

Analysis of Landscape Pattern Changes and Driving Factors of Desertified Land in the Shiyang River Basin

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Abstract: Quantifying the spatial heterogeneity and evolutionary processes of desertified land is essential for improving understanding of ecological dynamics in inland river basins of arid regions and for formulating ecological restoration strategies and sustainable oasis development. This study used nearly 30 years (1992–2022) of remote sensing imagery for the basin as the data source. Desertified-land landscapes were extracted with ENVI and ArcGIS, and landscape pattern metrics were used to analyze changes and trends. The geographic detector model was further applied to explore driving factors influencing the landscape pattern of desertified land. The results show that: (1) Over the past three decades, the area of desertified-land landscapes fluctuated but decreased overall by 4,631.86 km². Fixed sandy land exhibited the largest change magnitude, with a dynamic rate of –2.31%. Desertified-land types were mainly distributed in non-channel areas of the mid- to lower-reach of the basin; the centroids of fixed and semi-fixed sandy land shifted generally southwestward, whereas mobile dunes and deflation residual dunes expanded northeastward. (2) The landscape pattern of desertified land shifted from dispersed toward more aggregated, with an overall reduction in landscape fragmentation and a tendency toward a relatively stable ecological configuration. (3) Changes in desertified-land landscape pattern were primarily driven by natural factors, with climate (temperature and precipitation) consistently identified as the core drivers. Interaction effects among factors were generally stronger than single-factor effects, indicating a driving regime dominated by natural forces with human activities serving a coordinating role.

Keywords: Desertified Land; Landscape Pattern; Spatiotemporal Change; Geographic Detector; Shiyang River Basin.

1. Introduction

Desertification, a global ecological degradation phenomenon, primarily occurs in arid, semi-arid, and certain semi-humid regions. Its mechanisms are complex and multifaceted, influenced both by climate change and human activities. The key characteristics of desertification include soil degradation, reduced vegetation cover, and frequent wind erosion activities [1-3]. Currently, approximately one-quarter of the world's land area, two-thirds of the countries, and nearly one billion people are affected by desertification to varying degrees [4]. This not only threatens ecosystem stability but also poses significant risks to food security, public health, and socio-economic development [5]. In China, the area of desertified land is about 183.94×10^4 km², with the northwest region facing particularly severe desertification issues, which significantly impact the region's ecological functions [6-8].

Landscape pattern is a key representation of the spatial structure of surface landscapes, and it can quantify the types, shapes, scales, and spatial distribution characteristics of landscape patches [9]. Landscape patterns vary with scale, exhibiting clear scale dependency. Without scale analysis, landscape heterogeneity and pattern lack practical significance. Therefore, studying landscape patterns at different scales within the same region is an essential approach for revealing the ecological status and spatial variability characteristics of the region [10]. Desertification, as a typical landscape change process, is characterized by significant spatial heterogeneity and temporal dynamics [11]. Landscape ecology, utilizing remote sensing and GIS technologies, characterizes the desertification process from a

spatial structural perspective, effectively supporting large-scale, long-term monitoring and analysis [12]. Previous studies have explored trends in desertification such as fragmentation and aggregation, from both temporal and spatial scales [13], providing a basis for assessing desertification degrees and prioritizing management areas for control [14].

Investigating the driving factors of desertification is fundamental for understanding its causes, predicting future trends, and formulating management strategies [15]. Although previous studies have indicated that climate factors such as precipitation and temperature, as well as human activities like agricultural and pastoral development and water resource utilization, play significant roles in the desertification process [16-18], there remains a lack of in-depth and systematic research on the interactions between these factors, their spatial heterogeneity, and the identification of their relative weights. With the development of spatial statistics and machine learning methods, the geographical detector model has emerged as a new tool for quantifying the driving mechanisms of desertification [19]. However, its comprehensive application at the regional scale is still insufficient, especially in the context of landscape pattern changes, where analysis of the driving factors remains inadequate.

The Shiyang River Basin, as a typical inland river basin, is one of the regions in Northwest China where water resource utilization is most concentrated [20-21]. Over the years, under the dual pressures of climate change and resource development, the ecosystem degradation in this basin has worsened, and the expanding trend of desertification has attracted widespread attention. Although previous studies

have addressed aspects such as land use change, water resource management, and ecological restoration in this region [22-23], there has been limited comprehensive research on the changes in desertified land landscape patterns and their driving factors. This study focuses on the Shiyang River Basin, employing remote sensing technology in conjunction with landscape ecology methods to analyze the spatiotemporal changes in desertified land landscape patterns from 1992 to 2022. Additionally, the geographical detector model is used to explore the driving factors behind the changes in these landscape patterns. The findings contribute to a deeper understanding of the current state of desertified land, landscape characteristics, and driving factors in the basin, and provide a scientific basis for ecological management and sustainable development in arid regions.

2. Materials and Methods

2.1. Study Area Profile

The Shiyang River Basin (36°29'~36°27'N, 101° 22'~104°16'E) is located in the central part of Gansu Province, in the eastern part of the Hexi Corridor [24]. It lies to the north of the Qilian Mountains and west of the Wushaoling Range,

with the middle and lower reaches of the basin surrounded by the Badain Jaran and Tengger Deserts [25-26]. The basin exhibits a topography that slopes from south to north, and can be broadly divided into three major geomorphic units: the southern Qilian Mountain area, the central Corridor Plain area, and the northern low mountain, hill, and desert area. The elevation within the basin ranges from 1,247 m to 4,853 m, covering an area of approximately $4.16 \times 10^4 \text{ km}^2$ [20]. Due to its location deep within the continental interior, the climate is classified as temperate continental arid, characterized by large diurnal temperature variations, low and concentrated precipitation from June to September, with annual rainfall ranging from 120.8 to 431.1 mm, while evaporation rates reach 1,550 to 2,600 mm [21]. The basin includes several municipal administrative units, including Zhangye, Jinchang, Wuwei, and Baiyin, with a population of about 2.27 million. The distribution of landforms is closely related to ecological functions: the southern Qilian Mountains serve as the main water supply area, the central Corridor Plain area is the primary concentration of population and agricultural activities, while the northern low mountain, hill, and desert area is the most severely desertified and water-scarce region, also facing the most prominent ecological issues [20, 25].

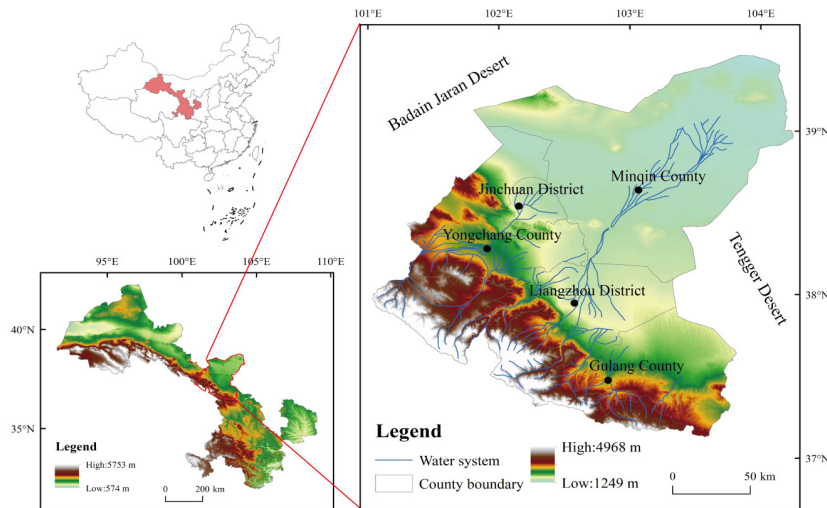


Figure 1. Research Area Overview

2.2. Source of Data

The remote sensing data used in this study were sourced from the Google Earth Engine platform (<https://earthengine.google.com/>). Landsat 5 imagery from 1992, 2002, and 2012, along with Landsat 8 imagery from 2022, were selected as data sources, with a spatial resolution of 30 m. The images were acquired between June and September, a period when vegetation is in optimal growth, facilitating the identification of desertified land. Images with minimal cloud cover (i.e., less than 10%) were chosen. The raw data were processed using ENVI 5.6, which included atmospheric correction and clipping. Field verification was conducted during a site visit in July 2024, comparing the false-color composite images with corresponding desertified land types to establish interpretation standards. The verification showed an interpretation accuracy of 85%, which meets the requirements of the study.

Meteorological data (temperature, precipitation, wind speed) and NDVI data were obtained from the National Tibetan Plateau Data Center (<https://data.tpdc.ac.cn/home>), population density data from LandScan Global (<https://landscan.ornl.gov/>), GDP data from the Scientific Data website (<https://www.nature.com/articles/s41597-025-04487-x#Sec12>), cropland area data from the 30m annual cropland dataset (1986-2021) on the Zenodo platform (<https://zenodo.org/records/7936885>), and grazing intensity data from the 1980-2024 grazing intensity dataset for China on the Figshare website (<https://doi.org/10.6084/m9.figshare.26195684>).

After processing the above data into raster format in ArcGIS, they were unified to the WGS_1984_Albers Equal Area Conic projection and resampled to a resolution of 1 km.

2.3. Research Methods

2.3.1. Desertification Land Landscape Type Extraction

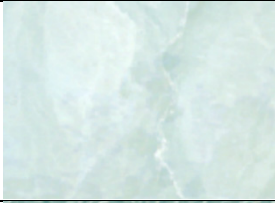
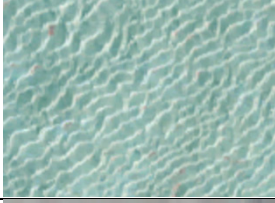
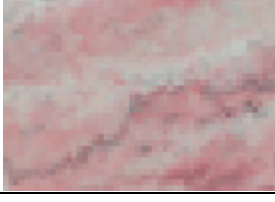
Based on previous desertification classifications [27] and the specific conditions of the Shiyang River Basin, desertified land in the basin is classified into two types: gravel desertification and sandy desertification. Gravel desertification is further subdivided into two landscape types based on surface morphology: wind-eroded residual mounds and exposed gravel areas. Sandy desertification is categorized into three landscape types based on vegetation cover: shifting

sand dunes, fixed sand dunes, and semi-fixed sand dunes [28]. Therefore, desertified land in the basin is divided into five categories: wind-eroded residual mounds, exposed gravel areas, shifting sand dunes, fixed sand dunes, and semi-fixed sand dunes (Table 1).

In this study, the ROI (Region of Interest) tool in ENVI software (ENVI 5.6) was used to select and define training

samples, ensuring that 300 recognizable and evenly distributed samples for each desertification landscape type were selected. The separability of the training samples (ROI) was greater than 1.8, indicating good separability of the samples [26]. A remote sensing interpretation system was finally established through supervised classification using the Support Vector Machine (SVM) algorithm.

Table 1. Desertification land landscape types and interpretation signs in the Shiyang River Basin

Desertification land type	Landscape types of desertification	Vegetation cover	Landscape characteristics	Interpretation Features	Remote sensing image
Gravel desertification	Aeolian monadnocks	<5%	Severe wind erosion, high fragmentation, and sparse vegetation.	The dominant color is gray-white, with rough texture and distinct residual mounds.	
	Bare gravel ground	<10%	The landscape is primarily a desert plateau, exposed to wind erosion, with coarse sand and gravel.	Smooth texture in shades of gray-white.	
Sandy desertification	Mobile sandy land	<10%	Intense wind and sand activity, with various types of sand dunes widely distributed, and sparse desert vegetation present.	Bright white sand dunes are clearly visible, forming a wave-like pattern.	
	Semi-fixed sandy land	10~30%	The sand dunes are sparsely distributed, with limited vegetation and large expanses of shifting sand dunes.	The tone is light pink, with the sand dune shapes clearly recognizable.	
	Fixed sandy land	30~50%	Obvious wind erosion marks, with abundant vegetation and a few sand dunes.	Primarily light red, with darker red spots, and a rough texture.	

2.3.2. Transition Matrix

The transition matrix reflects the mutual transformation between landscape types. Through the transition matrix, the changes in landscape types can be quantitatively analyzed [29]:

$$K_{ab} = \begin{bmatrix} k_{11} & \cdots & k_{1n} \\ \vdots & \ddots & \vdots \\ k_{s1} & \cdots & k_{sn} \end{bmatrix}$$

In the equation, K_{ab} refers to the area of the a-th landscape type in the initial period transforming into the b-th landscape type in the final period, and n is the total number of landscape types.

2.3.3. Center of Gravity Migration Model

The center of gravity migration model is used to calculate the distribution center of different desertified land landscape types and to analyze the spatial variation characteristics of desertified land. The coordinates of a certain desertified land landscape type in year t are [3,30]:

$$X_t = \frac{\sum_{i=1}^m (C_t \times Y_i)}{\sum_{i=1}^m C_t}$$

$$Y_t = \frac{\sum_{i=1}^m (C_t \times X_i)}{\sum_{i=1}^m C_t}$$

In the equation, X_t and Y_t represent the longitude and latitude of the center of gravity of the desertified land landscape in year t, respectively. C_t is the area of the i-th desertified land landscape type in time period t, X_i and Y_i are the longitude and latitude of the center of gravity of small patches of the i-th desertified land landscape, and m is the total number of small patches of the i-th desertified land landscape in time period t.

2.3.4. Landscape Pattern Index

Landscape pattern indices can effectively reflect the spatial patterns and distribution characteristics of landscape types, providing a high-level summary of spatial landscape patterns [31]. Based on the desertification characteristics of the Shiyang River Basin, this study selected six landscape pattern indices to describe landscape pattern changes: from the patch level, patch number, patch density, patch shape index, and

patch aggregation index; and from the landscape level, the Shannon diversity index and Shannon evenness index. These indices were calculated using Fragstats 4.2 software [32].

2.3.5. GeoDetector

Based on existing studies on the driving factors of desertification in the Shiyang River Basin [30], and considering the actual conditions of the basin as well as the scale effects and spatiotemporal heterogeneity of landscape patterns [26], this study selected eight driving factors for the analysis of landscape pattern changes: four natural factors—temperature, precipitation, wind speed, and NDVI—and four anthropogenic factors—population density, cropland area, grazing intensity, and GDP. The q -value was used to measure the spatial heterogeneity of landscape pattern changes (Y) and to assess the explanatory power of each driving factor (X) on landscape pattern changes [33–34]. The formula is as follows:

$$q=1-\frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2}$$

In the equation, the q -value represents the explanatory power of a driving factor on the desertified land landscape

pattern, where $q \in [0,1]$. A larger q -value indicates a more significant impact of the factor on landscape pattern changes. The parameter h refers to the stratification of landscape changes and driving factors, while σ is the variance at the h -th layer. N_h and N represent the number of units for driving factor X at the h -th layer and the total number of units in the study area, respectively [35].

Interaction factor detection is used to study the interactions between different factors and to assess the combined impact of two distinct factors on the changes in desertified land landscape patterns in the Shiyang River Basin. This method analyzes the explanatory power of independent variables on the dependent variable, which is the desertified land landscape pattern changes [19].

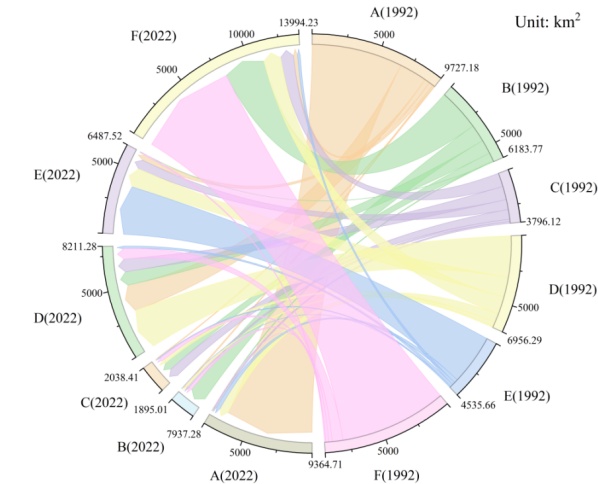
3. Results

3.1. Temporal Changes in Desert Land Landscape

Table 2. Desertified Land Landscape Area and Dynamic Degree in the Shiyang River Basin from 1992 to 2022

Landscape types of desertification	Area (km ²)				Dynamic attitude (%)			
	1992	2002	2012	2022	1992-2002	2002-2012	2012-2022	1992-2022
Aeolian monadnocks	6962.84	7550.00	6699.05	8213.68	0.84	-1.13	2.26	0.60
Fixed sandy land	6185.33	5128.10	4279.31	1896.47	-1.71	-1.66	-5.57	-2.31
Semi-fixed sandy land	3796.49	4530.87	4170.34	2039.29	1.93	-0.80	-5.11	-1.54
Bare gravel ground	4535.88	3523.18	3751.76	6489.55	-2.23	0.65	7.30	1.44
Mobile sandy land	9729.60	8475.69	10396.47	7939.29	-1.29	2.27	-2.36	-0.61

(The positive and negative values of the dynamic degree reflect the expansion and contraction of landscape types.)



(A: Mobile sandy land; B: Fixed sandy land; C: Semi-fixed sandy land; D: Aeolian monadnocks; E: Bare gravel ground; F: Non-desert landscape)

Figure 2. Sankey Diagram of Desertified Land Landscape Area Transitions in the Shiyang River Basin from 1992 to 2022

From 1992 to 2022, the total area of desertified land in the Shiyang River Basin showed a fluctuating decreasing trend (Table 2), with the total area decreasing from 31,210.14 km² to 26,578.28 km², a net reduction of 4,631.86 km². Among the five types of desertified land landscape, fixed sand dunes, semi-fixed sand dunes, and shifting sand dunes all showed a net reduction trend. The most significant reduction occurred in fixed sand dunes (4,288.86 km², dynamic degree -2.31%),

followed by semi-fixed sand dunes, which decreased by 1,757.20 km² (-1.54%). Shifting sand dunes fluctuated, with an overall decrease of 1,790.31 km² (-0.61%). Wind-eroded residual mounds and exposed gravel areas, on the other hand, showed a net expansion, increasing by 1,250.84 km² (0.6%) and 1,953.67 km² (1.44%), respectively.

The change process of each desertified land landscape type exhibited phase differences: wind-eroded residual mounds and exposed gravel areas experienced a shift from reduction to expansion, while shifting sand dunes showed a pattern of reduction—expansion—reduction. Regarding dynamic fluctuations, exposed gravel areas showed the most dramatic change from 1992 to 2002 (-2.23%), shifting sand dunes showed the most notable change from 2002 to 2012 (2.27%), and from 2012 to 2022, the change amplitude was again significant (7.30%).

From the transition relationships (Figure 2), fixed sand dunes and semi-fixed sand dunes mainly transformed into non-desert land types, with transition areas of 3,137.55 km² and 1,019.97 km², respectively. Semi-fixed sand dunes transitioned into wind-eroded residual mounds by 998.10 km². Shifting sand dunes primarily transitioned into wind-eroded residual mounds (2,065.97 km²). Wind-eroded residual mounds transitioned most significantly into exposed gravel areas (1,475.76 km²), which is an important source of expansion for exposed gravel areas.

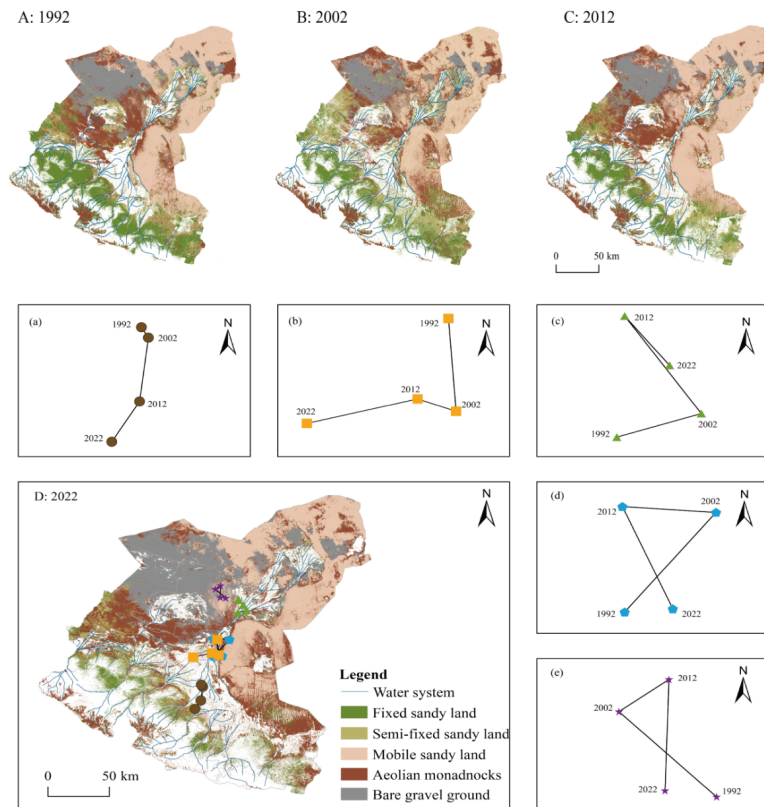
3.2. Spatial Changes in Desertified Land Landscape

Desertified land landscape types are primarily concentrated in the northern, western, central, and eastern regions of the middle and lower reaches, with their distribution becoming more widespread as the distance from the river increases. In contrast, non-desertified land landscapes are mainly concentrated in the southern foothills of the Qilian Mountains and the upper reaches of the basin (Figure 3). The desertified land landscape types in Minqin County, Wuwei City, are dominated by shifting sand dunes, wind-eroded residual mounds, and exposed gravel areas; in Gulang County, the main landscape types are fixed sand dunes and semi-fixed sand dunes; while in Yongchang County, Jinchang City, wind-eroded residual mounds and semi-fixed sand dunes are predominant.

The changes in desertified land landscape types exhibit clear characteristics in different stages: from 1992 to 2002, wind-eroded residual mounds in the central and western regions decreased while semi-fixed sand dunes expanded; from 2002 to 2012, wind-eroded residual mounds in the central and western regions expanded again while semi-fixed sand dunes decreased; and from 2012 to 2022, exposed gravel areas in the northwest significantly expanded and extended

southward, while wind-eroded residual mounds spread eastward and merged with shifting sand dunes.

The centers of gravity of shifting sand dunes and exposed gravel areas are located in the northern part of the basin, while the centers of gravity of semi-fixed sand dunes and wind-eroded residual mounds are situated in the central region. The center of gravity of fixed sand dunes is located in the southern part. The specific migration trends are as follows: from 1992 to 2002, fixed sand dunes migrated southeast, and from 2002 to 2022, they migrated southwest, showing an overall trend of moving southwestward (Figure 3a). Semi-fixed sand dunes migrated southeast from 1992 to 2002, northwest from 2002 to 2012, and southwest from 2012 to 2022, with the center of gravity overall shifting southwestward (Figure 3b). Shifting sand dunes migrated northeast from 1992 to 2002, moved significantly northwest from 2002 to 2012, and then southeast from 2012 to 2022, with an overall trend of moving northeastward (Figure 3c). Wind-eroded residual mounds migrated significantly northeast from 1992 to 2002, northwest from 2002 to 2012, and then southeast from 2012 to 2022, with the center of gravity overall shifting eastward (Figure 3d). Exposed gravel areas migrated significantly northwest from 1992 to 2002, northeast from 2002 to 2012, and southward from 2012 to 2022, with an overall trend of moving westward (Figure 3e).



(a: Fixed sandy land; b: Semi-fixed sandy land; c: Mobile sandy land; d: Aeolian monadnocks; e: Bare gravel ground)

Figure 3. Spatial Distribution and Center of Gravity Changes of Desertified Land Landscapes in the Shiyang River Basin during Different Periods

3.3. Changes in Landscape Pattern Indices of Desertified Land

Landscape patterns reflect the spatial composition and distribution of landscape types within a region [36], while landscape pattern indices are statistical indicators that quantitatively characterize landscape features, reflecting the degree of landscape fragmentation and spatial heterogeneity.

At the patch level, the number of desertified land landscape patches (NP) and patch density (PD) in 1992, 2002, and 2022, ranked from highest to lowest, are as follows: wind-eroded residual mounds > semi-fixed sand dunes > fixed sand dunes > exposed gravel areas > shifting sand dunes. This indicates that wind-eroded residual mounds have the highest fragmentation and mosaic degree, making the landscape most dispersed, followed by semi-fixed sand dunes, while shifting sand dunes

are the most concentrated. In 2012, the NP and PD values of semi-fixed sand dunes surpassed wind-eroded residual mounds, making them the landscape type with the highest fragmentation and mosaic degree. For the patch shape index (LSI), semi-fixed sand dunes had the highest LSI values in both 1992 and 2012, indicating the most complex landscape shapes. In contrast, wind-eroded residual mounds had the highest LSI values in 2002 and 2022, indicating the most complex landscape shapes during these years. The patch aggregation index (AI) shows that shifting sand dunes have the highest aggregation degree, meaning their landscape is the most concentrated, while semi-fixed sand dunes have the lowest aggregation degree, indicating the most dispersed

landscape.

At the landscape scale, both the Shannon diversity index (SHDI) and Shannon evenness index (SHEI) initially increased and then decreased, ultimately showing a downward trend. This reflects the gradual aggregation of the desertified land landscape patterns in the basin and a reduction in fragmentation.

Overall, wind-eroded residual mounds and semi-fixed sand dunes have complex and dispersed landscape shapes, while shifting sand dunes are the most concentrated. The desertified land landscape patterns exhibit a trend toward centralization (Table 3).

Table 3. Landscape Pattern Indices of Desertified Land in the Shiyang River Basin

Years	Landscape types of desertification	Landscape pattern indices					
		NP	PD	LSI	AI	SHDI	SHEI
1992	Fixed sandy land	640	0.0205	28.8726	63.9093		
	Semi-fixed sandy land	774	0.0248	38.2419	38.2950		
	Mobile sandy land	228	0.0073	16.5152	84.1027	1.5544	0.9658
	Aeolian monadnocks	842	0.0270	35.7262	57.7919		
	Bare gravel ground	327	0.0105	17.3284	75.2489		
2002	Fixed sandy land	811	0.0278	38.6364	46.4104		
	Semi-fixed sandy land	987	0.0339	41.4222	38.6371		
	Mobile sandy land	230	0.0079	20.9946	78.0514	1.5588	0.9685
	Aeolian monadnocks	1030	0.0353	45.2601	48.1057		
	Bare gravel ground	327	0.0112	19.175	68.8518		
2012	Fixed sandy land	585	0.0200	31.0611	53.3578		
	Semi-fixed sandy land	910	0.0311	40.5769	37.5758		
	Mobile sandy land	149	0.0051	15.7745	85.3333	1.5281	0.9495
	Aeolian monadnocks	886	0.0303	38.7301	53.0283		
	Bare gravel ground	300	0.0103	16.4919	74.2217		
2022	Fixed sandy land	619	0.0223	32.4375	33.1117		
	Semi-fixed sandy land	895	0.0323	36.3636	26.3722		
	Mobile sandy land	232	0.0084	19.6236	78.6817	1.4805	0.9199
	Aeolian monadnocks	1140	0.0411	46.7312	50.2806		
	Bare gravel ground	402	0.0145	21.9259	73.5322		

(NP: Number of patches, reflecting the fragmentation of the landscape; PD: Patch density, reflecting the mosaic degree of the landscape; LSI: Patch shape index; AI: Patch aggregation index, reflecting the concentration of the landscape; SHDI: Shannon diversity index, reflecting the spatial heterogeneity of the landscape; SHEI: Shannon evenness index, reflecting the evenness of the landscape distribution [26])

3.4. Driving Factors of Changes in Desertified Land Landscape Patterns

The results of the single-factor detection (Figure 4a) show that temperature and precipitation have the strongest explanatory power for changes in the desertified land landscape patterns in the basin, with average q-values of 0.162 and 0.182, respectively. This indicates that these two factors are key drivers of the changes in desertified land landscape patterns. Following this, the average q-values for NDVI and cultivated land area are 0.121 and 0.101, respectively. Although their explanatory power is lower than that of temperature and precipitation, they still exert a certain influence on landscape pattern changes. In contrast, wind speed and grazing intensity have weaker explanatory power, with average q-values of 0.085 and 0.081, respectively. Population density and Gross Domestic Product (GDP) have the lowest average q-values of 0.005, indicating a very limited explanatory role in the changes of desertified land landscape patterns.

The interaction factor analysis (Figure 4b) indicates that the interaction effects are significantly stronger than the single-factor effects, with the predominant interaction types being two-factor enhancement and nonlinear enhancement. This suggests that changes in the desertified land landscape patterns in the basin are driven by a clear multi-factor

coupling mechanism. Among them, temperature and precipitation consistently show higher interaction explanatory power across all periods, and in most cases, they dominate the enhancement relationships of key factor combinations.

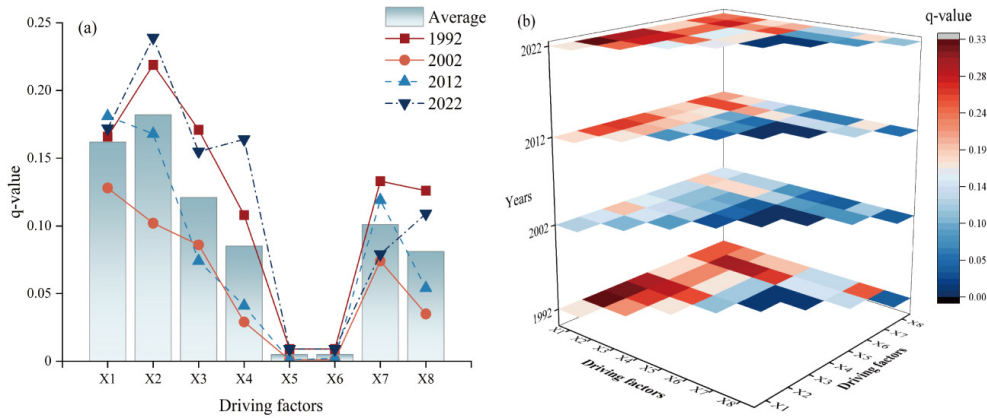
From a temporal perspective, the interaction relationships in 1992 were mainly characterized by enhancement: temperature $\cap$ wind speed, temperature $\cap$ population density, temperature $\cap$ GDP, as well as cultivated land area $\cap$ wind speed, cultivated land area $\cap$ population density, and cultivated land area $\cap$ GDP, all exhibited nonlinear enhancement. Other combinations were primarily two-factor enhancement. By 2002, the enhancement relationships were further strengthened and underwent structural adjustments: interactions between wind speed and all factors except grazing intensity showed nonlinear enhancement, and interactions between population density and other factors also exhibited nonlinear enhancement. The GDP $\cap$ population density interaction showed an independent relationship, while interactions among other factors were mainly nonlinear enhancement. In 2012, the interaction patterns stabilized: overall, interactions continued to predominantly exhibit nonlinear enhancement, but in key natural-ecological/land use combinations, clear two-factor enhancement emerged, such as temperature $\cap$ precipitation, temperature $\cap$ cultivated land area, temperature $\cap$ grazing intensity, as well as precipitation $\cap$ NDVI, precipitation $\cap$ wind speed,

precipitation $\cap$ cultivated land area, and precipitation $\cap$ grazing intensity, all showing two-factor enhancement. In 2022, significant changes in interaction relationships were observed again: most factor interactions shifted to two-factor enhancement, while in some "natural-human" coupling pairs, nonlinear enhancement relationships were maintained or strengthened, such as temperature $\cap$ population density, temperature $\cap$ GDP, temperature $\cap$ cultivated land area, as well as grazing intensity $\cap$ population density, and grazing intensity $\cap$ GDP, all showing nonlinear enhancement.

From 1992 to 2022, the interaction effects of temperature, precipitation, and NDVI were generally stronger than other combinations, consistently exhibiting nonlinear or two-factor enhancement. In contrast, the interactions among human factors (population density, GDP) were weaker, mainly

characterized by two-factor enhancement, with independent relationships observed in some years. Moreover, the nonlinear enhancement relationship between temperature $\cap$ wind speed persisted across all periods, demonstrating its continuous coupling amplification effect on changes in the desertified land landscape patterns.

Overall, the high explanatory power of temperature and precipitation in both single-factor and interaction factor analyses further highlights their core driving role in the changes of desertified land landscape patterns. In general, natural factors (especially temperature and precipitation) play a dominant role in the changes of desertified land landscape patterns in the basin, while human factors mainly exhibit a synergistic effect. Both natural and human factors jointly influence the desertified land landscape patterns in the basin.



(X1: Temperature; X2: Precipitation; X3: Normalized Difference Vegetation Index (NDVI); X4: Wind Speed; X5: Population Density; X6: Gross Domestic Product (GDP); X7: Cultivated Land Area; X8: Grazing Intensity)

Figure 4. Results of main effects and interaction detection

4. Discussion

4.1. Changes in Desertified Land Landscape Patterns

Using remote sensing images of the Shiyang River Basin from 1992 to 2022 as the data source, this study combines remote sensing, GIS, and landscape ecology methods to quantify changes in desertified land landscape patterns in the basin. The results reveal that from 1992 to 2022, the area of desertified land in the Shiyang River Basin consistently decreased (Figure 2), and the landscape patterns of desertified land showed a trend of reduction (Table 3). Over the long time scale, the areas of mild, moderate, severe, and extremely severe desertification in the Minqin Oasis all showed a decreasing trend [30]. Studies on the water resource characteristics of the Shiyang River Basin indicate that the total desertified land area in the basin reduced from 1975 to 2014 [23]. Long-term remote sensing monitoring of the Shiyang River Basin has shown that the oasis area has increased, while the desert area has decreased, reflecting the significant success of desertification control efforts in the basin [37]. Further research by Wei et al. [38] showed that from 2003 to 2008, the desertification area in the Minqin Oasis decreased, and the desertification trend was effectively controlled, consistent with the conclusions of this study.

From the perspective of landscape type changes, the area of desertified land has continually decreased, while non-desertified land landscapes have significantly expanded, reflecting the notable effectiveness of ecological restoration measures in the basin. Within the non-desertified land

landscape, the growth of cultivated land, forest and grassland, and built-up areas has compressed the distribution of desertified land landscapes, especially in the Minqin Oasis. After 2002, with the implementation of the "Key Management Plan for the Shiyang River Basin," protective measures such as sand control and land rehabilitation were introduced, leading to a significant decrease in the area of desertified land [10]. In terms of the spatial distribution of desertified land landscapes, they are mainly concentrated in the northern, central, eastern, and western parts of the middle and lower reaches of the basin, consistent with the geographic characteristics of the basin, which is surrounded by deserts on three sides [20,39]. However, it is noteworthy that during the study period, the centroid of the desertified land landscape shifted towards regions with relatively poorer ecological conditions. This trend, particularly the migration of moving sand dunes and wind-eroded landforms towards the northeast of the Badain Jaran Desert, aligns with the findings of previous studies [30], and may be influenced by a combination of regional wind-sand corridors, water resource management, and land use changes.

The results of the changes in landscape pattern indices indicate that both patch-level and landscape-level indicators generally show a declining trend during the study period (Table 3), suggesting that desertified land patches are becoming more consolidated, boundary shapes are gradually simplified, the degree of landscape fragmentation is weakening, and the overall landscape pattern is shifting towards a relatively stable and orderly structure. This trend aligns with studies on the reduction of landscape fragmentation in the Minqin Oasis from 1999 to 2013 [10],

which also indicate that under desertification control measures, desertified land has transformed from a scattered pattern into a more concentrated and blocky spatial configuration. This evolution in landscape patterns reflects, to some extent, the optimization of the regional ecosystem's spatial structure and, from a landscape ecology perspective, demonstrates the shift of land use towards ecological security and more stable ecological functions [40].

The evolution of landscape patterns not only reveals the phased transition of desertification in the Shiyang River Basin from expansion to degradation but also reflects the interaction between human activities and ecological restoration. The transformation of desertified land landscape patterns from fragmentation to concentration, with patch structures becoming more orderly, directly reflects the gradual restoration of ecosystem functions and the increasing effectiveness of desertification control measures. This evolution provides a foundational basis for the future construction of the basin's ecological security pattern and sustainable management [22,41].

4.2. Analysis of Main Driving Factors

The key to desertification control lies in the quantitative analysis of the driving mechanisms of factors in the desertification process [42]. This study uses the geographic detector model to explore the driving factors behind changes in the landscape patterns of desertified land. The results show that from 1992 to 2022, the changes in landscape patterns of desertified land in the Shiyang River Basin were significantly driven by natural factors, with a multi-factor synergistic effect. Changes in temperature, precipitation, and NDVI had high explanatory power for landscape pattern changes in the basin's desertified land. Among these, climate factors (temperature and precipitation) showed long-term explanatory power, highlighting their core role in landscape changes in the basin's desertified areas (Figure 4).

Studies on desertification in the Shiyang River Basin generally agree that environmental factors are the primary drivers, while human activities also have a profound impact on desertification [30, 43-44]. Other studies also point out that desertification in the Shiyang River Basin is a result of the combined effects of natural and human factors [24], which aligns with the findings of this study, showing that both natural and human factors have jointly influenced the changes in landscape patterns of desertified land over the past 30 years. Around 2010, comprehensive governance projects were implemented in the basin, such as sustained water transfer projects [45] and the "Grain-to-Green" reforestation and grassland restoration projects [46], which changed the local environment and effectively promoted ecological restoration. Precipitation not only directly influences vegetation growth and soil moisture but also amplifies its ecological effects through interactions with other natural factors like temperature. The increase in precipitation significantly promoted vegetation growth [47], expanded the oasis area [37], and raised the overall NDVI [21], indicating that climate factors, to some extent, affected desertification trends and highlighted the decisive impact of climate change on the ecological stability of the basin.

Furthermore, interaction detection results reveal that most factor interactions exhibited "two-factor enhancement" or even "nonlinear enhancement" relationships, indicating that desertification driving mechanisms are not isolated linear responses but rather complex processes driven by multi-

variable interactions. The nonlinear enhancement between wind speed and temperature remained significant, revealing that under the dual effects of wind erosion and enhanced evapotranspiration, surface structures are more prone to degradation, thereby accelerating desertification. Regarding human factors, while the explanatory power of population density as a single factor is weak, its nonlinear enhancement relationship with natural factors like temperature and precipitation suggests that human activities indirectly affect desertification by altering surface structures and resource utilization patterns. However, the interactions among human factors (population density, GDP, cultivated land area, and grazing intensity) are weak, indicating that the driving forces of human activities have not yet formed a strong coupling mechanism. This may be related to regional land development restrictions and policy interventions.

In conclusion, the changes in desertified land landscape patterns are primarily driven by natural factors. However, these changes exhibit multi-factor coupling characteristics at different stages. Therefore, future desertification control strategies should focus on strengthening the ability to adapt to climate change, improving regional water resource management efficiency, and addressing the potential impact of human activities on fragile ecological areas. This will enable more targeted and differentiated desertification control approaches. On the one hand, efforts should be intensified in afforestation and the protection of ecological infrastructure to promote vegetation restoration. On the other hand, scientifically sound restoration measures should be implemented to ensure the sustainable use of resources, thereby achieving coordinated development of both the ecological environment and socio-economic conditions in the basin [48].

5. Conclusion

This study analyzes the changes in the desertified land landscape and its driving factors in the Shiyang River Basin from 1992 to 2022, and the following conclusions are drawn:

(1) From 1992 to 2022, the desertified land landscape in the Shiyang River Basin showed a general trend of reduction over time, with the total area of desertified land decreasing by 4,631.86 km². Among the different landscape types, the fixed sand dune landscape experienced the greatest change (-2.31%), exhibiting a clear trend of retreat. Spatially, desertified land landscape types were primarily distributed in the non-riverine areas of the middle and lower reaches of the basin, forming a concentrated distribution zone with Minqin County at its core. The centers of gravity of fixed and semi-fixed sand dunes shifted overall to the southwest, while the shifting sand dunes and wind-eroded remnants expanded towards the northeast.

(2) The landscape pattern of desertified land in the Shiyang River Basin has shifted from a dispersed to a more concentrated distribution, with a significant reduction in the overall fragmentation (as indicated by patch number and patch density). Different types of desertified land landscapes show distinct characteristics: wind-eroded remnants and semi-fixed sand dunes exhibit complex patch shapes and are relatively dispersed, while shifting sand dunes display a high degree of aggregation. Landscape diversity (as measured by the Shannon Diversity Index) has decreased, indicating a trend towards relative stability in the desert ecological pattern of the basin. However, this conclusion requires further analysis through long-term monitoring and process-based

research.

(3) The changes in the desertified land landscape pattern in the Shiyang River Basin are primarily driven by natural factors, with climate elements (temperature and precipitation) remaining the core drivers. Interactions between factors are generally stronger than single-factor effects, with temperature and precipitation exhibiting nonlinear enhancement with other factors. Among human-driven factors, the interaction between cultivated land area and other factors is significant, indicating a driving mechanism characterized by natural dominance and human collaboration.

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