Hongliuhe Horticultural Farm and central Aidinghu Town; urbanized areas were point-distributed in central Gaochang District. Statistical analysis of functional land distribution across townships showed that unused land was mostly distributed in Qiatkale Township; grassland was mainly in Hongliuhe Horticultural Farm and townships of Qiquanhu, Shengjin, Erbao, Sanbao, and Ya'er; industrial/mining land increased mainly in Daheyuan Town, Ya'er Town, and Putaogou Subdistrict; urban land increased primarily in Daheyuan Town; water area increased in northern Qiatkale Township; forest land decreased in Hongliuhe Horticultural Farm, Erbao Township, and northern Qiatkale Township; water bodies were sporadically distributed in central Gaochang District and southern Qiatkale Township; forest land was mainly distributed in Hongliuhe Horticultural Farm, Erbao Township,

and Putaogou Subdistrict; rural residential land was distributed in central Aidinghu Town, Gaochang Subdistrict, Laojie Subdistrict, Yuanzhong Farm, and Erbao Township; agricultural land was mainly distributed in Erbao, Sanbao, Aidinghu Town, and Putao Town. From 2010 to 2018, industrial/mining land increased mainly in Ya' er Town, Putaogou Subdistrict, and Qiquanhu Town; grassland increased in Ya' er Town and Qiatkale Township; water area increased in Qiatkale Township; rural residential land increased in Ya' er Town, Aidinghu Town, and Qiatkale Township; agricultural land decreased in Aidinghu Town, Putao Town, and Yuanzhong Farm; unused land decreased in Ya' er Town, Putaogou Subdistrict, and Qiquanhu Town, mainly due to new construction projects and housing projects for improving people's livelihoods that converted unused land to industrial/mining and urban land.

2.1.2 Transfer Situation and Quantitative Characteristics of Land Use Types

Table 3 shows the area transfer flows of leading functional land types in the study area. From 1990 to 2000, land transition scale was small, with the largest transfer to agricultural land (13.52 km²), mainly from grassland (6.26%) and forest land (0.71%). Among all land type changes, grassland showed the most obvious circulation changes (13.52 km²), mainly flowing to agricultural land, forest land, water bodies, and rural residential land. This is because the grassland ecosystem, as a transition zone between cultivated land and desert, has low system stability and fragile ecological environment.

From 2000 to 2010, the frequency and magnitude of land type transfers increased significantly, dominated by grassland outflow (194.45 km²), unused land outflow (107.26 km²), and forest land outflow (52.78 km²). The main inflows were agricultural land (194.45 km²) and industrial/mining land (79.67 km²). Agricultural land was mainly converted from unused land (39.89 km², 18.91%), grassland (12.00%), and forest land (5.63%). Industrial/mining land was mainly converted from unused land (90.23%) and rural residential land (4.08%). As a typical arid oasis environment, unused land accounted for over 65.94% of all land type changes in Gaochang District under water scarcity conditions. Unused land was the largest source of land type transformation, and its reduction was mainly influenced by economic development, primarily converting to industrial/mining land and partially to agricultural land.

From 2010 to 2018, unused land outflow (46.41 km²) and agricultural land outflow (22.44 km²) were most prominent, while industrial/mining land inflow was most significant (40.05 km²), mainly from unused land (65.94%), grassland (3.01%), and agricultural land (0.87%).

2.2 Land Use Spatial Aggregation Analysis

Kernel density estimation analysis reveals the temporal evolution of land use spatial aggregation characteristics during the study period. Using ArcGIS 10.2,

we generated $5\text{ km} \times 5\text{ km}$ grids with land use area attributes, then applied zonal statistics to extract land use information for each grid, followed by spatial analysis tools for kernel density analysis.

Based on land use area distribution in Gaochang District, kernel density analysis reveals the spatial distribution pattern (Fig. 3). Land use kernel density mainly aggregated in central Ya' er Town, Gaochang Subdistrict, Laojie Subdistrict, Putaogou Subdistrict, Putao Town, Yuanzhong Farm, Aidinghu Town, and central Qiatkale Township. The maximum kernel density values were 109.41 km^2 , 103.56 km^2 , 109.59 km^2 , and 120.56 km^2 for the four periods, respectively. In 1990, slight aggregation occurred in Daheyan Town, Hongliuhe Horticultural Farm, Erbao Township, and Sanbao Township. By 2000, kernel density in Qiquanhu Town and Shengjin Township grew rapidly, with enhanced aggregation. Overall, spatial kernel density changes were not substantial. The large spatial aggregation difference between northern and southern Gaochang District was due to significant topographic variations—the central region has lower elevation with more township distributions, while the northern townships (Hongliuhe Horticultural Farm, Qiquanhu Town, Shengjin Township) have higher northern terrain. Only Qiatkale Township exists in the south. Uneven economic development across townships and different driving factors such as terrain, transportation, and policies resulted in distinct land use spatial aggregation patterns. From an agglomeration perspective, northern aggregation was significantly higher in 2018 than in 1990, due to increased industrial/mining and agricultural land in Daheyan Town, Hongliuhe Horticultural Farm, Qiquanhu Town, and Shengjin Township, which drove local economic growth and increased kernel density and spatial aggregation.

2.3.1 Spatiotemporal Evolution of Eco-environmental Quality

The spatiotemporal differentiation of Gaochang District's eco-environmental quality index can be expressed through the eco-environmental quality index. Using ArcGIS 10.2 with $5\text{ km} \times 5\text{ km}$, $10\text{ km} \times 10\text{ km}$, $500\text{ m} \times 500\text{ m}$, and $50\text{ m} \times 50\text{ m}$ grids for comparative analysis, and considering the study area size, research requirements, and computational efficiency, we determined through repeated testing that the $5\text{ km} \times 5\text{ km}$ vector grid was optimal. Kriging interpolation generated eco-environmental quality distribution maps, classified into five quality zones using natural breaks: low quality, relatively low quality, medium quality, relatively high quality, and high quality [25].

Overall, the eco-environmental quality index was relatively high in northern and central Gaochang District and low in the south (Fig. 4), mainly because the north and center have larger areas of grassland and agricultural land with higher eco-environmental indices, while the south is dominated by unused land with lower indices. From 1990 to 2018, high-quality and low-quality zones decreased while relatively high-quality and relatively low-quality zones increased: (1) In the north, high-quality and low-quality zones gradually decreased while relatively high-quality and relatively low-quality zones increased, mainly because

the eco-environmental quality improvement from increased unused land area exceeded the degradation from decreased grassland area. (2) In the central region, high-quality zones increased because the eco-environmental quality improvement from increased agricultural land exceeded the degradation from increased urban and industrial/mining land. (3) In the south, high-quality zones gradually decreased while low-quality zones increased, mainly because eco-environmental quality degradation from decreased grassland area exceeded improvement from increased unused land and Aiding Lake water area.

2.3.2 Main Land Use Types Affecting Eco-environmental Quality

Regional ecological environment changes often involve two opposite phenomena—improvement and degradation—which can offset each other in index calculations, making the overall ecological quality index appear relatively stable. Therefore, stable ecological environment indices do not necessarily mean no environmental changes have occurred. It is necessary to calculate and analyze ecological contribution rates separately.

Table 4 shows the main land use transitions leading to ecological environment improvement: (1) Conversion of unused land to grassland (602.89 km²) accounted for 87.56% of the ecological contribution rate. Simultaneously, conversion of unused land to agricultural land, water bodies, and forest land also contributed positively to improving Gaochang District's eco-environmental quality. (2) Conversion of agricultural land to grassland, combined with the first factor, accounted for 98.77% of the ecological contribution rate.

Table 5 shows the main land use transitions causing ecological environment degradation: Conversion of grassland to unused land (659.95 km²) accounted for 84.41% of the ecological contribution rate, representing an important cause of ecological environment degradation in some areas of Gaochang District. Additionally, conversions of grassland to agricultural land, forest land to agricultural land, water bodies to unused land, and forest land to unused land accounted for 6.27%, 4.14%, 1.05%, and 1.02% of the ecological contribution rate, respectively, cumulatively reaching 12.48%.

Combined with the above analysis: (1) In northern Gaochang District from 1990 to 2018, grassland converted to unused land, agricultural land, and industrial/mining land, with enhanced kernel density and spatial aggregation, causing ecological environment quality to shift from high-quality to relatively high-quality zones and the eco-environmental quality index to decrease. (2) In the central region, unused land converted to agricultural land, grassland, and industrial/mining land, maintaining high kernel density and strong spatial aggregation, with expanded high-quality and relatively high-quality zones and increased eco-environmental quality index. (3) In southwestern Gaochang District, grassland converted to unused land and industrial/mining land, with decreased spatial aggregation, causing ecological environment quality to decline from high to relatively high, medium, and relatively low levels, indicating a

certain degree of degradation.

3 Conclusions

Through analysis of spatial patterns and change characteristics, transfer situations and quantitative features, spatial aggregation characteristics, spatiotemporal evolution of eco-environmental quality, and main land use types affecting eco-environmental quality in Gaochang District, we found that land use transition exhibited spatiotemporal heterogeneity and significantly impacted ecological environment quality. The main conclusions are:

- (1) From 1990 to 2018, urbanized land area in Gaochang District showed fluctuating growth, point-distributed in the central region; main agricultural production land area generally increased, patch-distributed in the central region; ecological function land area showed a decreasing trend, mainly distributed in the north and south. The growth of urbanized and agricultural production land encroached upon ecological function land. Spatial aggregation of land use was consistently higher in the central region than in the north and south. In the north, increased industrial/mining and agricultural land drove local economic growth, increased kernel density, and enhanced spatial aggregation.
- (2) From 1990 to 2018, high-quality and low-quality ecological environment zones in Gaochang District decreased, while relatively high-quality and relatively low-quality zones increased. Conversion of unused land to grassland was the main reason for ecological environment improvement, while conversion of grassland to unused land was the main cause of ecological degradation in some areas. The central region showed a trend of ecological environment quality improvement, while the northern and southwestern regions showed degradation trends. However, the overall degradation trend was slightly smaller than the improvement trend, and the ecological environment quality is developing favorably.

Drawing on existing research results, this study classified land use types into urbanized areas, main agricultural production areas, and ecological function areas based on dominant functions. However, functional overlaps and intersections remain, and the proposed land extraction scheme requires further refinement to accurately quantify the proportion of various land types. Gaochang District should intensify rational development of unused land in the coming years and plan for eco-tourism development. As a main agricultural production area on the northern slope of the Tianshan Mountains, it can also develop ecological agriculture and explore a new urbanization path with ecological agriculture and eco-tourism as main functions to address issues of excessive land resource development and degradation. Therefore, land use transition and structural optimization will become the focus of future research.

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