Spatiotemporal Changes in Desertification in the Arid Zone of Central Ningxia over the Past 50 Years and Its Driving Forces in the Reversal Period

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Abstract

The arid belt of central Ningxia is one of the most severely desertified regions in China and a core area of the campaign to control desertification in the "Ji-shaped bend" of the Yellow River. Based on a long-term desertification dataset spanning nearly 50 a (1975–2025), this study analyzed the spatiotemporal evolution characteristics and focused on the quantitative attribution of desertification changes during the reversal period. The results show that: (1) Over the past nearly 50 a, desertification in the study area generally showed a trend of first increasing and then decreasing, with the reversal point occurring in 1990. (2) In 2025, the desertified area in the study area was 4257.63 km2, representing a net decrease of 285.68 km2 (6.28%) compared with 1975; among the different degrees of desertification, extremely severe desertification showed the largest decline, with a reduction of 61.56%. Spatially, the reversal areas were mainly distributed in western Shapotou District, central and western Lingwu City, and central and northern Yanchi County. (3) Both geographical detector and partial least squares structural equation model analyses indicate that climatic factors were the dominant driving force for desertification reversal from 1990 to 2020, with aridity having the highest explanatory power (q value) for the spatial differentiation of desertification. After 2020, the explanatory power of population density increased rapidly (q value of 0.32), becoming the dominant factor driving desertification development in local areas, indicating that recent high-intensity human activities such as urban development and cultivated land reclamation have intensified desertification in local areas. The results provide a scientific basis for targeted desertification control in the "Ji-shaped bend" of the Yellow River.

Full Text

Spatiotemporal Changes in Desertification in the Arid Zone of Central Ningxia over the Past 50 Years and Its Driving Forces in the Reversal Period

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Abstract: The arid zone of central Ningxia is one of the areas with the most severe desertification in China and is also the core area of the Yellow River "Jiziwan"campaign. Based on a long time-series desertification dataset for nearly 50 years (1975—2025), this study carried out an analysis of the spatiotemporal evolution characteristics and focused on exploring the quantitative attribution of desertification changes during the reversal period. The results show that: (1) Over the past 50 years, desertification in the study area as a whole exhibited a trend of first increasing and then decreasing, with the reversal point occurring in 1990. (2) In 2025, the desertified area in the study area was 4257.63 km^2, a net decrease of 285.68 km^2 (6.28%) compared with 1975. Among the categories, extremely severe desertification showed the largest reduction, with a decrease of 61.56%; spatially, the reversal areas were mainly distributed in the western part of Shapotou District, the central-western part of Lingwu City, and the north-central part of Yanchi County. (3) Analyses using the Geodetector and the partial least squares structural equation model both indicate that climate factors were the dominant driving force of desertification reversal from 1990 to 2020, among which aridity had the highest explanatory power (q value) for the spatial differentiation of desertification; after 2020, the explanatory power of population density increased rapidly (q value of 0.32), becoming the dominant factor driving the development of desertification in local areas, indicating that recent high-intensity human activities such as urban development and land reclamation have intensified the development of desertification in some local areas. The research results can provide scientific evidence for precise desertification control in the Yellow River "Jiziwan" .

Keywords: spatiotemporal change; desertification index; Geodetector; partial least squares structural equation model; arid zone of central Ningxia

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Desertification is one of the most important ecological and environmental issues in today' s world, and China is one of the countries most seriously affected by desertification[1-2]. Since signing the *United Nations Convention to Combat Desertification* in 1994, China has earnestly fulfilled its responsibilities and obligations under the convention, formulated national action plans for convention implementation, and actively participated in global desertification governance. Ningxia Hui Autonomous Region (hereinafter referred to as Ningxia) is located in northwestern China, at the intersection of the Inner Mongolian Plateau, the Loess Plateau, and the Qinghai-Tibet Plateau. Surrounded by deserts on three sides, it is one of the regions in China where desertification is relatively severe, and it is also an important ecological security barrier in northern China. The arid zone of central Ningxia is the concentrated distribution area of desertification in Ningxia, accounting for 92.58% of the region' s desertified area[3]. In recent years, Ningxia has continuously implemented major ecological restoration projects such as the construction of the "Three-North"shelterbelt system and the enclosure and protection of desertified land; desertification control has achieved remarkable results, and the regional ecological environment has gradually improved. However, affected by the regional arid and windy climatic conditions and unreasonable human activities, wind-sand erosion remains strong throughout the region, desertification problems are prominent, and the fragile ecological system has not yet been fundamentally reversed. Therefore, exploring the spatiotemporal change patterns and driving forces of land desertification in this region is of great significance for winning the Yellow River "Jiziwan" campaign and promoting the construction of the ecological protection and high-quality development pilot zone in the Yellow River Basin.

For a long time, the spatiotemporal changes of desertification have been an important focus of the Chinese government and scholars[4]. Since the early 1980s, researchers have carried out a large number of studies based on remote sensing technology at different scales such as the national, regional, and watershed scales. From 1994 to 2019, once every 5 years, six rounds of national monitoring of desertification and sandy desertification were completed[5]. At the national scale, although results differ owing to differences in data sources and research methods, with 2000 as a key time node, the area and degree of change of desertification have differed.

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The view that China' s desertification as a whole has shown a reversal trend has basically become a consensus[^6-^8]. However, at regional and watershed scales, desertification conditions in different study areas are relatively complex. Owing to the combined effects of natural factors (such as climate fluctuations, geomorphology, and soil conditions) and human activities, such as changes in land-use modes, water-resource development and utilization, and ecological engineering, the timing of desertification development or reversal varies. Relevant studies have conducted in-depth analyses of 29 typical desert and desertification regions in northern China and found that, in some typical regions, the timing of desertification reversal is not consistent with the national-scale timing of desertification reversal (2000). For example, mitigation or reversal had already appeared in the Shiyang River Basin and the lower Yellow River plain by the late 1970s; deserts such as the Kubuqi Desert and the Tengger Desert mostly showed reversal around 1990; and the source region of the Yangtze River showed a relatively later reversal (around 2005)[^9–^10]. This indicates that there are significant differences in the evolutionary processes of desertification and in key reversal nodes among different regions. Therefore, it is necessary to carry out long-term dynamic monitoring of desertification at different regional scales, so as to provide a scientific basis for accurately identifying governance effectiveness and scientifically formulating sand-control and desertification-control strategies.

Research on the driving forces of spatiotemporal changes in desertification is a prerequisite for scientifically formulating desertification-control plans[^4]. At present, whether desertification is dominated and driven by natural factors or by human factors remains controversial[^11–^14]. The ultimate reason is that the driving factors do not exist independently; rather, they are intertwined, influence one another, and jointly act on the desertification process. Traditional statistical analysis methods can reveal simple relationships between one or a few factors and desertification, but they have difficulty comprehensively resolving the complex interactions and internal causal mechanisms among multiple factors[^15–^16]. Geographical detectors can effectively detect the degree to which different driving factors influence the spatial distribution of desertification, as well as interactions among factors, but they are relatively weak in causal inference[^17]. Structural equation models, on the basis of considering correlations among multiple variables, can construct causal relationship models and quantitatively evaluate the direct and indirect effects of various driving factors on desertification[^18]. Combining the two methods and applying them to research on the driving forces of desertification not only makes it possible to screen out key driving factors, but also further and deeply analyze the causal paths and effect strengths among these factors, thereby comprehensively interpreting the driving forces of desertification from different perspectives, overcoming the limitations of a single method, and providing more comprehensive, in-depth, and accurate scientific understanding for desertification research.

As an important component of the Yellow River's "Ji-shaped bend," the arid belt of central Ningxia has received much attention for its spatiotemporal changes in desertification, and it is one of the earliest regions in China to carry out desertification prevention and control. In the 1950s, the Shapotou Desert Research Experimental Station and the Baijitan National Sand-Prevention Forest Farm were established, and the history of sand control exceeds 70 years. The region is located in an arid and semi-arid zone, with a fragile ecological environment and relatively prominent desertification problems. Over the past several decades, affected by unstable precipitation, frequent sand-driving wind activity, unsuitable human activities, and other factors, the risk of desertification has been severe. Against the national backdrop of overall desertification reversal, Ningxia has implemented a series of sand-prevention and sand-control projects in its central arid belt and achieved certain results, yet some areas still face the risk of desertification. Therefore, studying the spatiotemporal variation characteristics of desertification in the arid belt of central Ningxia and analyzing the underlying driving factors are of important practical significance for formulating targeted sand-prevention and sand-control strategies and improving the regional ecological environment. However, most existing studies focus on long-term fixed-point observations of desertification and its prevention and control in the study area, while remote-sensing monitoring research on desertification at the regional scale is still clearly insufficient. In view of this, based on Landsat series satellite images, this study interprets a nearly 50-year (1975–2025) long-term desertification dataset through remote sensing, analyzes the spatiotemporal variation characteristics of desertification in the arid region of central Ningxia over nearly 50 years, and, through geographical detectors and a partial least squares structural equation model (PLS-SEM), reveals the driving mechanisms of desertification reversal, providing a scientific basis for regionally scientific and rational sand prevention and control.

1 Overview of the Study Area

The arid belt of central Ningxia is located in the combined zone of different geomorphic units, including the Loess Plateau, the Mu Us Sandy Land, the Tengger Desert, the Mongolian Plateau, and the alluvial plain along the Yellow River. It is a typical ecologically fragile area in Ningxia. The administrative scope of the region involves Lingwu City of Yinchuan City; Qingtongxia City, Litong District, and Hongsibu District of Wuzhong City; Tongxin County and Yanchi County; and Shapotou District and Zhongning County of Zhongwei City, with a total area of 2.84×10^4 km^2 (Fig. 1). The climate belongs to a temperate continental arid and semi-arid climate, with annual precipitation between 120 and 240 mm, mostly concentrated in July–September; annual evaporation is 2027.8 mm; the mean annual temperature is 10.8 °C[^19]. Disaster weather such as winter–spring drought and sandstorms occurs frequently, and the number of days with sand-raising winds above 6 m · s^{-1} is 45–60 d[^3]. Elevation in the region ranges from 1055 to 2622 m. In terms of geomorphic types, the southern part is dominated by loess hilly and gully areas, while the northern part consists of hilly terraces and crisscrossing gullies, with undulating beams and ridges and highly fragmented terrain[^20]. The soils are mainly aeolian sandy soil and sierozem, with an extremely high sand-particle content; vegetation types are mainly grassland and desert steppe, with coverage below 20%[^3]. The loose soil substrate and low vegetation cover provide ample environmental conditions for the development of desertification.

2 Data and Methods

2.1 Data Sources

(1) Desertification data. These include six periods of data: 1975, 1990, 2000, 2010, 2020, and 2025. The first five periods are data products produced by this research team under a unified interpretation system and classification standards, and have been published by the National Earth System Science

Data Center (https://

(a) Geographic location of the study area (b) Overview of the study area

Note: Based on the standard map with approval number GS(2020)4619 from the map service website of the Ministry of Natural Resources; the base-map boundaries were not modified. The same applies below.

Figure 1 Schematic diagram of the study area

Fig. 1 Schematic diagram of the study area

www.geodata.cn)[5]. To ensure consistency between the earlier and later data, the 2025 desertification data were obtained by visual interpretation on the basis of the existing 2020 desertification data. The specific procedure was as follows: using Landsat 8/9 OLI remote-sensing images from 2020 and 2025 as the main data sources, supplemented by contemporaneous Sentinel-2 images, and according to the classification criteria proposed by Wang Tao[9], desertification was divided by degree into slight desertification, moderate desertification, severe desertification, and extremely severe desertification. In combination with field survey sample points, the 2020 desertification data were used as the base map, and dynamic-change patches in the two periods of remote-sensing images were delineated through visual interpretation, thereby dynamically updating the 2020 desertification data to 2025. The obtained data were verified for accuracy using field sample points (323 points); the overall accuracy of desertification classification in the study area in 2025 was 90.4%. For the classification criteria and dynamic updating method, see the relevant literature[5].

(2) Driving-factor data. The driving factors selected in this study mainly include four categories—topographic factors, climatic factors, human activities, and soil vegetation—with a total of 21 items. Information on data sources is shown in Table 1. Data processing included data clipping, resampling, data interpolation, data synthesis, projection transformation, and format conversion. The spatial resolution of all data was 1 km, the projected coordinate system was WGS_1984_Albers, and the data format was GeoTIFF.

2.2 Research Methods

2.2.1 Desertification index

The desertification index (NADI) is a quantitative indicator that transforms the original area data for different degrees of desertification through mathematical transformation, making it a more intuitive and comparable measure of the degree of regional desertification. Studies have shown that, compared with vegetation indices, it is more suitable as a dependent variable for analyzing the driving factors of desertification. Therefore, this study used NADI to analyze desertification characteristics and driving factors. The specific calculation formula is as follows:

$$\text{NADI} = (0.25S_{\text{SL}} + 0.5S_{\text{M}} + 0.75S_{\text{S}} + S_{\text{VS}})/S_{\text{A}} \qquad (1)$$

In the formula: NADI is the desertification index, with values ranging from 0 to 1. A NADI value of 0 indicates that the grid has no desertification; the larger the NADI, the more severe the desertification within the grid. A NADI value of 1 indicates that the grid is extremely severely desertified. S_{SL} is the area of slight desertification within the grid; S_{M} is the area of moderate desertification within the grid; S_{S} is the area of severe desertification within the grid; S_{VS} is the area of extremely severe desertification within the grid; and S_{A} is the total area of the grid. In this study, because the resolution of the desertification-degree data was 30 m and the resolution of the driving-factor data was 1 km, NADI was calculated using a 1 km × 1 km grid to facilitate subsequent analysis of the driving factors of desertification.

2.2.2 Geodetector

Geodetector is a spatial analysis method[21] that can better avoid multicollinearity and nonlinear relationships among driving factors[22]. In this study, the explanatory power of each potential driving factor for the spatial distribution of desertification was evaluated by calculating the q value, thereby identifying the dominant factors affecting desertification. The analysis was completed using the GeoDetector package in R. The specific calculation formula is as follows:

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

In the formula: q is the explanatory power of the Geodetector factor, ranging from 0 to 1; the larger the q value, the stronger the explanatory power of that factor for the spatial distribution of desertification.

Table 1 Data sources and processing methods of driving factors

Tab. 1 Data sources and processing methods of driving factors

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Topographic factors	Elevation	90 m	–	–	Google Earth Engine; digital elevation model data were directly exported from the Google Earth Engine platform and resampled
Topographic factors	Slope	90 m	–	–	Google Earth Engine; slope was calculated from digital elevation model data on the Google Earth Engine platform and exported

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Topographic factors	Aspect	90 m	–	–	Google Earth Engine; aspect was calculated from digital elevation model data on the Google Earth Engine platform and exported
Climatic factors	Aridity	1 km	a	1990—2020	National Earth System Science Data Center; obtained by directly converting the data in generic grid format

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Climatic factors	Humidity index	1 km	a	1990—2020	National Earth System Science Data Center; obtained by directly converting the data in generic grid format
Climatic factors	Spring wind speed	1 km	a	1990—2020	National Earth System Science Data Center; the mean wind speed for March, April, and May was calculated using Python

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Climatic factors	Winter wind speed	1 km	a	1990–2020	National Earth System Science Data Center; the mean wind speed for December, January, and February was calculated using Python
Climatic factors	Annual mean wind speed	1 km	a	1990–2020	National Earth System Science Data Center; the mean wind speed for January–December was calculated using Python

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Climatic factors	Probability of erosive wind speed occurrence	0.25°	a	1990–2020	Google Earth Engine; ERA5 3 h wind speed data were used to calculate the proportion of 3 h periods in each year with wind speed >4.5 m · s^{-1}, and then the sample was interpolated and resampled to 1 km

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Climatic factors	Annual precipitation	1 km	a	1990—2020	National Earth System Science Data Center; total precipitation for January–December was calculated using Python
Climatic factors	Mean temperature in the growing season	1 km	a	1990—2020	National Earth System Science Data Center; the mean temperature in the growing season from May to September was calculated using Python

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Human activities	Land use	30 m	5 a	1990—2020	Independently produced data of the project team; an object-oriented random forest method combined with visual interpretation was used, with data accuracy >90%
Human activities	Population density	1 km	5 a	1990—2020	National Earth System Science Data Center
Human activities	Gross regional product	1 km	5 a	1992—2020	National Earth System Science Data Center

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Soil and vegetation	Vegetation type	1:1000000	–	–	National Tibetan Plateau Scientific Data Center; vector data were directly converted to 1 km grid data
Soil and vegetation	Soil organic matter	1:1000000	–	–	National Tibetan Plateau Scientific Data Center; vector data were directly converted to 1 km grid data

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Soil and vegetation	Soil type	1:1000000	–	–	National Tibetan Plateau Scientific Data Center; vector data were directly converted to 1 km grid data
Soil and vegetation	Soil texture	1:1000000	–	–	National Tibetan Plateau Scientific Data Center; vector data were directly converted to 1 km grid data

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Soil and vegetation	Clay content	1:1000000	–	–	National Tibetan Plateau Scientific Data Center; vector data were directly converted to 1 km grid data
Soil and vegetation	Silt content	1:1000000	–	–	National Tibetan Plateau Scientific Data Center; vector data were directly converted to 1 km grid data

Variable type	Variable name	Spatial resolution	Temporal resolution	Years	Source and processing method
Soil and vegetation	Sand content	1:1000000	–	–	National Tibetan Plateau Scientific Data Center; vector data were directly converted to 1 km grid data

the stronger the effect; L is the number of classification intervals; N is the total number of samples in the study area; N_h is the number of samples in the h-th classification interval; and σ^2 and σ_h^2 are the variances of NADI in the whole area and within the h-th classification interval, respectively.

2.2.3 Partial least squares structural equation model

PLS-SEM integrates principal component analysis, multiple regression analysis, and path analysis functions[^23]. Its basic principle is to construct a structural equation model through latent variables and observed variables, so as to reflect the complex relationships among variables. In this study, the model takes desertification driving factors as observed variables and NADI as a latent variable. Through the model, the direct and indirect effects of each factor on NADI are estimated, characterizing the causal relationship network among factors in the desertification process and between these factors and desertification change. The analysis was completed using the `plspm` package in R.

3 Results and Analysis

3.1 Current distribution of desertification

In 2025, the total desertified area in the arid zone of central Ningxia was 4257.63 km^2. Of this, the area of mild desertification was 1452.07 km^2 (34.11%), moderate desertification was 1229.57 km^2 (28.88%), severe desertification was 1041.62 km^2 (24.46%), and extremely severe desertification was 534.37 km^2 (12.55%)

(Fig. 2a). Mild and moderate desertification are mostly distributed in interspersed patches in Yanchi County and Hongsibu District east of the Yellow River; severe and extremely severe desertification are concentrated in large contiguous patches in Shapotou District and Lingwu City. Spatially, the overall pattern is "more in the east and west, less in the middle, concentrated and contiguous," mainly concentrated in Shapotou District on the southeastern margin of the Tengger Desert and in Lingwu City and Yanchi County on the western margin of the Mu Us Sandy Land (Fig. 2b). The NADI is 0.08. The counties and districts, in descending order of desertification degree represented by NADI, are Lingwu City, Yanchi County, Shapotou District, Litong District, Hongsibu District, Qingtongxia City, Zhongning County, and Tongxin County.

3.2 Spatiotemporal changes in desertification

3.2.1 Characteristics of temporal changes in desertification

From 1975 to 2025, the total area of desertified land in the study area showed a trend of increasing first and then decreasing. It increased from 4543.31 km^2 in 1975 to 4748.96 km^2 in 1990, and then continued to decline to 4257.63 km^2 in 2025, with a net decrease of 285.68 km^2 over 50 a, down 6.29% compared with 1975. Correspondingly, NADI also increased from 0.10 in 1975 to 0.11 in 1990, and then decreased to 0.08 in 2025. Both the total desertified area and NADI indicate that aeolian desertification in the arid zone of central Ningxia began to reverse in 1990 (Fig. 3).

In terms of desertification degree, in 1990 the study area was dominated by extremely severe desertification, accounting for 33.38%; in 2025, mild desertification rose to 34.11% and became the dominant type, indicating that the study area not only achieved a net reduction in the total desertified area, but that the degree of desertification also shifted overall from severe toward mild.

Judging from the changing trends of different desertification degrees (Figs. 3–4), mild desertification increased from 1251.33 km^2 in 1975 to 1553.17 km^2 in 2020, and then decreased to 1452.07 km^2 in 2025. The increase in mild desertification from 1975 to 2000 mainly came from non-desertified areas; the increase from 2010 to 2020 mainly came from the reversal of moderate desertification; and the decrease from 2020 to 2025 was converted to non-desertification. Moderate desertification decreased from 1086.83 km^2 in 1975 to 1063.48 km^2 in 1990, and then increased to 1229.57 km^2 in 2025. The decrease in moderate desertification from 1975 to 1990 was mainly converted to extremely severe desertification, while the decrease in moderate desertification from 1990 to 2025 mainly came from the reversal of severe and extremely severe desertification. Severe desertification decreased from 814.84 km^2 in 1975 to 692.67 km^2 in 2000, and then increased to 1041.62 km^2 in 2025. The decrease in severe desertification from 1975 to 2000 was mainly converted to severe desertification, while the increase in severe desertification from 2000 to 2025 mainly came from the reversal of extremely severe desertification. Extremely severe desertification increased from

Fig. 2 Area proportion and spatial distribution of aeolian desertification in the central Ningxia arid zone in 2025

Figure 1: Fig. 2 Area proportion and spatial distribution of aeolian desertification in the central Ningxia arid zone in 2025

Fig. 3

Figure 2: Fig. 3

1390.31 km^2 in 1975 to 1585.24 km^2 in 1990, and then decreased to 534.37 km^2 in 2025. The increase in extremely severe desertification in 1975 mainly came from the conversion of severe desertification; the decrease in extremely severe desertification from 1990 to 2000 was mainly reversed to non-desertification,

(a) Area proportion of different types of desertification

(b) Spatial distribution of desertification

Legend

Category	Meaning
Provincial boundary	Provincial boundary
County boundary	County boundary
River	River
Mild desertification	Mild desertification
Moderate desertification	Moderate desertification
Severe desertification	Severe desertification
Extremely severe desertification	Extremely severe desertification

Desertification degree

Color/category	Area and proportion
Mild desertification	1452.07 km^2; 34.11%
Moderate desertification	1229.57 km^2; 28.88%
Severe desertification	1041.62 km^2; 24.46%
Extremely severe desertification	534.37 km^2; 12.55%

Fig. 2 Area proportion and spatial distribution of aeolian desertification in the central Ningxia arid zone in 2025

Note: NADI is the desertification index. The same below.

Fig. 3 Changes in the aeolian desertification area and NADI in the central Ningxia arid zone from 1975 to 2025

Fig. 4 Sankey diagram of flow directions of different aeolian desertification types in the central Ningxia arid zone from 1975 to 2025

Fig. 4

Figure 3: Fig. 4

From 2000 to 2020, the decrease in extremely severe desertification was mainly converted into severe desertification; from 2020 to 2025, the decrease in extremely severe desertification was mainly converted into severe desertification and non-desertification.

3.2.2 Spatial characteristics of desertification change

Based on the spatial distribution of desertification change between successive years, desertification change in the region was divided into development zones and reversal zones (Fig. 5). Overall, from 1975 to 2025, the spatiotemporal differences in desertification change in the central Ningxia arid zone were significant. The area of desertification that changed over the past nearly 50 years accounted for 49.42%, with reversal predominating and development as a supplement. Among these, reversal zones were mainly distributed in western Shapotou District, the central-western part of Lingwu City, and the central-northern part of Yanchi County, while development zones were mainly distributed in northeastern Shapotou District and at the junction of Yanchi County and Lingwu City (Fig. 5a). From 1975 to 1990, desertification in the study area was dominated by development, mainly distributed in Yanchi County of the Hedong sandy land; reversal zones were scattered in Zhongwei City and Lingwu City (Fig. 5b). From 1990 to 2000, the area of desertification reversal in the study area was slightly larger than the area of development; reversal zones were mainly distributed in Shapotou District and the central part of Yanchi County in the Hedong sandy saline-alkali land, while development zones were mainly distributed on the north and south sides of Lingwu City and Yanchi County within the Hedong sandy land. The patterns of desertification change in the two periods 2000–2010 and 2010–2020 were basically consistent, dominated by desertification reversal, mainly distributed in the marginal zones around the Hedong sandy land and along the southern margin of the Tengger Desert. From 2020 to 2025, desertification in the study area continued to reverse, but the area of development zones increased compared with 2000–2020; among them, the southern margin of the Tengger showed a large-area reversal trend, while development zones were located in the northeastern part of the Tengger Desert Shapotou District.

3.3 Analysis of driving forces of desertification change

3.3.1 Analysis of driving forces of spatial differentiation of desertification based on geographical detectors

The results of the geographical detector factor detection (Table 2) show that, from 1990 to 2020, the explanatory power (q value) of different types of driving factors for the spatial differentiation of desertification exhibited significant spatiotemporal differences. Specifically, climatic factors had the strongest overall explanatory power for the spatial differentiation of desertification (mean q value of 0.21). Among them, aridity ranked first in 1990, 2010, and 2020 (highest q value of 0.23). The humidity index and annual precipitation also consistently ranked near the front, indicating that changes in moisture are the core factors

Fig. 5 Spatial distributions of aeolian desertification changes in the central Ningxia arid zone from 1975 to 2025

Figure 4: Fig. 5 Spatial distributions of aeolian desertification changes in the central Ningxia arid zone from 1975 to 2025

in the spatial differentiation of desertification. The seasonal difference in wind-speed factors was significant: spring wind speed ranked first in 2000 in terms of q value, because spring is a key period for vegetation green-up, and strong winds readily damage seedlings and topsoil, aggravating desertification; winter wind speed ranked third in 1990 in terms of q value, because in winter vegetation is dormant, the ground surface is exposed, and wind speed has a significant basic driving effect on wind erosion; annual mean wind speed ranked second in 2010 in terms of q value, reflecting the comprehensive influence of aeolian driving forces throughout the year. The three respectively correspond to the impacts of wind speed on desertification in different periods. The q value of human activity factors showed a marked upward trend. Among them, in 2020 the q value of population density jumped to 0.32 (ranked first), indicating that after 2020, high-intensity human activities such as urban expansion and land reclamation became important driving forces affecting desertification change in the study area. The q value of land use remained consistently between 0.15 and 0.21, reflecting the sustained and stable influence of land-use type change on desertification. Although the q value of the soil vegetation factor was relatively low, it reflected differences in the basic resistance to wind erosion among different vegetation communities and soil textures. The q value of the topographic factor was always the lowest ($q < 0.04$), indicating that at the regional scale, topography had a limited direct impact on desertification.

3.3.2 Path effects of desertification driving factors based on PLS-SEM

Taking NADI as the dependent variable and different types of driving factors as independent variables, PLS-SEM path analysis was used to further reveal the direct, indirect, and total effects among the factors (Fig. 6, Table 3). Because a larger NADI value indicates a higher degree of desertification, a negative effect indicates that the factor inhibits desertification development (i.e., promotes reversal), whereas a positive effect indicates that the factor drives desertification ...

(a) 1975–2025
Legend
Provincial boundary
County boundary
River
Aeolian desertification change trend
Reversal zone
Development zone

Stable/unchanged zone

(b) 1975–1990
Legend
Provincial boundary
County boundary
River
Aeolian desertification change trend
Reversal zone
Development zone
Stable/unchanged zone

(c) 1990–2000
Legend
Provincial boundary
County boundary
River
Aeolian desertification change trend
Reversal zone
Development zone
Stable/unchanged zone

(d) 2000–2010
Legend
Provincial boundary
County boundary
River
Aeolian desertification change trend
Reversal zone
Development zone
Stable/unchanged zone

(e) 2010–2020
Legend
Provincial boundary
County boundary
River
Aeolian desertification change trend
Reversal zone
Development zone
Stable/unchanged zone

(f) 2020–2025
Legend
Provincial boundary
County boundary
River
Aeolian desertification change trend

Reversal zone
Development zone
Stable/unchanged zone

Fig. 5 Spatial distributions of aeolian desertification changes in the central Ningxia arid zone from 1975 to 2025

Desertification developed. In 1990, 2010, and 2020, the total effects of climatic factors were all negative and had the largest absolute values ($-0.41 \sim -0.55$), indicating that they were the principal driving factors for the reversal of desertification. This mainly resulted from changes in climatic conditions, such as decreased aridity, increased annual precipitation, and reduced wind speed, which directly weakened wind erosivity and enhanced the potential for vegetation growth, thereby promoting the reversal of desertification

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. Path decomposition showed that the direct effect of climatic factors accounted for more than 90% (for example, in 1990 the direct effect was −0.45, and the total effect was −0.41), while the indirect effect was weak (0.04), indicating that climate influenced desertification mainly through direct regulation. The total effect of soil-vegetation factors was likewise negative ($-0.14 \sim -0.21$), making them secondary driving factors promoting desertification reversal. Human-activity factors had negative effects during 1990–2010, but turned positive in 2020 (0.03). The negative effects during 1990–2010 originated from government-led ecological restoration projects such as the "Three-North" shelterbelt program and the enclosure of desertified land, which increased the proportion of forest and grassland in land use and inhibited the development of desertification. The shift to a positive effect in 2020 was due to intensified human activities caused by increased population density, which drove desertification development; this is consistent with the result that the population-density q value was highest in the geographical detector in 2020. The total effects of topographic factors were positive in all four years but had the smallest values ($0.01 \sim 0.07$). Path decomposition showed that although topographic factors had positive direct effects, they generated larger indirect negative effects through their negative influence on climatic factors and human activities; after the two offset each other, the total effect was weak. This result explains why the q value of topographic factors in the geographical detector was always the lowest, and also indicates that traditional single–

Table 2 Ranking and q value of the contribution degrees of the driving factors

Variable type	Variable name	1990 *q* value	1990 rank	2000 *q* value	2000 rank	2010 *q* value	2010 rank	2020 *q* value	2020 rank
Topographic factors	Elevation	0.04	17	0.03	18	0.03	17	0.02	17
Topographic factors	Slope	0.01	21	0.01	21	0.01	21	0.01	21
Topographic factors	Aspect	0.02	20	0.02	20	0.03	18	0.03	14
Climatic factors	Aridity	0.17	1	0.08	10	0.23	1	0.22	2
Climatic factors	Humidity index	0.14	7	0.15	5	0.21	4	0.22	3
Climatic factors	Spring wind speed	0.11	8	0.20	1	0.20	5	0.03	15
Climatic factors	Winter wind speed	0.16	3	0.16	4	0.02	19	0.01	20
Climatic factors	Annual mean wind speed	0.15	5	0.17	3	0.22	2	0.01	18
Climatic factors	Probability of dust-raising wind occurrence	0.09	11	0.06	14	0.11	8	0.11	6
Climatic factors	Annual precipitation	0.16	4	0.10	7	0.20	6	0.20	4

Variable type	Variable name	1990 *q* value	1990 rank	2000 *q* value	2000 rank	2010 *q* value	2010 rank	2020 *q* value	2020 rank
Climatic factors	Mean temperature in the growing season	0.04	16	0.05	17	0.03	16	0.03	16
Human activities	Land use	0.15	6	0.17	2	0.21	3	0.17	5
Human activities	Population density	0.09	9	0.11	6	0.10	9	0.32	1
Human activities	Gross regional product	0.17	2	0.09	9	0.16	7	0.05	12
Soil and vegetation	Vegetation type	0.03	18	0.06	15	0.07	13	0.08	9
Soil and vegetation	Soil organic matter	0.07	13	0.08	12	0.10	10	0.10	7
Soil and vegetation	Soil type	0.07	14	0.08	11	0.07	14	0.06	11

Variable type	Variable name	1990 q value	1990 rank	2000 q value	2000 rank	2010 q value	2010 rank	2020 q value	2020 rank
Soil and vegetation	Soil texture	0.03	19	0.03	19	0.02	20	0.01	19
Soil and vegetation	Clay content	0.05	15	0.05	16	0.04	15	0.03	13
Soil and vegetation	Silt content	0.08	12	0.08	13	0.08	12	0.07	10
Soil and vegetation	Sand content	0.09	10	0.09	8	0.09	11	0.08	8

Note: The q value is the explanatory power.

On the one hand, this method tends to underestimate the importance of factors that indirectly influence desertification.

4 Discussion

Remote-sensing monitoring results over nearly 50 years show that desertification in the arid zone of central Ningxia exhibited a significant decreasing trend in both degree and area from 1975 to 2025. The area of extremely severe desertification decreased by 61.56%; the overall NADI declined from 0.11 in 1990 to 0.08 in 2025, with the reversal turning point occurring in 1990. Compared with the national scale after 2000, this was about 10 years earlier [6, 27], indicating that desertification control in this region began relatively early and that the effectiveness of desertification control was more pronounced.

The main driving force of desertification reversal in the arid zone of central Ningxia was the synergistic effect of climatic factors and human activities. At the long-term scale from 1990 to 2020, both the geographical detector and PLS-SEM showed that climatic factors made the greatest contribution—with aridity having the highest q value—which is consistent with the conclusions of Li Sen et al. [5] for the entire "Ji" -shaped bend region of the Yellow River. PLS-SEM further verified that the influence was dominated by direct regulation, reflecting the core driving role of climate change in the reversal of desertification. Since the 1950s, a series of sand-prevention and sand-control projects have been continuously implemented in this region—including the Shapotou Desert Research and Experiment Station in 1953, the Baijitan Sand-Control Experimental Station in 1955, the two major demonstration projects of the Yellow River "Ji" -shaped bend campaign in 2023 for fixing shifting sand along the Tengger Desert margin and the Maowusu mobile-sand-land systematic management project, and the expansion of areas of green land along the Yellow River by 3,600 km^2 from 1987 to 2017, mainly through the increase of cultivated land [28]. In local areas, these projects played an important role in promoting and consolidating the reversal of desertification. This corresponds to the negative effect of human activities on NADI from 1990 to 2010 in the PLS-SEM. The rapid shrinkage of extremely severe desertification from 2020 to 2025 was directly related to recent major engineering projects. However, despite the overall reversal trend, desertification development still occurred in local areas. From 2020 to 2025, the northeastern part of Shapotou shifted from non-desertification to slight desertification. This is highly consistent with the result of the geographical detector that the q value of population density ranked first in 2020, and also closely matches the PLS-SEM result that the total effect of human activities changed from negative to positive in 2020, indicating that local desertification development at this stage was mainly driven by high-intensity human activities. Comparison of remote-sensing images shows that human activities mainly manifested as urban expansion, cultivated-land reclamation, and disturbance from energy and industrial-mining project construction [29].

This study is consistent with the view of Zhao Hongyan et al. [16] and Wang Yaozong et al. [15] that "human

(a) 1990 (b) 2000

(b) 2010 (d) 2020

Note: Arrows indicate connections between latent variables; dashed lines indicate negative effects, and solid lines indicate positive effects. ***and*** indicate effects passing significance tests at $P < 0.05$ and $P < 0.01$, respectively.*

Figure 6 Relationship of impacts of latent variables on desertification from 1990 to 2020

Fig. 6 Relationships of impacts from latent variables on aeolian desertification from 1990 to 2020

Table 3 Direct, indirect, and total effects of driving variables on desertification

Tab. 3 Direct, indirect and total effects of driving factors on aeolian desertification

Year	Effect	Human activities	Soil vegetation	Topographic factors	Climatic factors
1990	Direct effect	−0.11	−0.21	0.23	−0.45
1990	Indirect effect	–	0.01	−0.22	0.04
1990	Total effect	−0.11	−0.21	0.01	−0.41
2000	Direct effect	−0.12	−0.20	0.22	0.27
2000	Indirect effect	–	−0.01	−0.17	−0.01
2000	Total effect	−0.12	−0.21	0.05	0.26
2010	Direct effect	−0.08	−0.17	0.35	−0.53
2010	Indirect effect	–	0.00	−0.33	0.03
2010	Total effect	−0.08	−0.17	0.03	−0.50
2020	Direct effect	0.03	−0.14	0.46	−0.51
2020	Indirect effect	–	−0.00	−0.39	−0.04
2020	Total effect	0.03	−0.14	0.07	−0.55

The conclusion that "human activities are the main driving factor" is discrepant, for the following reasons:

On the one hand, desertification is represented differently. This study uses NADI at a 1 km grid scale to comprehensively characterize the structure and intensity of desertification at different grades, focusing on differences in long-term background conditions and regional scales; whereas Wang Yaozong et al.[15] mostly used area change or pixel-level change as the dependent variable, making it more sensitive to land use and to boundary displacement and patch conversion caused by human disturbance. On the other hand, the connotations and pathways of action of human-activity variables are delineated differently. Many existing studies use regression residuals to attribute the unexplained portion to human activities, which can easily classify unincorporated differences in soil texture, topographic indirect effects, and nonlinear climate-underlying-surface responses as human activities.

···activities. On the basis of incorporating four categories and 21 factors—climate, soil-vegetation, topography, and human activities—this paper combines

GeoDetector with PLS-SEM to simultaneously characterize direct, indirect, and interaction effects. The results show that although topographic factors have a positive direct effect, they are offset by stronger negative indirect effects produced through their influence on local climate and land-use patterns, thereby mechanistically explaining the possible systematic differences in "human-activity contribution" under different frameworks. Methodologically, this study uses GeoDetector to identify the explanatory power of each factor for spatial differentiation of desertification and its interaction-enhancement/nonlinear effects, and further uses PLS-SEM to characterize the direct pathways of factor effects and the indirect pathways generated through mediating variables such as climate and land use. Therefore, combining GeoDetector with PLS-SEM can more comprehensively reveal direct, indirect, and interaction effects among factors, providing a new perspective for quantifying the driving forces of desertification.

Constrained by the availability of driving-factor data, the quantitative analysis of driving forces in this study covers only 1990–2020; it could not analyze the expansion stage of desertification from 1975 to 1990 or the specific driving mechanisms in the latest stage from 2020 to 2025, which need to be supplemented in future work. Future planning for desertification prevention and control should prioritize assessments of desertification risk and sensitivity, and include potential risk areas such as northeastern Shapotou in key prevention-and-control targets.

5 Conclusion

(1) In the current year (2025), the desertified area in the arid belt of central Ningxia is 4,257.63 km^2. Spatially, it presents a distribution pattern of "more in the east and less in the west, concentrated and contiguous"; in the east it is concentrated in the Shapotou area on the southeastern margin of the Tengger Desert, while in the west it is concentrated in Lingwu City and Yanchi County on the western margin of the Mu Us Sandy Land.

(2) Over the past nearly 50 years, desertification in the arid belt of central Ningxia has shown an overall reversal trend, with the turning point occurring in 1990. From 1975 to 2025, the area decreased by a net 285.68 km^2 (6.29%); the area of extremely severe desertification declined the most, with a reduction proportion of 61.56%.

(3) On the long time scale of 1990–2020, climatic factors were the dominant driving force for desertification reversal (with the strongest q value for aridity). After 2020, locally high-intensity human activities (represented by population density, corresponding to expansion of construction land, engineering disturbances, and cultivation of wasteland, etc.) have become the dominant factors in desertification development.

(4) It is recommended that high-risk areas such as northeastern Shapotou be included in the scope of key monitoring and prevention/control of desertification.

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Spatiotemporal changes of aeolian desertification over the past 50 years and driving force analysis during the reversal period in the central Ningxia arid zone, China

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Abstract: The central Ningxia arid zone is one of the most severely desertified regions in China and a key area within the Ordos Loop of the Yellow River campaign. Based on a long-term dataset of aeolian desertification covering the past 50 years (1975–2025), this study examines the spatiotemporal dynamics of aeolian desertification and conducts a quantitative attribution analysis, with a focus on the reversal phase from 1990 to 2020. The results show that: (1) Over the past 50 years, aeolian desertification in the study area presented a trend of first intensification followed by subsequent reversal, with the turning point occurring in 1990. (2) By 2025, the total desertified area was 4257.63 km^2, representing a net decrease of 285.68 km^2 (6.28%) compared with 1975. Among desertification categories, the extremely severe desertified area experienced the largest percentage reduction of 61.56% over the study period. Spatially, reversal zones were mainly distributed in the western Shapotou District, central-western Lingwu City, and central-northern Yanchi County. (3) Combined analysis using geographical detector and partial least squares structural equation modeling reveals that climatic factors were the dominant driving forces of desertification reversal from 1990 to 2020 (mean q=0.21), with the aridity index exhibiting the strongest explanatory power. After 2020, population density surged in explanatory power (q=0.32), becoming the primary factor associated with localized desertification expansion. Overall, the results reveal that desertification reversal in the arid zone of central Ningxia is mainly driven by the synergistic effect of climatic factors and human activities. However, recent intensive human activities, such as urban expansion and cropland reclamation, have contributed to the development of desertification in local areas. These findings provide a scientific basis for precision-oriented desertification control in the Ordos Loop of the Yellow River.

Keywords: spatiotemporal changes; desertification index; geographical detector; partial least squares structural equation modelling (PLS-SEM); the central Ningxia arid zone

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