Postprint: Spatiotemporal Variation of Human Activities and Landscape Ecological Risk in the Tarim River Basin over the Past 20 Years

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Abstract

Human activities are critical factors exacerbating regional ecological risks, necessitating urgent investigation into the impacts of human activity intensity on landscape ecological risk. This study examines the Tarim River Basin as the research area, utilizing five-phase land use, spatial population distribution, and nighttime light data from the past 20 years. A comprehensive land use degree index is introduced to enhance the human activity intensity (HAI) evaluation system, enabling quantitative assessment of spatiotemporal variations in basin landscape ecological risk (LER) under intensive human activities. The Copula function and bivariate local spatial autocorrelation model are employed to reveal the spatiotemporal association between LER and HAI. Results indicate that: (1) HAI in the Tarim River Basin has increased significantly over the past two decades, with intensive human activities predominantly distributed in oasis areas with relatively abundant water resources; the basin's human activity intensity demonstrates an increasing trend, with the areal proportion of low-intensity zones decreasing by 17.88% and that of medium-high intensity zones increasing by 3.57%. (2) LER in the Tarim River Basin generally exhibits a peripheral-high, central-low pattern, with high-risk areas primarily located in oasis regions with frequent human activities; basin LER showed an aggravating trend before 2015, but this trend slowed after 2010, with an improving trend gradually emerging after 2015. (3) Over the past 20 years, HAI and LER have exhibited a positive correlation, with the positive effect of human activities on LER continuously strengthening; after 2010, the increasing trend of this relationship has plateaued, with the positive effect entering a transitional phase from increase to decrease; spatially, H-H cluster areas show an increasing trend, with distribution patterns shifting from dispersed to concentrated; after 2015, L-L and H-L cluster areas have slowly increased, while L-H cluster areas have slowly decreased. The research findings can provide scientific reference for rational land resource utilization and landscape ecological protection in the Tarim

River Basin.

Full Text

Temporal and Spatial Variations of Human Activities and Landscape Ecological Risks in the Tarim River Basin, China, during the last 20 years

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Abstract

Human activity is an essential factor in the intensification of regional ecological risk. Hence, it is urgent to discuss the impact of human activity intensity (HAI) on landscape ecological risk. This paper took the Tarim River Basin as the research object. Based on the land use, population spatial distribution, and night light data during five periods from 2000 to 2020, it introduces the comprehensive index of land use degree to improve the evaluation system of HAI and quantitatively evaluates the temporal and spatial changes of landscape ecological risk (LER) in the basin under robust human activity. Combined with the Copula function and bivariate local spatial autocorrelation model, the spatiotemporal correlation between LER and HAI is revealed. The results showed that (1) The HAI in the Tarim River Basin enhanced markedly in the past 20 years, and extensive human activities were mainly distributed in the oasis areas with rich water resources. The intensity of human activities in the basin increased, with the proportion of low-intensity areas diminished by 17.88% and that of medium-high-intensity areas elevated by 3.57%. (2) The overall LER in the Tarim River Basin was characterized by a high surrounding area and a low central area, and the high-risk area was mainly distributed in the oasis areas with more frequent human activities. The LER in the basin intensified before 2015, which slowed down after 2010, and gradually emerged after 2015. (3) The HAI and LER were positively correlated during the past 20 years, and the positive effect of human activities on LER was enhanced. After 2010, the increasing correlation between the two flattened, and a positive effect appeared in the stage of transition from increase to decrease. The H-H cluster area elevated in space, and the distribution pattern changed from dispersion to concentration. After 2015, the L-L and H-L cluster areas slowly increased, unlike the L-H cluster areas. The results can provide a scientific reference for the rational use of land resources and protection of the landscape ecology in the Tarim River Basin.

Keywords: landscape ecological risk; human activity; spatio-temporal correlation; Tarim River Basin

1 Materials and Methods

1.1 Study Area Overview

The Tarim River is located in southern Xinjiang (34°55 –43°08 N, 73°10 – 94°05 E) and originates from the Tianshan and Karakoram Mountains. The Tarim River Basin is the largest inland river basin in China, with an elevation of 768–7249 m and an area of 103.33×10^{4} km^{2}. It has the dual characteristics of abundant natural resources and fragile ecological environments. The river originates in mountainous areas, is mainly supplied by snow and ice meltwater, has a length of 1521 km, and eventually dissipates in deserts and oases. The landscape pattern of the basin is dominated by deserts, composed of mountains, glaciers, valley grasslands, and oases. The Tarim River Basin has a continental arid climate, with an average annual precipitation of 30–50 mm, an average annual temperature of 10–15 °C, and an annual potential evaporation of 2000–2900 mm. The Tarim River Basin is a typical ecologically fragile area that plays a key role in ensuring economic development and ecological restoration in southern Xinjiang. Under the influence of human activities, increasingly prominent problems such as desertification and soil salinization within the basin are typical representatives of ecological environment degradation.

[Figure 1: see original paper]

1.2 Data Sources

The data selected for this paper include land use data, population spatial distribution data, and night light data for five periods (2000, 2005, 2010, 2015, and 2020). Land use data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/), with a spatial resolution of 30 m × 30 m. Population spatial distribution data were obtained from the Oak Ridge National Laboratory of the U.S. Department of Energy (https://landscan.ornl.gov), with a spatial resolution of 30 arcseconds. Night light data were obtained from the long-time series night light dataset for China in the Global Change Scientific Research Data Publishing System (https://geodoi.ac.cn/), with a spatial resolution of 1 km × 1 km.

1.3 Methods

1.3.1 Human Activity Intensity Index Calculation Human activity intensity (HAI) represents the capacity of humans to transform nature. At present, the quantitative expression of HAI mainly includes land use, population spatial distribution, night light data, and landscape types. Chen et al. introduced night light data and integrated population spatial distribution and land use data to characterize the spatiotemporal changes of human activities on the northern slope of the Tianshan Mountains. Therefore, based on previous research, this study replaced land use data with the comprehensive index of land use degree, combined with population spatial distribution and night light data to construct an HAI evaluation model for the Tarim River Basin. The model is expressed as:

$$HAI = 100 \times \sum_{i=1}^{n} (L_i \times m + P_i \times n + N_i \times s)$$

where HAI is the human activity intensity index, with larger values indicating stronger human activities; L is the comprehensive index of land use degree; A_i is the land use degree grading index for landscape type i, which refers to existing research where unused land, water bodies, forest land, grassland, and construction land are assigned values of 1, 2, 3, 4, and 5, respectively; C_i is the percentage of area occupied by landscape type i; P is the population distribution data; N is the night light index; and m, n, and s are the weights of L, P, and N after normalization, respectively. Referring to existing research, m, n, and s are taken as 0.4, 0.3, and 0.3, respectively.

1.3.2 Landscape Ecological Risk Evaluation To reasonably analyze the spatial distribution of landscape ecological risk, the study area was divided into evaluation units of 20 km × 20 km, considering the patch area of different land use types and the computational load. To better characterize the degree of ecological risk in each evaluation unit, this study started from the landscape structure of the Tarim River Basin and selected landscape disturbance, loss, and vulnerability indices based on Fragstats software to construct a landscape ecological risk (LER) evaluation model to analyze the spatiotemporal changes of LER. The evaluation model is as follows, and the specific calculation process is detailed in reference [2]:

$$ERI_k = \sum_{i=1}^{n} \left(\frac{A_{ik}}{A_k} \times R_i \right)$$

where ERI_k is the ecological risk index of evaluation unit k; A_{ik} is the area of landscape type i in evaluation unit k (km^2); A_k is the area of evaluation unit k (km^2); R_i is the loss index of landscape type i; and n is the number of landscape types in evaluation unit k.

1.3.3 Spatiotemporal Correlation Analysis of Landscape Ecological Risk and Human Activity (1) Temporal Correlation Model

The Copula function can effectively characterize the correlation between variables and reveal their complex relationships. Therefore, the Copula function was selected to intuitively describe the temporal correlation between HAI and LER. The type of Copula function affects the accuracy of the calculation results.

This study selected five commonly used Copula functions—Frank Copula, Clayton Copula, Gumbel Copula, Gaussian Copula, and t Copula—and used the square Euclidean distance for optimization [3]. The Kendall and Spearman rank correlation coefficients can simultaneously measure linear and nonlinear relationships between variables, and the correlation measurement results are more reliable [4]. Therefore, this study used the Kendall and Spearman rank correlation coefficients to measure the relationship between HAI and LER over time.

(2) Bivariate Local Spatial Autocorrelation

To explore the spatial correlation between variables, scholars have proposed the bivariate local spatial autocorrelation index based on the traditional Moran's I index to describe the correlation characteristics of spatial distribution between different variables [5]. Compared with traditional univariate spatial autocorrelation methods, the bivariate local spatial autocorrelation method can better characterize the spatial features between different variables by measuring the spatial aggregation between variables and has been widely applied. Therefore, this study used the bivariate local spatial autocorrelation analysis method to explore the spatial correlation between HAI and LER in the Tarim River Basin [6].

2 Results

2.1 Land Use Change

Based on the land use transfer matrix in the Tarim River Basin from 2000 to 2020 (Table 1), it can be seen that the area of different land use types changed significantly during the past 20 years. Overall, the transfer area between different land use types was approximately 24.56×10^{4} km^2. Specifically, the area of ecological land such as forest land, grassland, and water bodies decreased, while the area of other land use types (cultivated land, construction land, and unused land) increased. The increase in cultivated land area mainly came from the conversion of grassland, the increase in construction land area mainly came from the conversion of cultivated land, and the increase in unused land area mainly came from the conversion of grassland and water bodies. The decrease in ecological land indicates that the ecological environment within the basin has been damaged to a certain extent, thereby intensifying regional ecological risk, while the increase in cultivated land and construction land area also increases the pressure on the regional ecological environment. Forest land, grassland, and water bodies, as ecological land, transferred out approximately 10.89×10^{4} km^2, 2.36×10^{4} km^2, and 4.05×10^{4} km^2, respectively, accounting for 44.36%, 9.60%, and 16.68% of the total transfer area, respectively, indicating that regional ecological land changes were active and stability was low. Overall, the increase in activity and the reduction in area of ecological land in the Tarim River Basin have intensified regional ecological risk, and the increase in construction land and cultivated land area further demonstrates the strengthening of regional human activities.

2.2 Characterization of Human Activity Intensity

Based on the Kriging interpolation method, the spatial distribution of HAI in the Tarim River Basin for the five periods was obtained. Using 2000 as the baseline, the HAI data for different periods were compared and analyzed, and combined with the natural breakpoint method, HAI was divided into five grades: high intensity, relatively high intensity, medium intensity, relatively low intensity, and low intensity. From the spatiotemporal variation characteristics of HAI in the Tarim River Basin during the past 20 years (Figure 2), it can be seen that the area proportion of strong human activity regions showed an increasing trend, increasing from 1.35% and 0.01% in 2000 to 3.39% and 0.13% in 2020 for high-intensity and relatively high-intensity areas, respectively. The area proportion of low-intensity regions decreased from 80.42% to 62.37%. Overall, the spatial distribution pattern of HAI is closely related to suitable ecological environments and is mainly distributed in the oasis areas of the Tarim River main stream with abundant water resources. The gradual strengthening of regional human activities may have adverse effects on the ecological environment.

[Figure 2: see original paper]

2.3 Spatiotemporal Variation of Landscape Ecological Risk

Based on the landscape ecological risk index, the spatial distribution of LER in the Tarim River Basin for the five periods was obtained using the Kriging interpolation method. Using 2000 as the baseline, the LER data for different periods were compared and analyzed, and combined with the natural breakpoint method, LER was divided into five grades: low risk ($ERI < 0.0527$), relatively low risk ($0.0527 \leq ERI < 0.0713$), medium risk ($0.0713 \leq ERI < 0.0906$), relatively high risk ($0.0906 \leq ERI < 0.1121$), and high risk ($ERI \geq 0.1121$). It can be seen that the overall LER in the basin is characterized by high surrounding areas and low central areas, with high-risk areas mainly distributed in the oasis areas with more frequent human activities. Overall, during the past 20 years, the area proportion of high-risk and relatively high-risk areas in the Tarim River Basin showed an increasing trend, while the area proportion of medium-low-risk areas showed a decreasing trend. The area proportion of high-risk and relatively high-risk areas increased by 17.7% and 26.95%, respectively, before 2015, but the increasing trend slowed down after 2010, and the trend reversed after 2015, indicating that the LER decreased and the landscape ecological anti-interference ability of the basin enhanced. This may be related to the implementation of landscape ecological management and protection measures locally. From the changes in the area proportion of each LER grade (Table 2), it can be seen that the Tarim River Basin is dominated by relatively low-risk and medium-risk grades, with multi-year average area proportions of 38.65% and 28.90%, respectively. The area proportion of medium-low-risk areas showed a decreasing trend, while the area proportion of relatively high-risk and high-risk areas showed an increasing trend. Before 2015, the area proportion of relatively high-risk and high-risk areas showed an increasing trend, but the increasing trend slowed down after 2010, and a reversal occurred after 2015, indicating that the LER decreased and the landscape ecological anti-interference ability of the basin enhanced.

2.4 Landscape Ecological Risk Distribution by Land Use Type

The distribution of landscape ecological risk grades for different land use types shows that cultivated land and construction land are mainly distributed in relatively high-risk and high-risk areas, forest land and water bodies are mainly distributed in medium-risk and high-risk areas, grassland is mainly distributed in relatively high, medium, and relatively low-risk areas, and unused land is mainly distributed in medium-low-risk areas. Overall, during the past 20 years, the area proportion of cultivated land in relatively high-risk and high-risk areas increased from 83.58% to 90.69%. The area proportion of forest land and water bodies in medium-risk areas decreased by 5.96% and 12.82%, respectively, while the area proportion in high-risk areas increased by 6.15% and 17.7%, respectively. The area proportion of grassland in relatively low-risk areas decreased by 3.57%, while the area proportion in relatively high-risk areas increased by 12.82%. In 2015, the construction land area was larger than in other years, and the change amplitude was more significant in the northeastern part of Bosten Lake. The large area of construction land reduced landscape fragmentation and disturbance, leading to a decrease in ecological risk. Unused land has strong integrity and connectivity, and its ecological risk is relatively stable, without showing obvious fluctuations.

[Figure 3: see original paper]

2.5 Spatiotemporal Correlation Characteristics Between Landscape Ecological Risk and Human Activity

Temporal Correlation Characteristics

Using the square Euclidean distance, the optimal Copula function was selected, and the Frank Copula function was ultimately chosen as the optimal function. The rank correlation coefficients were calculated to analyze the correlation between HAI and LER. Based on the Kendall and Spearman rank correlation coefficients (Figure 5), it was found that both rank correlation coefficients were greater than 0, indicating a significant positive correlation between HAI and LER. That is, the increase in HAI will significantly enhance regional LER, and this positive correlation became more significant in the past 20 years. Specifically, the rank correlation coefficient increased slowly after 2010, and the positive correlation became more significant relative to before 2010. The results reflect that the influence scope of human activities on LER continuously improved, and the impact on the ecological environment became more significant.

Spatial Correlation Characteristics

According to the bivariate local spatial autocorrelation analysis results, the HAI-LER cluster distribution was obtained (Figure 6). Overall, the H-H cluster areas showed a dispersed distribution pattern, mainly located in mountainous areas and regions with high human activity intensity, while the L-L cluster areas were mainly distributed in the Taklamakan Desert and its eastern regions. During 2000–2010, the H-H cluster areas increased significantly and gradually changed from a dispersed state to a concentrated state. During 2010–2020, the H-H cluster areas slowly decreased, the L-L cluster areas slowly increased, and the L-H cluster areas showed a trend of first increasing and then decreasing. In summary, the analysis reflects the complex spatial relationship between landscape ecological risk and human activities in the Tarim River Basin.

[Figure 6: see original paper]

3 Discussion

3.1 Land Use Change and Landscape Ecological Risk Analysis

The Tarim River Basin is highly sensitive to climate environmental changes and human activities. Since 2000, land use types and patterns have changed significantly, with the area of forest land, grassland, and water bodies decreasing, while the area of cultivated land, construction land, and unused land increased. These land use changes have had extensive impacts on the ecology. The degradation and reduction of forest and grassland weakened the infiltration capacity of surface runoff and increased soil erosion, leading to a reduction in water conservation capacity. The decrease in water body area caused a severe decline in biodiversity and a reduction in available ecological water resources, producing obvious ecological problems. Due to rapid population growth, cultivated land area expanded rapidly, and some cultivated land may experience quality decline due to water resources and soil fertility constraints, leading to secondary salinization and land desertification, thereby increasing regional landscape ecological risk. Therefore, comprehensive land management and ecological protection strategies are needed to balance economic development and ecological protection, ensure sustainable land use, and minimize adverse consequences. To mitigate or improve these adverse impacts, effective landscape ecological protection measures need to be formulated from different levels, such as strictly implementing ecological compensation mechanisms, strictly controlling extensive land use, and rationally planning land resource utilization.

In recent years, the population of the Tarim River Basin has continued to grow, leading to a rapid increase in demand for different land types. Production and living activities have increased the demand for various land types, and development and construction activities have caused frequent conversion of limited land resources, changing the original landscape pattern and increasing landscape ecological risk. The study reflects that the area of construction land and cultivated land, which represent human activities, increased substantially, altering the pattern of natural landscape ecology; therefore, these regions have relatively high landscape ecological risk. In addition to human activities, climate change is also an important factor inducing landscape ecological risk. Under the background of climate change, extreme drought events have increased, and wind-sand disasters have become frequent, negatively impacting the integrity and connectivity of landscape patterns and increasing regional landscape ecological risk.

3.2 Correlation Analysis Between Human Activity and Landscape Ecological Risk

The disturbance of human activities to landscape ecology has significantly increased, triggering many landscape ecological problems. With the continuous increase in human activity disturbance, ecological land within the basin has decreased substantially, while cultivated land and construction land have continued to expand, resulting in weakened regional landscape ecological anti-interference capacity and intensified LER. Deng et al. also found that human activities enhanced interference with landscape ecology in the Tarim River Basin, leading to a substantial increase in cultivated land and construction land, a reduction in green ecological space, and continuously deepening landscape fragmentation. Through research on the correlation between HAI and LER in the Tarim River Basin during the past 20 years, it was found that the two showed a significant positive correlation, indicating that human activities affected basin LER, consistent with previous research conclusions. The difference from previous studies is that the positive effect of human activities on LER in the Tarim River Basin gradually increased, but this increasing trend flattened after 2010. The main reason is that the intensification of human activities and rapid socio-economic development in the basin triggered this phenomenon, leading to lagging landscape ecological protection behind socio-economic development, increased conflict and decreased coordination between HAI and LER, and greater potential impacts on regional landscape ecology. As this impact continues to increase, it has intensified the conflict between humans and land to a certain extent, thereby aggravating LER. Fang et al. found similar conclusions in their study on the correlation between HAI and LER in the Yangtze River Delta region, where the positive effect of human activities on LER showed a trend of first increasing and then decreasing in the long term. In the Tarim River Basin, the positive effect of human activities on LER only slowly showed a transition stage from increase to decrease after 2010, and this transition is a long process. Only with the continuous implementation of ecological water conveyance, ecological protection measures and policies, enhanced protection efforts, improved ecological protection awareness, and the establishment of long-term sustainable development strategies based on social development can the ecological improvement effects in the Tarim River Basin continue to manifest, the positive effect of human activities on LER remain stable and decline, and further transform toward human-land harmony.

3.3 Uncertainty Analysis

Natural conditions and human activity disturbances affect the role of ecosystems and ecological processes, thereby influencing landscape ecological patterns. Previous studies have shown that land use change can alter landscape patterns, affecting ecological health and safety. To reveal the human-land relationship in the Tarim River Basin, this study used the landscape ecological risk index calculated based on land use change to characterize LER and integrated population spatial distribution and night light data to characterize HAI, analyzing the correlation between the two. Considering the complexity of influences from different factors, there are still some uncertainties in the study. This study quantified land use data in the original HAI evaluation system and introduced the comprehensive index of land use degree to improve the HAI evaluation system, further supplementing the evaluation indicators. However, due to the limited evaluation data, the HAI evaluation system remains relatively simple and needs continuous supplementation and improvement. The rationality of evaluation unit division is the basis for affecting the accuracy of regional LER evaluation results. Due to the obvious scale effect of landscape evaluation, refined grid units can better reflect microscopic features, but they also increase the workload and computational difficulty. The uncertainty in selecting the optimal evaluation unit scale affects the rationality of the results and needs continuous verification and improvement in future research. Despite certain uncertainties in the study, the LER evaluation results have good consistency with reality, and the results have certain rationality, providing guidance for regional landscape ecological protection.

4 Conclusion

Based on land use, population spatial distribution, and night light data for five periods from 2000 to 2020, this study introduced the comprehensive index of land use degree to improve the HAI evaluation system, quantitatively evaluated the spatiotemporal changes of LER in the Tarim River Basin under robust human activity, and combined the Copula function and bivariate local spatial autocorrelation model to analyze the spatiotemporal correlation between HAI and LER. The main conclusions are as follows:

(1) The HAI in the Tarim River Basin increased significantly during the past 20 years, with robust human activities mainly distributed in oasis areas with abundant water resources, especially in the main stream area of the Tarim River Basin. The intensity of human activities in the entire study area showed an increasing trend, with the proportion of low-intensity areas decreasing by 17.88% and the proportion of medium-high-intensity areas increasing by 3.57%.

(2) The overall LER in the Tarim River Basin was characterized by high surrounding areas and low central areas, with high-risk areas mainly distributed in oasis areas with frequent human activities. The LER in the

basin intensified before 2015, but the intensification trend slowed after 2010, showing a transitional stage of improvement, and the improvement trend gradually emerged after 2015.

(3) HAI and LER were positively correlated during the past 20 years, and the positive effect of human activities on LER continuously increased, aggravating regional LER. With the implementation of ecological water conveyance and ecological protection measures, the increasing trend of the relationship between the two flattened after 2010, and the positive effect showed a transition stage from increase to decrease. Spatially, H-H cluster areas showed an increasing trend, and the distribution pattern changed from dispersion to concentration. After 2015, L-L and H-L cluster areas slowly increased, while L-H cluster areas slowly decreased.

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