

Evolution of Oasis-Urban-Desert Landscape and Its Eco-environmental Effects in Arid Regions: Postprint

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Abstract

Oases, towns, and deserts are important landscape types in the inland river basins of arid regions. With the socio-economic development of river basins, ecological and environmental issues in arid regions have become increasingly prominent. This study selects the oasis-town-desert landscape combination within the Heihe River Basin—the second largest inland river in the arid region of northwestern China—as the research object. Using landscape transition kernel density and landscape structure indices, we analyze the spatiotemporal patterns and transition characteristics of oasis-town-desert landscapes in the Heihe River Basin during 2000–2020. Employing the Multivariate Regression Tree (MRT) model, we explore the trade-off and synergy relationships among the three types of landscape transitions. Based on the Remote Sensing Ecological Index (RSEI) and ecological contribution rate of landscape transitions, we reveal the eco-environmental effects of oasis-town-desert landscape transitions. The results show that: (1) The Heihe River Basin is extensively covered by deserts, with oases concentrated only along the river channels in the middle and lower reaches, while towns occupy the smallest area proportion and their spatial distribution and scale structure are closely associated with oases; (2) The oasis-town-desert landscape transitions in the Heihe River Basin can be summarized as: an agriculture-dominated period (2000–2005), a rapid industrial development period (2005–2015), and a development transition coordination period (2015–2020); (3) Temperature, GDP, altitude, and precipitation are the main factors influencing the trade-off and synergy relationships among oasis-town-desert landscape transitions; (4) During 2000–2020, basin landscape transitions were dominated by positive eco-environmental effects, with cropland expansion being the leading factor for positive effects; cropland degradation, water body reduction, and grassland degradation were the main factors bringing negative effects. The research results can provide theoretical guidance for implementing

ecological protection and high-quality development in inland river basins of arid regions.

Full Text

Landscape Evolution and Eco-Environmental Effects of Oasis-Urban-Desert in Arid Regions

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Abstract

Oasis, urban, and desert landscapes represent critical landscape types in the inland river basins of arid zones. As socio-economic development accelerates in these basins, ecological and environmental problems have become increasingly prominent. This study examines the oasis-urban-desert landscape complex in the Heihe River Basin, the second largest inland river in the arid northwest of China. Using landscape transition kernel density and landscape structure indices, we analyzed the spatio-temporal patterns and transition characteristics of the oasis-urban-desert mosaic. A multivariate regression tree (MRT) model was employed to explore the trade-off and synergy relationships among the three landscape transitions, while the remote sensing ecological index (RSEI) was used to reveal the eco-environmental effects of these transitions. The results show that: (1) Deserts are widespread throughout the Heihe River Basin, oases are concentrated along the middle and lower reaches of the river corridor, and urban areas account for the smallest proportion, with their spatial distribution and scale structure closely associated with oases. (2) The oasis-urban-desert landscape transitions in the Heihe River Basin can be summarized into three periods: the agricultural activity-dominated period (2000–2005), the rapid industrial development period (2005–2015), and the coordinated development transformation period (2015–2020). (3) During 2000–2020, landscape transitions produced predominantly positive eco-environmental effects, with farmland expansion being the dominant factor for positive effects, while farmland degradation, water area reduction, and grassland degradation were the main factors causing negative effects. Temperature, altitude, and precipitation are the main factors affecting the trade-off and synergy relationships among oasis-urban-desert landscape transitions. (4) These findings provide theoretical guidance for implementing ecological protection and high-quality development strategies in inland river basins of arid zones.

Keywords: Oasis-urban-desert; landscape pattern; spatial-temporal evolution; eco-environmental effect; Heihe River Basin

Introduction

Since the Earth entered the Anthropocene, various natural ecological processes have been profoundly altered by human activities, triggering a series of ecological and environmental problems that challenge global ecosystem security. Landscape pattern evolution represents the integrated outcome of regional human activities and natural processes. In the inland river basins of northwest China's arid zones, characterized by special natural ecological conditions and extreme environmental vulnerability, desert, oasis, and urban areas constitute important landscape types. Desert serves as the matrix landscape, occupying an absolutely dominant area proportion in arid regions. Oasis, with significantly higher vegetation coverage and productivity than surrounding deserts, represents a unique landscape type in arid zones. Urban areas, with the densest population and most developed economy, represent the landscape type with more complete socio-economic functions. In recent years, rapid economic development and intensified human activities in arid zones, particularly oasis expansion and urbanization, have exacerbated contradictions among desert, oasis, and urban development, endangering watershed ecological security and threatening the stability and sustainable development of inland river basin ecosystems.

The interrelationship between landscape pattern and process constitutes the core issue in landscape ecology research. Scholars have employed various methods to study the relationship between landscape pattern and process in arid zones, revealing oasis and desert expansion or retreat processes. For instance, complex network methods and redundancy analysis have been used to analyze oasis transformation processes and stability in the Tarim Basin, thereby revealing the driving forces behind oasis changes. Other researchers have divided oases into natural and artificial oasis zones and constructed models to determine appropriate oasis scales and irrigation areas. Some have focused on desert-oasis ecotones, studying the impact mechanisms of land use change on ecosystem services and revealing different landscape stability levels and their maintenance mechanisms. Oasisization and desertification represent two important geographical processes in inland river basins of arid zones, developing in opposite directions but closely related. Urbanization plays a key role in promoting integrated urban-rural development and comprehensively advancing rural revitalization in China. Quantitatively revealing the eco-environmental effects of landscape pattern changes at the watershed scale is of great significance for ecosystem stability and sustainable development in inland river basins.

The trade-offs and synergies among multiple elements have been studied using correlation analysis, spatial autocorrelation analysis, and constrained line fitting. Multivariate regression tree (MRT), an extension of univariate regression trees, is primarily used to study relationships between species distribution and environmental factors. MRT can determine split nodes based on indicator gradients of independent variables, dividing the spatial range defined by dependent variables into basically homogeneous categories without manual classification, making it more objective and scientific. The model can input one or more de-

pendent variables simultaneously, making it suitable for revealing trade-off and synergy relationships among multiple elements and their driving factors. For example, Ndong et al. innovatively applied MRT to analyze trade-off and synergy effects between multiple ecosystem services and their drivers, while Lyu et al. used it to explore impact thresholds of different landscape pattern indices on ecosystem service trade-offs and synergies. However, existing studies mostly treat oases, deserts, or oasis-desert transition zones as independent units, focusing on their internal stability and spatio-temporal variability. Research treating the “oasis-urban-desert” as a landscape pattern in inland river basins of arid zones remains scarce. Therefore, this study employs MRT to analyze the trade-off and synergy relationships in the transformation of the “oasis-urban-desert” landscape combination and explores its spatial driving mechanisms, aiming to expand MRT application scenarios.

The Heihe River Basin, with its long history of agricultural oasis development, serves as an important commodity grain, vegetable, and seed production base in western China, exhibiting overall characteristics of “mainly stable with local changes” in oasis landscapes. In recent years, population growth and accelerated urbanization have rapidly expanded agricultural oases and urban areas in the middle reaches, gradually replacing natural oases with artificial ones and causing a series of ecological security problems in the basin. Based on the “pattern-process” framework, this study focuses on the typical “oasis-urban-desert” landscape pattern combination in arid zones, using landscape transition information entropy, equilibrium, dominance, and other indices combined with landscape transition kernel density analysis and multivariate regression tree models to reveal the landscape transition patterns and eco-environmental effects of the Heihe River Basin. The findings aim to provide theoretical support for ecosystem management in inland river basins of arid zones.

1 Data Sources and Research Methods

1.1 Study Area Overview

The Heihe River is China’s second largest inland river, located in the transition zone between the Qinghai-Tibet Plateau and the Inner Mongolia Plateau. It originates from the northern foothills of the Qilian Mountains in Qinghai Province, flows through Qinghai, Gansu, and Inner Mongolia, and terminates in the East and West Juyan Lakes in Ejin Banner, Inner Mongolia. The main stream extends approximately 821 km with a drainage area of about 13×10^4 km². The basin features a typical arid climate, with an average annual precipitation of 400 mm and average annual potential evapotranspiration of 1600 mm. The basin can be divided into three geomorphic units from south to north: the Qilian Mountains in the upper reaches, the Corridor Plain in the middle reaches, and the Alxa Plateau in the lower reaches. The upper reaches above Yingluoxia feature high, steep terrain with cold, humid climate. Modern glaciers develop on mountains above 4000 m, and meltwater from these glaciers accounts for approximately 10% of the total water volume. The upper

mountainous area serves as the runoff generation and water conservation zone, primarily engaged in pastoralism with relatively high per capita income. The middle reaches between Yingluoxia and Zhengyixia are located in the Hexi Corridor, characterized by flat terrain, arid climate, and ecological fragility. This area concentrates the most extensive and economically developed oases in the entire basin, with major towns distributed across various oases in the middle reaches. The lower reaches below Zhengyixia form an open, flat basin, mostly covered by deserts, sand, and gobi, except for the Ejin Oasis, with an extremely arid climate.

1.2 Data Sources and Processing

The main data sources used in this study are listed in . Since the latest GDP spatial distribution data was only available until 2017, this study first extracted the proportion of GDP value for each grid cell in 2017 relative to the total GDP of its administrative county. This proportion was used as a weight and multiplied by the total GDP value of the administrative county where the grid cell was located in 2020 to obtain the GDP spatial distribution grid data for the study area. The processed data had a resolution of 1 km \times 1 km. Compared with previous data, the relative error after spatialization ranged from 0.04% to 4.47%, with a minimum error, indicating good data processing results that meet research requirements.

For data with low precision or missing time series, an image super-resolution method was used for synthesis to obtain high-precision complete time series data. After processing, the data precision was unified to 1 km \times 1 km resolution. The specific model is as follows:

$$y = kx + b + \delta$$

where y represents the standardized high-precision real data; x represents the standardized low-precision reference data after interpolation; k and b are coefficients; and δ is the random error. Using high-precision data, the values of k and b were calibrated by the least squares method, and the model could be established as:

$$\hat{y} = kx + b$$

where \hat{y} is the reference value of high-precision data established for model inversion.

1.3 Research Methods

1.3.1 Oasis-Urban-Desert Landscape Classification

This study referred to the 2015 oasis distribution dataset and oasis reconstruction vector data for the Heihe River Basin (Table 1) and divided the oasis area of the Heihe River Basin

into seven zones from south to north: the Shandan-Minle piedmont alluvial fan oasis, the Ganzhou oasis, the Linze-Gaotai oasis, the Jiuquan oasis, the Jinta-Dingxin oasis, and the Ejin oasis. From the land use map, cultivated land, forestland, grassland, water area, and marshland within these seven zones were extracted as oasis landscapes. The extraction results were compared with oasis reconstruction data, and the relative errors were all within 5%. Sandy land, gobi, saline-alkali land, low-coverage grassland, bare land, bare rock land, and other unused land in the middle and lower reaches were extracted as desert landscapes. Urban land, rural residential areas, and other construction land were extracted as urban landscapes. The oasis-urban-desert landscape classification system is shown in .

1.3.2 Oasis-Urban-Desert Landscape Transition Analysis Landscape Transition Matrix. The transition matrix can be used to describe state changes in multi-component systems and intuitively shows the mutual conversion among various land use types. The calculation formula is as follows:

$$Trans_{i,j} = \begin{pmatrix} trans_{1,1} & \cdots & trans_{1,n} \\ \vdots & \ddots & \vdots \\ trans_{p,1} & \cdots & trans_{p,q} \end{pmatrix}$$

where $Trans_{i,j}$ represents the transition matrix from time point i to time point j ; $trans_{p,q}$ represents the area of land type p converted to land type q during this process. The sum of elements in each row represents the total area of that land type at time point i , the sum of elements in each column represents the total area of that land type at time point j , and the sum of all elements represents the total area of the study region.

Landscape Transition Kernel Density. Kernel density analysis is a method for spatial attenuation visualization of point or line data. This study used landscape transition kernel density to reveal the spatio-temporal characteristics of landscape transitions in the Heihe River Basin. The calculation formula 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 value at location x ; n is the sample size; h is the search radius; K is the kernel density weight value; and $x-x_i$ represents the distance between the estimated point x and sample point x_i .

Using a 2 km×2 km grid as the basic unit, the area of landscape transition within each grid cell was calculated, and the landscape transition information for each grid was extracted to point data. The kernel density results of landscape transitions in the study area were obtained using ArcGIS 10.2 software. Kernel density analysis identifies landscape transition hotspots, with density attenuating from the core area of land transfer to the periphery, reflecting the

magnitude of influence of landscape transitions diffusing from hotspot areas to surrounding regions. The kernel densities of landscape transitions to desert, oasis, and urban landscapes were defined as desertification intensity, oasisization intensity, and urbanization intensity, respectively.

Landscape Information Entropy, Equilibrium, and Dominance. Landscape transition structure indices can effectively reveal the degree of order and evolution direction of land use in different landscape processes. This study used landscape information entropy, equilibrium, and dominance to reveal the internal structural characteristics of landscape transitions in the Heihe River Basin. Landscape information entropy reflects the diversity and orderliness of regional land use, representing the degree of human disturbance to the land system to some extent. Landscape equilibrium and dominance reflect differences in area size among various land use types, characterizing the spatial pattern of land use structure. Landscape equilibrium focuses on measuring whether the development of various land use types is balanced, while landscape dominance indicates whether there is a dominant land use type in the study area. These complementary indices enable more objective and comprehensive evaluation of the evolution trend of typical landscape systems. The calculation formulas are:

$$H = - \sum_{i=1}^n P_i \ln P_i = - \sum_{i=1}^n \left(\frac{A_i}{\sum_{i=1}^n A_i} \right) \ln \left(\frac{A_i}{\sum_{i=1}^n A_i} \right)$$

$$J = \frac{H}{\ln(n)} = \frac{- \sum_{i=1}^n P_i \ln P_i}{\ln(n)}$$

$$D = 1 - J = 1 + \sum_{i=1}^n \frac{P_i \ln P_i}{\ln(n)}$$

where H is landscape information entropy; P_i is the proportion of land use area (which can be understood as probability); A_i is the area of land use type i ; n is the number of land use types; J is landscape equilibrium; D is landscape dominance; and P_e is the probability in a completely equilibrium state.

1.3.3 Trade-off and Synergy Effects of Landscape Transitions This study used the MRT model to analyze trade-off and synergy relationships among oasis-urban-desert landscape transitions in the Heihe River Basin and to determine the environmental driving mechanisms of spatial differences in these effects. The goal of MRT is not to establish regression relationships between dependent and independent variables but to use independent variables as classification nodes, employing binary splitting to divide the spatial region defined by dependent variables into basically homogeneous categories, with cross-validation determining the classification results. Generally, the result with the minimum cross-validation error within one standard deviation range is retained. MRT

can effectively simulate non-linear relationships and threshold effects among multiple natural elements.

Based on principles of scientificity, rationality, and accessibility, seven factors were selected as driving factors for trade-off and synergy relationships of landscape transitions: population density, GDP, annual precipitation, average annual temperature, altitude, slope, and distance to water. These driving factors were used as independent variables, and the cumulative values of oasisization, urbanization, and desertification intensity for three periods were used as dependent variables for multivariate regression tree analysis. Since landscape transition processes outside oases in arid inland river basins are not intense, to avoid excessive null values in watershed statistics, most null value data were removed when statistically clustering landscape transition intensities to maximize reflection of commonalities within each cluster and differences between clusters. This study selected five clustering results as the final simulation results to maximize the commonalities within categories and differences between categories. The analysis was implemented using the “mvpart” package in R software.

1.3.4 Analysis of Eco-Environmental Effects of Landscape Transitions Landscape transition processes are often accompanied by changes in eco-environmental quality. In recent years, with the vigorous development of remote sensing technology, eco-environmental quality assessment has become increasingly sophisticated, particularly through the remote sensing ecological index (RSEI). Using principal component analysis, RSEI integrates four indicators—greenness, wetness, heat, and dryness—to comprehensively assess regional eco-environmental quality. This study used RSEI to reflect the eco-environmental quality of landscapes and employed the ecological contribution rate of landscape transition (LEI) to characterize the eco-environmental effects of landscape transitions, including both negative and positive effects. The calculation formula is:

$$LEI = \frac{LE_1 - LE_0}{A_t} \times 100\%$$

where LEI is the ecological contribution rate of landscape transition; LE_0 and LE_1 represent the remote sensing ecological indices of the landscape before and after change, respectively; A_t is the area of changed landscape; and A is the total area of the study region.

2 Results

2.1 Spatial Distribution Pattern of Oasis-Urban-Desert Landscapes in the Heihe River Basin

As shown in [Figure 2: see original paper], desert is the most widely distributed landscape type in the Heihe River Basin, accounting for more than 85% of

the total watershed area and widely distributed in the northeastern part of the middle reaches and the lower reaches. Oases are mainly distributed in the middle and lower reaches of the river, with the middle reaches being the largest and most concentrated oasis area in the basin. Urban areas account for the smallest proportion (0.65%), and their spatial distribution and scale are closely associated with oases. Large-scale towns are mostly distributed in larger oases or water-rich areas, particularly in the middle reaches where oases have formed prefecture-level cities such as Zhangye, Jiuquan, and Jiayuguan, as well as county towns including Shandan, Minle, Linze, Gaotai, Sunan, and Jinta, representing the most rapidly urbanizing region in the basin.

2.2 Spatio-Temporal Characteristics of Oasis-Urban-Desert Landscape Transitions

2.2.1 Spatio-Temporal and Quantitative Characteristics As shown in [Figure 3: see original paper], landscape transitions in the Heihe River Basin from 2000 to 2020 exhibited fluctuating changes, with oasisization being the most intense process, followed by urbanization, and desertification being the least severe. The period from 2005 to 2015 was the most intense period for oasisization, desertification, and urbanization, with relatively severe land use conflicts and competition, active land transitions, and complex and diverse transition directions. From 2000 to 2020, the main body remained relatively stable, with oasis area increasing from 7,579 km² to 8,513 km², an expansion of 934 km². The middle reaches contain the largest and most concentrated oases in the basin, dominated by cultivated land and serving as an important grain base in western China. The lower reaches are dominated by forestland and grassland, mostly growing salt-tolerant and drought-resistant plants, particularly *Populus euphratica* forests, with the Ejin Oasis being an important pastoral area.

From 2000 to 2020, desertification processes were relatively weak in the Heihe River Basin, with hotspot areas located in the central part of Gaotai County in the middle reaches (2000-2005) and near the delta of the Ejin Oasis in the lower reaches (2010-2015). The oasisization process experienced a fluctuating pattern of “rapid development-slowdown-rapid development again.” Oasis expansion areas were mainly distributed near the river channels in the middle and lower reaches and on the periphery of oases. Urbanization accelerated significantly after 2010, mostly manifested as expansion of major towns outward. Urbanization and oasisization areas were concentrated in the middle reaches, developing along the east-west axis of the Lianhuo Expressway, National Highway 312, and the Lanxin Railway, as well as the diagonal axis of the Lanxin Railway’s second line. In the western part of the middle reaches, Jiuquan City and Jiayuguan City experienced continuous urban expansion, while in the eastern part, urban expansion centered on Zhangye City’s Binhe New District and the junction of Minle and Shandan counties. Additionally, urban construction centered on the Ceke Port in Ejin Banner in the lower reaches during 2015-2020 was a key focus of urbanization in this period.

2.2.2 Internal Characteristics of Landscape Transitions As shown in [Figure 4: see original paper] and the chord diagram, from 2000 to 2020, the increase in oasis area mainly came from the reclamation of sandy land, gobi, saline-alkali land, low-coverage grassland, and bare land, with reclamation areas of 343 km², 47 km², 94 km², 98 km², and 47 km², respectively. Desertification mainly came from sporadic degradation of cultivated land and reduction of water area, while urban development mainly occupied gobi and saline-alkali land.

From 2000 to 2005, landscape information entropy H and equilibrium J remained basically stable with a slight increase, while dominance showed a fluctuating trend of first decreasing and then increasing. The overall development speed of the watershed was slow, with low land use diversity and a single landscape transition direction, manifested mainly as agricultural oasis expansion dominated by cultivated land increase, with an expansion of 343 km². From 2005 to 2015, obvious inflection points appeared in the landscape structure indices of urban and desert landscapes. Urban information entropy H and equilibrium J increased rapidly, while dominance D decreased rapidly, with the opposite trend for desert landscapes. Meanwhile, watershed dominance D decreased significantly, with cultivated land, grassland, water area, urban land, and construction land increasing by 2,874 km², 287 km², 53 km², 120 km², and 298 km², respectively, mostly from the conversion of gobi, saline-alkali land, and bare land. Desertification was manifested as water area conversion to gobi or bare land. This period saw the most intense landscape transition process, with agricultural oasis expansion shifting from cultivated land expansion dominance to coordinated expansion of cultivated land, grassland, and water area. The dominance index within oases decreased significantly, and the land use structure became more coordinated and diversified, marking the beginning of rapid development.

From 2015 to 2020, landscape information entropy H and equilibrium J increased significantly for watershed, oasis, and urban landscapes, while dominance D decreased accordingly. After intense changes in the previous stage, desert landscape structure indices stabilized. Accelerated urbanization made landscape transition directions more diverse, with urban land, rural residential areas, and construction land increasing by 280 km², 104 km², and 113 km², respectively, mostly from the conversion of gobi, saline-alkali land, and bare land.

In summary, from 2000 to 2020, oasis expansion mainly came from the reclamation of sandy land, gobi, saline-alkali land, and bare land, followed by water area increase. Desertification trends were dominated by grassland degradation, cultivated land desertification, and water area reduction. The urbanization process mainly occupied cultivated land in the early stage, but after 2010, it increasingly occupied desert land such as gobi, medium-low coverage grassland, and saline-alkali land.

2.2.3 Stage Characteristics of Landscape Transitions As shown in [Figure 4: see original paper], the average landscape information entropy H of the Heihe River Basin from 2000 to 2020 was 0.57, remaining at a relatively high level and continuing to increase, while landscape equilibrium J increased and dominance D decreased, showing a fluctuating trend. Based on interannual variation trends of landscape structure indices, the landscape transition process in the Heihe River Basin can be divided into three stages:

The first stage is the agricultural activity-dominated period (2000–2005), during which the optimization trend of eco-environmental quality was most obvious, with 4,601 km² of level 3 eco-environmental quality land transferred in. The conversion of large areas of desert landscape to cultivated land increased the area of land with higher environmental quality, with significantly improved areas concentrated in the Shandan and Minle oases.

The second stage is the rapid industrial development period (2005–2015), during which rapid socio-economic development negatively impacted the watershed eco-environment. The transfer-in of level 3 eco-environmental quality land reached 3,274 km², while the transfer-out of level 4 eco-environmental quality land reached 3,274 km². Degraded areas were concentrated around the Ejin Oasis, the southwestern part of Jinta County, and the northeastern part of Ganzhou District. Urban expansion occupied some cultivated land and forestland, reducing high-quality habitat land and increasing human disturbance to the eco-environment, disrupting the overall ecological balance.

The third stage is the coordinated development transformation period (2015–2020), during which the eco-environmental quality of the Heihe River Basin improved again, with main improvement areas distributed in the middle reaches oasis area and along both sides of the river channels in the lower reaches.

2.3 Trade-off-Synergy Relationships and Environmental Driving Factors of Landscape Transitions

The MRT model quantitatively analyzed the trade-off and synergy relationships among the three landscape transition types in the Heihe River Basin and explored their environmental driving factors. The final classification had five hierarchical levels and five clusters, with a model simulation accuracy of $R^2 = 0.42$ and a standard error of $963.5 \times 10^{\{3\}}$. Qualitative analysis of the value ranges of landscape transition intensities in each cluster showed that among the seven driving factors, average annual temperature, altitude, and annual precipitation had the most significant effects.

The clusters showed aggregation trends in different regions of the basin. Box plots of the results and response variables were used for qualitative interpretation of the five clusters:

Cluster 1 (average annual temperature < 8.99 °C, GDP $\geq 963.5 \times 10^{\{3\}}$): Mainly distributed in Jiayuguan City, Jiuquan City, and scattered urban and

residential areas in Zhangye City. Urbanization intensity was higher than other clusters, oasisization intensity was below the watershed average, and desertification intensity was moderate, showing a trade-off relationship between urbanization and oasisization. The main environmental driving factor was average annual temperature (< 8.99 °C).

Cluster 2 (average annual temperature < 8.99 °C, $GDP < 963.5 \times 10^3$): Distributed in desert areas of the basin. Most areas in this cluster showed weak transitions in all three landscape types, but some areas had intense transitions, with urbanization intensity at the watershed average, desertification intensity above the watershed average, and oasisization intensity below the average, showing a trade-off relationship between oasisization and desertification.

Cluster 3 (average annual temperature ≥ 8.99 °C, altitude < 1376 m, annual precipitation ≥ 83.46 mm): Including the northwestern part of the Ganzhou oasis and the Jinta oasis area and surrounding regions in the lower reaches, distributed in strips along the Heihe River in the eastern part of Ejin Banner. Urbanization intensity was slightly above the watershed average, desertification intensity was the lowest, oasisization intensity was moderate, and urbanization and desertification showed a trade-off relationship. The main environmental driving factors were average annual temperature (≥ 8.99 °C) and altitude (< 1376 m).

Cluster 4 (average annual temperature ≥ 8.99 °C, altitude > 1376 m): Concentrated in Shangba Town and Huajian Township in Suzhou District. Oasisization intensity was the highest, while desertification and urbanization intensities were relatively low, showing trade-off relationships between oasisization and desertification and between oasisization and urbanization. The main environmental driving factors were average annual temperature (≥ 8.99 °C) and altitude (> 1376 m).

Cluster 5 (average annual temperature ≥ 8.99 °C, altitude < 1376 m, annual precipitation < 83.46 mm): Distributed in the eastern and southern parts of the Zhangye oasis. This cluster showed high desertification intensity, oasisization intensity above the watershed average, and urbanization intensity slightly below the watershed average, with trade-off relationships between urbanization and both oasisization and desertification. The main environmental driving factors were average annual temperature (≥ 8.99 °C), altitude (< 1376 m), and annual precipitation (< 83.46 mm).

The results showed that temperature served as the first-level split node of the regression tree, being the primary factor affecting the trade-off and synergy effects of landscape transitions in the Heihe River Basin. Temperature significantly promotes agricultural production, so in Cluster 3 (average annual temperature ≥ 8.99 °C), oasisization intensity was significantly higher than in Cluster 2 (average annual temperature < 8.99 °C). In areas where temperature reached the threshold (average annual temperature ≥ 8.99 °C), altitude began to affect landscape transitions. High-altitude areas often limit human development

and construction activities while providing more suitable habitat conditions for vegetation growth. Therefore, Cluster 4 (altitude > 1376 m) showed lower urbanization intensity but higher oasisization intensity, while Cluster 5 (altitude < 1376 m) showed higher urbanization intensity. In areas where both temperature and altitude reached thresholds, annual precipitation threshold (83.46 mm) distinguished Cluster 3 from Cluster 5, both showing high oasisization intensity. The oasisization process is most sensitive to precipitation, with increased precipitation promoting crop growth and accelerating oasis expansion.

2.4 Eco-Environmental Effects of Oasis-Urban-Desert Landscape Transitions

2.4.1 Spatio-Temporal Characteristics of Eco-Environmental Quality

Using the natural breaks method in ArcGIS, the eco-environmental quality of the Heihe River Basin was divided into five levels: poor (0-0.17), relatively poor (0.17-0.27), moderate (0.27-0.4), relatively good (0.4-0.5), and good (0.5-1). The eco-environmental quality of the Heihe River Basin was predominantly moderate, accounting for 79.8% of the total watershed area. Level 2 eco-environmental quality was mainly distributed in the desert area of the lower reaches, while level 3 was mainly distributed in the periphery of the middle and lower reaches oasis areas. The optimal level 5 eco-environmental quality accounted for only about 5% of the watershed area, mainly distributed in the middle reaches oasis area and the southeastern part of the Qilian Mountains in the upper reaches.

Areas where eco-environmental quality level increased or decreased by one level were defined as improvement or decline areas, respectively, while areas with changes of two or more levels were defined as significant improvement or significant decline areas. As shown in [Figure 6: see original paper], the spatio-temporal variation characteristics of eco-environmental quality from 2000 to 2020 align well with the three stages of landscape transitions described in Section 2.2.3. Overall, from 2000 to 2020, the eco-environmental quality of the Heihe River Basin showed a fluctuating but improving trend, with continuous oasis expansion significantly improving the eco-environmental quality of surrounding areas, while urbanization in the lower reaches caused significant declines in habitat quality.

2.4.2 Eco-Environmental Effects of Landscape Transitions

From 2000 to 2020, the eco-environmental effects of landscape transitions in the Heihe River Basin were dominated by positive effects, which mainly came from the conversion of desert landscapes to oasis and urban landscapes, while negative effects mainly came from the conversion of oasis landscapes to desert and construction land. Positive effects were significantly stronger than negative effects. The transition of desert landscapes such as sandy land, gobi, and saline-alkali land to cultivated land was the main reason for eco-environmental quality improvement, accounting for 79.8% of the total positive effect contribution rate. The

transition of gobi to construction land also contributed to eco-environmental quality improvement to some extent, accounting for 9.4% of the positive effect contribution rate.

The degradation of cultivated land to desert landscapes such as gobi, low-coverage grassland, and bare land was the main cause of eco-environmental degradation, accounting for 41.4% of the total negative effect contribution rate. Grassland degradation was also an important factor in eco-environmental quality deterioration, accounting for 20.0% of the total negative effect. The occupation of cultivated land by urban expansion caused negative eco-environmental effects accounting for 12.2% of the total contribution value. Rapid urbanization and industrialization have brought regional economic development, but if the relationship between economic development and eco-environmental protection cannot be properly coordinated, it will inevitably cause negative impacts on regional ecological security. Changes in regional landscape patterns are closely related to human activities, and the evolution of landscape patterns deeply reflects the transformation of the land surface by human activities and the natural environment in different times and spaces. Balancing the relationship between regional economic development and ecological protection has become a dilemma faced by many decision-making departments.

3 Discussion

3.1 Environmental Response Mechanism of Landscape Transitions

Due to harsh natural environmental conditions, the overall eco-environmental quality in the arid region of northwest China is relatively poor. In inland river basins of arid zones, oases are the most active areas of human activity and the most intense areas of landscape transition, while landscape pattern changes in other areas are relatively small. In this study, hotspot areas of oasis-urban-desert landscape transitions in the Heihe River Basin were also distributed around various oases. The oasisization process was mainly driven by natural factors such as precipitation, temperature, and altitude, while the urbanization process was mainly driven by altitude and socio-economic factors (Cluster 1), and the desertification process was more significantly affected by complex human factors. The oasisization process was most sensitive to precipitation factors, with increased precipitation promoting crop growth and accelerating oasis expansion. The impact of temperature on oasisization is more complex. Previous studies have found that temperature increases have positive effects on corn growth in the Heihe River Basin, thereby inducing agricultural oasis expansion. In areas with average annual temperature ≥ 8.99 °C, threshold effects occur, and the trade-off relationship between oasisization and urbanization reverses. Areas with suitable temperatures for crop cultivation prioritize oasis expansion (Cluster 3), while areas with lower temperatures prioritize urbanization development (Cluster 1). Urbanization drives economic development, which inevitably accelerates water resource consumption. Limited water resources cannot simultaneously support both oasisization and urbanization processes, resulting in trade-off relationships

between them (Cluster 5). Water resources remain the key factor constraining watershed development, consistent with conclusions from previous studies in the Heihe River Basin.

3.2 Watershed High-Quality Development Strategies Based on Landscape Transitions

This study used the MRT model to analyze the complex non-linear relationships and threshold effects in the transformation process of the oasis-urban-desert landscape combination. Based on the clustering results and eco-environmental quality effects, the following strategies are proposed to promote watershed ecological protection and high-quality development:

(1) Desert Ecological Zone: Including the middle and lower reaches desert areas (Cluster 2), characterized by vast deserts and gobi. To control desertification, it is necessary to focus on strengthening shelterbelt construction, returning grazing land to grassland, and sand prevention and control projects, while protecting the East and West riverbank oasis ecology, ensuring ecological water use, improving water resource allocation patterns, and building a solid ecological security barrier for the Juyan Oasis.

(2) Urban-Oasis Trade-off Zone: Including Clusters 1 and 5, focusing on solving the problem of water resource carrying capacity limiting population and economic growth, effectively protecting agricultural irrigation water in the Hexi Corridor, improving agricultural water use efficiency, and developing new water-saving irrigation facilities. Emphasis should be placed on developing characteristic agricultural and sideline product processing industries and tertiary industries, selectively expanding the scale of characteristic planting and breeding industries, and building oasis ecological cities with modern green agricultural trade and historical-cultural tourism functions.

(3) Desert-Oasis Trade-off Zone: Mainly Cluster 4, serving as the transition zone between desert and oasis. Vegetation coverage should be increased, with focus on protecting the oasis periphery transition zone, intensifying desertification control, preventing desert spread, and scientifically and rationally developing and utilizing wasteland to improve the overall regional eco-environment.

3.3 Research Limitations

This study has some limitations. Using landscape transition kernel density to characterize the intensity of various landscape transitions within the watershed and thereby reflect the intensity of urbanization, oasisization, and desertification provides only spatial quantification of the three landscape transition types. In reality, the evaluation mechanisms of urbanization and oasisization processes are more complex and sometimes require consideration of a series of related indicators such as population urbanization, economic urbanization, spatial urbanization, and social urbanization. Additionally, since landscape transitions

outside oases in arid inland river basins are not obvious, kernel density statistics may contain many null values, and spatial discontinuity in data may affect model results.

4 Conclusions

This study investigated the “pattern-process” of the typical “oasis-urban-desert” landscape in the Heihe River Basin. Based on analyses of the spatio-temporal, internal, and stage characteristics of landscape transitions, the MRT model was used to analyze trade-off and synergy relationships among the three landscape transitions and their spatial response mechanisms. The remote sensing ecological index was used to assess the eco-environmental effects of landscape transitions. The main conclusions are as follows:

- (1) Desert is the most widely distributed landscape type in the Heihe River Basin, mainly distributed in the northeastern part of the middle reaches and the lower reaches. Oases are concentrated in the middle and lower reaches, with the middle reaches oases being the largest and most concentrated in the basin. Urban areas account for the smallest proportion, and their spatial distribution and scale are closely associated with oases, with the middle reaches oases nurturing important cities such as Zhangye, Jiuquan, and Jiayuguan.
- (2) The oasis-urban-desert landscape transitions in the Heihe River Basin can be divided into three periods: 2000–2005 as the agricultural activity-dominated period, with cultivated land reclamation as the main transition direction; 2005–2015 as the rapid industrial development period, with complex and diverse transition directions, rapid urban-oasis development, and land use structure becoming more coordinated and diverse; and 2015–2020 as the coordinated development transformation adjustment period, with accelerated urban development while gradually emphasizing the construction of ecological and economic functional zones.
- (3) Temperature, altitude, and precipitation jointly affect the trade-off and synergy relationships among oasis-urban-desert landscape transitions, with temperature mainly affecting the oasisization process, altitude affecting the urbanization process, and complex interactions among temperature, precipitation, and altitude affecting regional agricultural development (oasisization) and ecological degradation (desertification) processes.
- (4) From 2000 to 2020, the eco-environmental effects of landscape transitions in the Heihe River Basin were dominated by positive effects, mainly from the conversion of desert landscapes to oasis and urban landscapes, while negative effects mainly came from the conversion of oasis landscapes to desert and construction land. Farmland expansion was the main cause of positive effects, while farmland degradation, water area reduction, and grassland degradation were the main causes of negative effects.

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