Analysis of Dynamic Changes and Driving Forces of Desertification Risk in Turpan City (Postprint)

Authors: Sun Guili, Li Xue

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Abstract

Desertification is one of the most severe ecological problems facing the world today. Conducting quantitative assessments of desertification risk contributes to risk regulation and the achievement of regional eco-economic sustainable development. This study constructs a desertification risk evaluation system for Turpan City by selecting indicators from climate, underlying surface, and socioeconomic factors, analyzes and evaluates the degree of desertification risk from 2000 to 2018 based on 3S technology, and employs Geographical Detector for driving force analysis. The results indicate: (1) From 2000 to 2018, desertification risk in Turpan City underwent considerable changes, displaying an overall trend of local deterioration with general improvement, and the risk level was higher in the eastern region than in the western region. (2) During the study period, the area of extremely high risk increased in Shanshan County in eastern Turpan City; the scope of extremely high risk in Toksun County in the western region was effectively controlled with a significant reduction in area; the area of extremely low risk in Gaochang District in the central region decreased, while the distribution of low risk remained relatively stable. (3) Single-factor driving forces: six factors—days of sand-driving wind, primary industry GDP, precipitation, habitat quality index, livestock numbers, and average temperature—exert substantial influence on desertification risk in Turpan City; among pairwise indicator interactions, the mutual coupling between days of sand-driving wind and primary industry GDP, precipitation, habitat quality index, average temperature, and livestock numbers constitutes the main factor influencing desertification risk.

Full Text

Dynamic Changes and Driving Forces of Desertification Risk in Turpan City

SUN Guili[1,2], LI Xue[1], LIU Yanyan[1], ZHENG Jiaxiang[1], MA Jing[1], RAN Yajun[1]

[1]College of Forestry and Landscape Architecture, Xinjiang Agricultural University, Urumqi 830052, Xinjiang, China
[2]Key Laboratory of Forestry Ecology and Industrial Technology in Arid Areas, Urumqi 830052, Xinjiang, China

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Abstract

Desertification is one of the most severe ecological problems facing the world today. Conducting quantitative assessments of desertification risk is essential for effective risk regulation and achieving sustainable regional ecological and economic development. This study selected indicators from climatic, underlying surface, and socioeconomic factors to construct a desertification risk evaluation system for Turpan City. Based on 3S technology, we assessed the degree of desertification risk from 2000 to 2018 and analyzed the driving forces using geographic detectors. The results show that: (1) During the study period, desertification risk in Turpan City changed significantly, showing an overall trend of local deterioration with general improvement, with higher risk levels in the eastern region compared to the western region. (2) From 2000 to 2018, the extremely high-risk area increased in Shanshan County in the east; the extremely high-risk range in Toksun County in the west was effectively controlled with a significant reduction in area; the extremely low-risk area in the central Gaochang District decreased, while low-risk distribution remained relatively stable. (3) Single-factor driving forces: six factors—sand-driving wind days, primary industry GDP, precipitation, habitat quality index, livestock quantity, and average temperature—had significant impacts on desertification risk in Turpan City. In the interaction between paired indicators, the coupling of sand-driving wind days with primary industry GDP, precipitation, habitat quality index, average temperature, and livestock quantity represents the main driving force affecting desertification risk in Turpan City.

Keywords: desertification risk; dynamic changes; driving force analysis; Turpan City

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1. Introduction

Desertification is currently one of the most serious ecological problems worldwide. According to statistics from the United Nations Food and Agriculture

Organization and the United Nations Environment Programme, approximately one-sixth of the global population is affected by desertification hazards, and about one-quarter of the global land area faces varying degrees of desertification threat. Desertification not only leads to ecological environment degradation and reduces available ecological resources, but also exacerbates poverty gaps, continuously eroding ecological, production, and living spaces, seriously endangering socio-economic development and ecological security.

China' s arid and semi-arid regions are the most severely affected areas by desertification, and numerous scholars have conducted extensive research on this issue. Current research primarily focuses on desertification land classification, environmental evolution of oasis-desert ecotones, desertification trends, and related studies, while research on desertification risk assessment is rarely involved. Turpan City is located in an extremely arid region with sparse vegetation, frequent wind-sand disasters, and is a typical desert area with an extremely fragile ecological environment. Desert areas account for 46.87% of Turpan City' s total area. Simultaneously, this region is a nationally important characteristic tourist destination and famous fruit-producing area. With rapid economic development, protecting the ecological environment to ensure the sustainable development of pillar industries has become urgent. Therefore, this study uses 3S technology to collect, organize, and analyze land use data, natural environment, climate, and socio-economic data for different periods in Turpan City, establishes a desertification risk evaluation model, analyzes the distribution range and change patterns of regional desertification risk, and provides a theoretical basis for future desertification control and prevention in Turpan City, as well as scientific references for improving the regional ecological environment.

2. Study Area

Turpan City is located in the central-eastern part of the Xinjiang Uygur Autonomous Region, geographically positioned between 87°50 -91°10 E and 42°30 -43°20 N. It borders Bayingolin Mongol Autonomous Prefecture to the southwest, Hami to the east, and is separated from Urumqi City and Changji Hui Autonomous Prefecture by the Tianshan Mountains to the north. The city has a complex topography, surrounded by high mountains on three sides with low-lying central areas, forming a typical closed basin. The northern part features the Bogda Mountains (a branch of the Tianshan range), the western part has the Kalawu Mountains, and the central Flaming Mountain divides the Turpan Basin into two parts. Ayding Lake, at -155 m elevation, is the lowest point in Turpan City and the lowest point in China' s inland areas.

Turpan City has a warm temperate continental arid desert climate, characterized by strong winds, high temperatures, large diurnal temperature variations, long sunshine hours, and minimal precipitation, earning it the nicknames "Wind Depot" and "Fire Prefecture." Different topographic and climatic conditions have created unique vegetation and soil conditions, with vegetation mostly consisting of drought-resistant and cold-resistant plants, while most of the Gobi Desert is barren.

Administratively, Turpan City governs Gaochang District, Shanshan County, and Toksun County [Figure 1: see original paper].

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3. Data Sources and Methods

3.1 Data Sources and Processing

Land use data for Turpan City from 2000, 2010, and 2018 were obtained from the Cloud Geographic Monitoring Platform (http://www.dsac.cn/). Meteorological data including precipitation, average temperature, sand-driving wind days, and average wind speed were sourced from the China Meteorological Data Network and the Resource and Environment Science Data Center of the Chinese Academy of Sciences. Underlying surface data included vegetation coverage, habitat quality index, slope, and aspect. Socioeconomic data comprised population density, livestock quantity, and primary industry GDP. Detailed data sources and processing methods are shown in .

3.2 Research Methods

3.2.1 Habitat Quality Index Based on Turpan City' s land classification secondary vector data, the habitat quality index was calculated according to the formula:

$$\text{Habitat Quality Index} = \sum_{i=1}^{n} \beta_i \times \frac{M_i}{Z}$$

where β_i is the normalized coefficient of habitat quality at the county level (reference value is bio $\times 10^{-3}$); β_i is the weight coefficient of the i-th land structure type; M_i is the area of a certain land type in the region; and Z is the total area of each county in Turpan City.

3.2.2 Index Standardization Desertification risk evaluation indicators include positive and negative indicators. Positive indicators mean that larger values correspond to lower desertification risk, and vice versa. Vegetation coverage, habitat quality index, precipitation, and primary industry GDP are positive indicators. Sand-driving wind days, average temperature, average wind speed, slope, aspect, population density, and livestock quantity are negative indicators. The standardization methods for positive and negative indicators are as follows:

Positive indicator:

$$F_i = \frac{f_i - f_{\min}}{f_{\max} - f_{\min}}$$

Negative indicator:

$$F_i = \frac{f_{\max} - f_i}{f_{\max} - f_{\min}}$$

where F_i is the standardized value of evaluation indicator i; f_i is the original value of evaluation indicator i; and $f_{\max}$ and $f_{\min}$ are the maximum and minimum values of evaluation indicator i, respectively.

3.2.3 Comprehensive Desertification Risk Assessment The desertification risk index is calculated as:

$$R = \sum_{i=1}^{n} F_i \times W_i$$

where R is the desertification risk index; F_i is the standardized value of the i-th indicator; and W_i is the weight of the i-th indicator. A larger R value indicates a lower risk index, while a smaller R value indicates a higher risk index.

3.2.4 Desertification Risk Transfer Matrix The desertification risk transfer matrix was used to analyze the transfer direction and area of desertification risk:

$$S_{ij} = \frac{n_{ij}}{\sum_{j=1}^{n} n_{ij}} \times 100\%$$

where S_{ij} is the probability of land type i transforming to type j; and n_{ij} is the area transferred from type i to type j.

3.2.5 Desertification Risk Driving Force Analysis The geographic detector model was used for desertification risk driving force analysis, including factor detection and interaction detection.

Factor detection calculates the correlation index (q value) between evaluation indicators and desertification risk:

$$q = 1 - \frac{\sum_{c=1}^{L} N_c \sigma_c^2}{N \sigma^2}$$

where q represents the degree of influence of the independent variable indicator (X) on desertification risk (Y), with a value range of [0,1]. A larger q value indicates stronger correlation between the indicator and desertification risk. N is the total number of samples in the study area; σ^2 is the total variance of desertification risk evaluation indicators in the study area; N_c is the number of samples in a certain zone; and σ_c^2 is the variance of desertification risk evaluation indicators within a certain zone.

Interaction detection identifies the interaction between different evaluation indicators, i.e., the impact of the combined action of evaluation indicators X_1 and X_2 on desertification risk Y. The method involves calculating the q values for each evaluation indicator (X_1 and X_2) separately, then calculating the q value when the evaluation indicators interact ($q(X_1 \cap X_2)$), and finally comparing $q(X_1)+q(X_2)$ with $q(X_1 \cap X_2)$. Based on the comparison results, the interactions can be classified as non-linear enhancement, single-factor non-linear weakening, two-factor enhancement, independent, or non-linear enhancement.

Based on previous studies [2,4,6-8,24,26] and the actual conditions of the study area, we selected climatic factors (precipitation, average temperature, sand-driving wind days, average wind speed), underlying surface factors (slope, aspect, vegetation coverage, habitat quality index), and social factors (population density, livestock quantity, primary industry GDP) as impact indicators for the desertification risk assessment. The selection basis is as follows:

Turpan City has a continental arid desert climate with scarce precipitation and high temperatures as prominent characteristics. Precipitation and average temperature are complementary—low precipitation and high temperatures result in dry air and low soil moisture content, creating harsh growing conditions for vegetation. This leads to poor plant growth or makes the environment unsuitable for some plants, and low vegetation coverage affects wind prevention and sand fixation effects. Turpan experiences frequent strong winds, with occasional extreme wind events. Due to the dry soil texture, strong winds can easily mobilize surface fine particles, causing wind-sand hazards and exacerbating desertification risk. Therefore, climatic factor indicators were selected based on local conditions.

Vegetation coverage is an important indicator for measuring desertification degree. Higher vegetation coverage indicates lighter desertification and lower risk, and vice versa. The habitat quality index, calculated according to the technical specifications for ecological environment status evaluation, measures land use intensity. Higher values indicate better ecological conditions and lower desertification risk. Turpan' s topography is characterized by surrounding mountains with the Flaming Mountain in the center. The northern mountains have steep slopes while the southern mountains are relatively gentle. Differences in slope and aspect lead to variations in light intensity, wind strength, and natural environmental conditions, all of which significantly affect desertification risk.

Desertification occurrence is greatly constrained by social factors, such as rapid population growth squeezing ecological space and neglecting environmental damage while focusing on economic growth. Turpan's economic development mainly depends on the primary industry. Growth in primary industry GDP not only increases economic income but also indicates improving desertification conditions, increasing land quality, and reducing desertification risk. Livestock grazing severely affects regional desertification risk. Excessive livestock numbers and concentrated grazing locations result in poor vegetation conditions, while strict control of livestock numbers helps reduce desertification risk. The weights of each indicator factor obtained through the analytic hierarchy process are shown in .

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4. Results and Analysis

4.1 Spatiotemporal Distribution of Desertification Risk

4.1.1 Spatial Distribution of Desertification Risk in Turpan City Using the desertification risk assessment model, we calculated the desertification risk index for Turpan City. The risk values (ranging from 321.42$\times10^{-3}$ to 737.39$\times10^{-3}$) were reclassified into five levels using the natural breaks method in ArcGIS: extremely high risk, high risk, moderate risk, low risk, and extremely low risk [Figure 2: see original paper].

The extremely high-risk areas are mainly distributed in Toksun County in the west (Kumishi Town, Yilahu Town, and Alehui Town) and in the central and southern parts of Shanshan County. High-risk areas are widely distributed across most of Toksun County and Shanshan County. Moderate-risk areas are mainly distributed at the boundaries between high-risk and low-risk areas. Low-risk and extremely low-risk areas are primarily located in Gaochang District.

From 2000 to 2018, the desertification risk level in Toksun County decreased significantly, while Gaochang District and Shanshan County showed increased risk levels. Compared with 2000, the overall desertification risk level in 2018 changed relatively little, but the extremely low-risk area increased and the overall risk level decreased. In 2010, the extremely high-risk area in Toksun County increased slightly, mainly in Bostan Township and Kumishi Township. Overall, Turpan City' s desertification risk shows a trend of local deterioration with general improvement, with higher risk levels in the eastern region than in the western region.

4.1.2 Desertification Risk Area Transfer in Turpan City The desertification risk area transfer matrix for the study period was calculated . From 2000 to 2010, desertification risk in Turpan City showed an upward trend, mainly manifested by the reduction of extremely low-risk area transferring to low-risk, and mutual transfer between extremely high-risk and high-risk areas with more forward transfer, primarily in Shanshan County. From 2010 to 2018, desertification risk showed a downward trend, with extremely high-risk area decreasing and transferring mainly to high-risk, low-risk area decreasing and transferring mainly to extremely low-risk, and moderate-risk area decreasing and transferring mainly to low-risk.

Overall, from 2000 to 2018, the extremely low-risk area decreased while extremely high-risk, high-risk, and moderate-risk areas increased, indicating an upward trend in desertification risk levels. During this period, livestock numbers in Turpan City increased substantially. Combined with drought climate, overgrazing, increased grassland ecological pressure, and regional environmental degradation, these factors likely contributed to increased desertification risk. In recent years, the number of farms in Toksun County has continuously increased, putting pressure on natural grasslands and causing partial grassland degradation, which may be one reason for the increased desertification risk level.

4.1.3 Abundance and Importance Indices of Desertification Risk in Turpan City The abundance and importance indices of desertification risk for different counties were calculated and [Figure 3: see original paper]. The results show significant differences in abundance indices among regions. In 2000, Gaochang District had the highest abundance indices for moderate risk, low risk, and extremely low risk, indicating these risk levels were most widely distributed. The extremely high-risk abundance index in Gaochang District was 0, indicating relatively light desertification risk and good ecological environment. In 2010, moderate risk had the highest abundance index, showing it was most dispersed during this period. In 2018, low risk had the highest abundance index, indicating the largest number of patches and most dispersed distribution.

In Shanshan County, the extremely high-risk abundance index decreased year by year, while the abundance indices for moderate, low, and extremely low risks increased year by year, indicating these three risk levels became more widely distributed and extremely high-risk distribution became more concentrated. In Toksun County, the highest abundance indices in 2000 were for extremely high risk and moderate risk. By 2010, high risk and moderate risk had the highest abundance indices, indicating the most patches and relatively dispersed distribution. By 2018, the extremely high-risk abundance index showed a yearly decreasing trend, while extremely low-risk and low-risk abundance indices remained relatively stable.

The importance indices for each district and county in Turpan City changed significantly from 2000 to 2018. In Gaochang District, the importance indices for extremely high risk and high risk remained small, while those for moderate and low risk showed little change, and the extremely low-risk importance index decreased significantly in 2010 before increasing to a stable state in 2018. The desertification risk level in Gaochang District has always been dominated by low risk and moderate risk.

In Shanshan County, the importance indices for extremely low, low, and moderate risks remained relatively stable and small. Desertification risk in Shanshan County has always been dominated by extremely high risk and high risk, which is closely related to the existence of the Kumtag Desert and its harsh ecological environment. The importance index for high risk in Shanshan County decreased significantly in 2018.

In Toksun County, the importance index changed most significantly, with the extremely high-risk importance index decreasing year by year (a substantial decline), while moderate risk increased year by year with significant growth.

The importance indices for extremely high risk and high risk showed signs of increase in 2010. The desertification risk situation in Toksun County is changing, with the dominance of extremely high risk gradually improving.

4.2 Driving Force Analysis of Desertification Risk

4.2.1 Single-Factor Detection Analysis The geographic detector was used to evaluate the correlation between each evaluation factor and desertification risk in Turpan City . The results show that the correlation indices (q values) of each evaluation factor are not very high, indicating that desertification risk distribution in Turpan City involves many influencing factors, and no single factor dominates its risk distribution changes. The six factors with q values greater than 0.1, ranked from largest to smallest, are: sand-driving wind days, primary industry GDP, precipitation, habitat quality index, livestock quantity, and average temperature. Population density, vegetation coverage, and aspect have relatively low explanatory power for desertification risk in Turpan City.

4.2.2 Multi-Factor Interaction Detection Analysis Interaction detection shows that the interaction types among various influencing factors of desertification risk in Turpan City are mainly two-factor enhancement and non-linear enhancement. This indicates that the impact of two-factor interactions is greater than that of single factors on desertification risk. Among them, the factor interactions with the greatest impact include 15 cases of two-factor enhancement and 21 cases of non-linear enhancement.

The interaction between sand-driving wind days and primary industry GDP has the largest interaction index, having the strongest impact on desertification risk distribution changes. This is followed by sand-driving wind days precipitation, sand-driving wind days habitat quality index, precipitation livestock quantity, and sand-driving wind days average temperature. The interactions between population density and livestock quantity, and between population density and habitat quality index have the lowest interaction values. In factor interactions, slope, sand-driving wind days, and precipitation, when interacting with other factors, increase their impact on desertification risk in Turpan City.

The significance test results of factor interactions on desertification risk impact show that the interactions between slope and sand-driving wind days, average wind speed and sand-driving wind days/precipitation/primary industry GDP, sand-driving wind days and vegetation coverage/population density, precipitation and population density, and population density with primary industry GDP/livestock quantity/habitat quality index all have significant effects on desertification risk distribution in Turpan City. In contrast, interactions between slope and other factors (except sand-driving wind days), between sand-driving wind days and other factors (except vegetation coverage and population density), between precipitation and other factors (except population density), and between average temperature and population density/primary industry GDP have non-significant effects on desertification risk distribution.

5. Discussion

This study selected 11 indicators from three aspects—climatic factors, underlying surface factors, and socioeconomic factors—and used the weighted comprehensive scoring method and analytic hierarchy process to construct a desertification risk evaluation system for Turpan City. The spatiotemporal analysis of desertification risk in Turpan City shows that, overall, the desertification risk status presents a trend of local deterioration with general improvement. Local deterioration is mainly manifested by the increase in extremely high-risk area in Shanshan County in the east, which directly affects the overall desertification risk situation in Turpan City. The extremely high-risk range in Toksun County in the west has been basically controlled within a smaller area with significant area reduction, while the desertification risk level in the central Gaochang District remains basically stable.

From 2000 to 2018, the increased desertification risk in the eastern part of the study area resulted from the combined effects of natural and human factors. This region is located in an extremely arid area with extreme water shortage, exacerbated by excessive exploitation and increased land salinization. The area is dominated by unused land such as deserts, bare land, and saline-alkali land, with low organic matter content that is unfavorable for plant growth, poor species diversity, and sparse vegetation—findings also verified in Zhang Jinchun' s research. In contrast, desertification risk in the western and central regions has developed steadily toward improvement. Toksun County in western Turpan has increasingly focused on ecological protection of natural grasslands by implementing fenced grazing areas, closing hillsides for grassland restoration, and intensifying artificial planting of high-quality forage, resulting in significantly accelerated grassland ecological restoration. Additionally, the county has emphasized the implementation of protective tillage, establishing 667 hm^2 of new protective tillage demonstration fields in 2018, which is conducive to reducing desertification risk. The industrial structure adjustment in Gaochang District, with systematic development of efficient water-saving agriculture and increased oasis area, is also gradually improving regional desertification risk levels.

This study used the overlay analysis method to analyze desertification risk levels of different spatial types and geographic detectors to analyze driving factors of desertification risk. According to comprehensive factor and interaction detection by geographic detectors, sand-driving wind days, primary industry GDP, precipitation, habitat quality index, livestock quantity, and average temperature are the main factors causing spatial differences in desertification risk in Turpan City. Turpan City has a warm temperate continental arid desert climate with high evaporation and scarce precipitation. Suitable temperature and precipitation result in better vegetation coverage in the north and west, with green areas distributed in patches and clusters. The eastern region is adjacent to the desert, and ecological conditions are favorable for vegetation and crop growth. Low temperatures are unfavorable for normal plant development, while high temperatures, scarce precipitation, and frequent wind-sand events are more likely to cause drought disasters and increase desertification risk—consistent with research results by Zhang Guolong and Xiong Ying. In western Turpan City, measures such as enclosure for grassland restoration, planned grazing, and strengthening artificial grassland planting have promoted forage industry development. However, Toksun County has a large area of water-deficient grassland, accounting for 58.5% of the total grassland area. High-intensity grazing combined with drought climate and water resource deficiency creates a vicious cycle that affects desertification risk levels.

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6. Conclusions

1) Desertification risk areas in Turpan City changed significantly from 2000 to 2018, showing an overall trend of local deterioration with general improvement. The extremely high-risk area increased in Shanshan County in the east; the extremely high-risk range in Toksun County in the west was effectively controlled with significantly reduced area; the extremely low-risk area in the central Gaochang District decreased, while low-risk distribution remained relatively stable.

2) The abundance and importance indices of desertification risk in Turpan City' s counties and districts maintained consistent change patterns. Shanshan County' s abundance index and Toksun County' s importance index changed most significantly. Single-factor detection results show that six indicator factors—sand-driving wind days, primary industry GDP, precipitation, habitat quality index, livestock quantity, and average temperature—had significant driving effects on desertification risk changes in Turpan City. In pairwise indicator interactions, the interactions between sand-driving wind days and primary industry GDP, precipitation, habitat quality index, average temperature, and livestock quantity are the main driving forces promoting desertification risk in Turpan City.

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