Spatiotemporal Changes in Vegetation Cover and Habitat Quality in the Loess Hilly Region of Central Gansu

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Abstract

The loess hilly region of central Gansu is located in the central Loess Plateau and is a typical ecologically fragile area, where severe soil erosion, fragmented terrain, and difficulties in vegetation restoration have long posed challenges to ecological conservation. Taking Dingxi City, Gansu Province, as an example, this study focuses on the spatiotemporal evolution of vegetation and the ecological environment. Based on land use and normalized difference vegetation index (NDVI) data from 2000 to 2020, and by comprehensively applying Sen+Mann-Kendall trend analysis and the InVEST model, this study investigates the dynamic evolution of vegetation cover and the ecological environment in a typical area of the loess hilly region of central Gansu (Dingxi City). The results show that the multi-year mean of the annual maximum NDVI in Dingxi City exhibits a spatial distribution pattern of "higher in the southwest and lower in the northeast." The annual maximum NDVI fluctuated upward at a rate of 0.0078, and 98.26% of the area showed an improving trend, among which 89.02% exhibited a significant improvement trend. The mean habitat quality index increased from 0.3329 in 2000 to 0.3376 in 2020, but more than 91.74% of the area remained at the "poor" level. High-quality areas (habitat quality index >0.6) were concentrated in forestland in the southwest, accounting for approximately 7.81% of the total area, whereas low-quality areas were distributed in farmland and grassland-dominated areas in the northeast with intensive human activities. This study reveals the evolution patterns of NDVI and habitat quality in Dingxi City and provides a quantitative basis for ecological conservation, land use planning, and policy formulation in the loess hilly region of central Gansu.

Full Text

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Spatiotemporal Changes in Vegetation Cover and Habitat Quality in the Loess Hilly Region of Central Gansu

A Case Study of Dingxi City, Gansu Province

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Abstract: The loess hilly region of central Gansu is located in the central part of the Loess Plateau and is a typical ecologically fragile area. Severe soil erosion, fragmented terrain, and the difficulty of vegetation restoration have long been major challenges for ecological conservation. Taking Dingxi City, Gansu

Province, as an example, this study focuses on the spatiotemporal evolution of vegetation and the ecological environment. Based on land-use and normalized difference vegetation index (NDVI) data from 2000 to 2020, and by comprehensively applying Sen + Mann–Kendall trend analysis and the InVEST model, we investigated the dynamic evolution of vegetation cover and the ecological environment in a typical area of the loess hilly region of central Gansu (Dingxi City). The results show that the multi-year mean of the annual maximum NDVI in Dingxi City exhibits a spatial distribution pattern characterized by "higher in the southwest and lower in the northeast." The annual maximum NDVI fluctuated upward at a rate of 0.0078, and 98.26% of the area showed an improving trend, of which 89.02% exhibited a significant improvement. The mean habitat quality index increased from 0.3329 in 2000 to 0.3376 in 2020, but more than 91.74% of the area remained at the "poor" level. High-quality areas (habitat quality index > 0.6) were concentrated in the forest land of the southwest, accounting for approximately 7.81% of the total area, whereas low-quality areas were distributed in the northeastern farmland and grassland-dominated zones with intensive human activities. This study reveals the evolution patterns of NDVI and habitat quality in Dingxi City and provides a quantitative basis for ecological conservation, land-use planning, and policy formulation in the loess hilly region of central Gansu.

Keywords: loess hilly region of central Gansu; NDVI; habitat quality; InVEST model

With increasingly prominent ecological and environmental problems, habitat quality and vegetation cover have become key indicators for evaluating the health and stability of regional ecosystems[1]. Habitat quality reflects the carrying capacity of ecosystems and the status of biodiversity. As a remote-sensing indicator of vegetation growth and ecosystem function, NDVI can reflect regional vegetation dynamics in real time[2–3]. An integrated study of these two indicators helps improve understanding of the dynamic evolution of regional ecosystems and their response mechanisms, thereby providing a scientific basis for ecological conservation and resource management.

As a core component of terrestrial ecosystems, vegetation is a sensitive indicator of climate change and human activities, and its dynamic changes reflect the evolutionary trend of the regional ecological environment[4]. Dingxi City' s distinctive geographic location and climatic conditions cause vegetation growth to show pronounced spatial differentiation in its response to climate change; the condition of its vegetation cover directly affects regional soil and water conservation, carbon cycling, and the pattern of agricultural production[5]. As a key parameter for monitoring vegetation cover and growth conditions, the normalized difference vegetation index (NDVI) can effectively capture the spatiotemporal heterogeneity of surface vegetation, providing an important basis for revealing the response mechanisms of ecosystems to climate change[6]. The spatiotemporal heterogeneity of habitat quality reveals the dynamic response capacity of ecosystems and provides a key basis for zoned management and control as well as the optimization of ecological engineering[7]. The spatiotemporal variation characteristics of habitat quality not only enable systematic identification of the spatiotemporal migration process of ecological risks, but also provide important support for scientifically assessing the effectiveness of ecological engineering, optimizing territorial spatial uses, and formulating differentiated governance strategies[8].

Dingxi City is located in central Gansu, deep in the hinterland of the hilly and gully region of the Loess Plateau. It is a typical loess hilly area of central Gansu. Affected by its special geology and geomorphology, climatic conditions, and human activities, soil and water loss is particularly severe, making it one of the areas with the most serious soil erosion in China[9]. In 1983, Dingxi was designated by the State Council as a key county for the "Three Wests" construction program, formally initiating large-scale ecological governance. In the same year, Dingxi was also identified as a national key area for soil and water conservation control, becoming a frontier zone for ecological restoration in China. In October 1999, Dingxi was designated as a pilot area for the Grain for Green Project[10], bearing the important mission of exploring new models of ecological restoration and accumulating successful experience. As a typical representative of the ecologically fragile areas of the Loess Plateau, the evolution of habitat quality in Dingxi City profoundly affects regional

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ecological security patterns and capacity for sustainable development[11].

At present, existing studies have provided a theoretical basis and data support for evaluating vegetation cover and the ecological environment in Dingxi City and the Longzhong Loess Hilly Region. For example, based on long-term land-use and vegetation data for Gansu Province, Jin Feng et al.[12] revealed the evolutionary trend of the vegetation-cover pattern over recent decades and predicted the potential direction of future vegetation change. Wang Nayun et al.[13] used MODIS-NDVI time series to analyze the response mechanisms of vegetation change in Gansu Province to temperature and precipitation, emphasizing the dominant roles of temperature and precipitation in regional vegetation change. From the perspective of ecological restoration, Niu Linan et al.[14] constructed an evaluation system for the degree and potential of ecological restoration on the Loess Plateau, systematically revealing spatial differences in ecological restoration and their limiting factors. Taking Yuzhong County as an example, Liu Chunfang et al.[15] evaluated habitat quality driven by land-use change and demonstrated the coupling relationship between habitat-quality degradation and land-use evolution in hilly areas. Based on long-term NDVI data, Yan Danni et al.[16] analyzed vegetation-change trends and their driving mechanisms on the Loess Plateau, emphasizing the combined effects of natural factors and human activities. Wang Jingmei et al.[17] further approached the issue from different ecological types and assessed the sensitivity and differentiated response characteristics of NDVI for multiple vegetation types to climate change. Sun Rui et al.[18] analyzed the spatiotemporal differences in NDVI among different ecological types on the Loess Plateau and their adaptability to climatic conditions from the perspective of ecological zoning. In summary, existing studies have been based on low-resolution land-use and NDVI data, and their research scales have mostly focused on large regional scales—Gansu Province or parts of the entire Loess Plateau—making it difficult to reveal the fine-scale evolutionary processes and long-term time-series change characteristics of the ecological environment and vegetation cover in Dingxi City. Accordingly, this study selects land-use data with a spatial resolution of 30 m for 2000–2020 and annual maximum NDVI data for 2001–2020, and combines the Sen+Mann-Kendall trend-analysis method with the InVEST ecosystem services model to systematically investigate the spatiotemporal evolution characteristics of land use and vegetation cover in Dingxi City. It further explores the spatiotemporal variation patterns of habitat quality and its degree of degradation, thereby providing a scientific basis for ecological-environmental protection and sustainable land-resource utilization in Dingxi City and the Longzhong Loess Hilly Region.

1 Overview of the Study Area

Dingxi City ($103°52'$–$105°13'$E, $34°26'$–$35°35'$N) is located at the junction of the Loess Plateau, the Gannan Plateau, and the Longnan Mountains. It administers seven county-level administrative units and has a total area of approximately 1.96×10^4 km^2. Dingxi City has a mid-temperate climate and a temperate continental climate, lies in the transition between semi-humid and semi-arid zones, has four distinct seasons, and experiences simultaneous rainfall and heat. The annual mean temperature is approximately 5.5–7.5 °C, and annual precipitation is approximately 350–600 mm. The spatial distribution of land use in Dingxi City in 2020 is shown in Fig. 1a; the land-cover types are dominated by grassland and cropland, accounting for approximately 55.12% and 36.62% of the regional area, respectively. The terrain of Dingxi City exhibits a spatial pattern of "high in the southwest and low in the northeast," as shown in Fig. 1b.

2 Data and Methods

2.1 Data Sources and Processing

The land-use data used in this study were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/data.aspx?DATAID=360), covering the period 2000–2020, with a spatial resolution of 30 m. The dataset classifies land types into eight categories: cropland, forest, shrubland, grassland, water bodies, ice and snow, bare land, and impervious surfaces. In this study, the land-use types were reclassified into cropland, forest, shrub–

Figure text:
(a) Land-use types. County/district labels: Anding District, Lintao County, Tongwei County, Weiyuan County, Longxi County, Zhang County, Min County. Legend: cropland 36.62%; forest 7.81%; shrubland 0.09%; grassland 55.12%; other 0.36%. Scale: 0–80 km. North arrow: N.
(b) Elevation spatial distribution. County/district labels: Anding District, Lintao County, Tongwei County, Weiyuan County, Longxi County, Zhang County, Min County. Elevation/m: 3958 to 1420. Scale: 0–80 km. North arrow: N.

Fig. 1 Schematic diagram of land-use types (a) and elevation spatial distribution (b) of Dingxi City in 2020

woody vegetation, grassland, and others. The NDVI data were obtained from the National Science and Technology Resource Sharing Service Platform (https://escience.org.cn/data-center), with a temporal resolution of 16 d, a spatial resolution of 30 m, and a temporal range of 2001–2020. The elevation data were obtained from the Geospatial Data Cloud (https://www.gscloud.cn/home#page1/2), with a spatial resolution of 30 m.

2.2 Research Methods

2.2.1 Sen+Mann-Kendall Trend Analysis

The Sen trend analysis and Mann-Kendall test methods can be effectively combined and constitute an important approach for determining trends in long time-series data. This method has been widely applied in long-term time-series analysis of vegetation cover, and can effectively characterize the spatiotemporal variation features of NDVI in Dingxi City during 2001–2020. The Sen trend degree is calculated as follows:

$$\beta = \text{Median}\left(\frac{\text{NDVI}_j - \text{NDVI}_i}{j-i}\right),\ \forall j > i \tag{1}$$

where NDVI_i and NDVI_j are the sample time-series data set; Median is the median function; $1 < j < i < n$, and i and j are different temporal dimensions of the set, respectively; n is the length of the time series; and $\forall$ denotes an arbitrary symbol. β is used to quantify the monotonic trend. When $\beta > 0$, the time series shows a monotonically increasing trend; otherwise, it shows a monotonically decreasing trend. The Mann-Kendall method was used to test the trend of the NDVI series, and the test statistic Z was set. Its calculation formulas are as follows:

$$Z = \begin{cases} \dfrac{S-0.5}{\sqrt{\mathrm{var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+0.5}{\sqrt{\mathrm{var}(S)}}, & S < 0 \end{cases} \tag{2}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(\mathrm{NDVI}_k - \mathrm{NDVI}_i) \tag{3}$$

$$\mathrm{var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{4}$$

$$\mathrm{sgn}(\mathrm{NDVI}_k - \mathrm{NDVI}_i) = \begin{cases} 1, & \mathrm{NDVI}_k - \mathrm{NDVI}_i > 0 \\ 0, & \mathrm{NDVI}_k - \mathrm{NDVI}_i = 0 \\ -1, & \mathrm{NDVI}_k - \mathrm{NDVI}_i < 0 \end{cases} \tag{5}$$

where var is the variance-calculation function; sgn is the sign function; $1 < j < k < n$, and i and k are different temporal lengths of the set, respectively. Depending on the value of the time-series length n, when the significance-test statistic S approximately follows the standard normal distribution, Z is used for a two-sided trend test. At a given significance level α, the critical value is obtained from the normal distribution table. When $|Z| < Z_{1-\alpha/2}$, the trend is not significant; when $|Z| > Z_{1-\alpha/2}$, the trend is significant. Combined with the Sen slope estimate, this study divided NDVI change trends into four categories: when the Sen slope > 0 and $|Z| \leq 1.96$, the trend is a slight increase; when the Sen slope < 0 and $|Z| \leq 1.96$, the trend is a slight decrease; when the Sen slope > 0 and $|Z| > 1.96$, the trend is a significant increase; and when the Sen slope < 0 and $|Z| > 1.96$, the trend is a significant decrease.

2.2.2 InVEST Model

The InVEST model calculates habitat quality by evaluating environmental threat factors and landscape sensitivity. This study mainly evaluated habitat quality in Dingxi City based on the Habitat Quality module of InVEST, version 3.14.3[19]. The habitat quality index output by this module is a dimensionless comprehensive indicator characterizing habitat conditions. The calculation formula is as follows:

$$Q_{xj} = H_j \times \left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right] \tag{6}$$

where Q_{xj} is the habitat quality index of grid cell x for land-use type j; H_j is the habitat suitability of land-use type j, with values ranging from 0 to 1; z is a scaling constant, generally taken as 2.5; and k is the half-saturation constant. The value of Q_{xj} ranges from 0 to 1; a value of Q_{xj} close to 0 indicates low habitat quality, while a value close to 1 indicates high habitat quality. In this study, the equal-interval method was used to divide the habitat quality index into five grades: poor (0–0.2), relatively poor (0.2-0.4), moderate (0.4-0.6), relatively good (0.6-0.8), and good (0.8-1.0).

The calculation formula for habitat degradation degree (D_{xj}) is as follows:

$$D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\frac{W_r}{\sum_{r=1}^{R} W_r}\right) \times r_y \times i_{rxy} \times \beta_x \times S_{jr} \tag{7}$$

where R is the total number of threat factors in the study area; W_r is the weight of each threat factor; Y_r is the number of grid cells in threat factor r; r_{xy} is the intensity value of the r-th threat factor at grid cell (x, y); i_{rxy} is the spatial influence degree of the r-th threat factor transmitted from grid cell y to grid cell x; r_y is the intensity of the threat factor; β_x is the anti-disturbance level of the habitat; and S_{jr} is the relative sensitivity of different habitats to different threat factors. Habitat degradation degree ranges from 0 to 1; a β_x value close to 1 indicates a high degree of habitat degradation. This study classified the habitat degradation degree in Dingxi City into low-degradation zones (0–0.2), moderate-degradation zones (0.2-0.4), and high-degradation zones (0.4–0.6).

Based on the actual conditions of Dingxi City, and in combination with the InVEST model manual and previous studies of similar regions[20–21], farmland, bare land, and impervious surfaces in the study area were defined as threat factors. Parameters including their influence ranges and weights, habitat suitability, and the sensitivity of habitats to threat factors were then set (Tables 1 and 2).

3 Results and Analysis

3.1 Spatiotemporal Variation of NDVI

3.1.1 Spatial Variation of NDVI The spatial distribution of the multi-year mean of the annual maximum NDVI in Dingxi City from 2001 to 2020 is shown in Fig. 2a. Dingxi City

Table 1 Weights of threat factors in the study region

Tab. 1 Weights of threat factors in the study region

Threat factor	Maximum stress distance/km	Weight	Decay correlation
Cropland	5	5	Exponential
Bare land	1	0.4	Exponential
Impervious surface	8	0.7	Linear

Table 2 Sensitivity of different land-use types to threat factors

Tab. 2 Sensitivity of different land use types to threat factors

Land-use type	Habitat suitability	Cropland	Bare land	Impervious surface
Cropland	0.3	0	0.4	0.55
Forest	1	0.3	0.5	0.9
Shrubland	1	0.4	0.4	0.8
Grassland	0.7	0.5	0.7	0.7
Water area	1	0.1	0.4	0.7
Bare land	0	0	0	0
Impervious surface	0	0	0	0

The spatial pattern of NDVI shows a distribution characterized by "higher in the south and lower in the north," with very pronounced spatial heterogeneity. The main reason is closely related to the spatial distribution of vegetation types. Southern Dingxi City contains the West Qinling Mountains and the Minshan Mountains, with mountains crisscrossing the area, dense forests, and large numbers of deciduous and evergreen trees. In contrast, vegetation in northern Dingxi City is mainly cropland and grassland, mostly in the loess plateau gully region, which is related to lower annual precipitation and abundant sunshine. From 2001 to 2020, the multi-year mean of the annual maximum NDVI in Dingxi City ranged from 0.20 to 0.92; among these values, the study area with NDVI between 0.5 and 0.6 accounted for the largest proportion (29.70%) and was mainly distributed in the northern part of Dingxi City. Among the seven districts and counties of Dingxi City, the multi-year mean annual maximum NDVI, ranked from highest to lowest, was Min County (0.76), Zhang County (0.74), Weiyuan County (0.67), Lintao County (0.58), Longxi County (0.55), Tongwei County (0.54), and Anding District (0.51).

The multi-year spatiotemporal change trend of the annual maximum NDVI in Dingxi City from 2001 to 2020 is shown in Fig. 2b. The area where NDVI increased accounted for approximately 98.26% of the total area of Dingxi City, of which the significantly increased area accounted for approximately 89.02%.

The area where NDVI decreased accounted for approximately 1.74% of the total area of Dingxi City, of which the significantly decreased area accounted for approximately 0.57%. This indicates that, from 2001 to 2020, areas with improved vegetation basically covered the whole of Dingxi City. The spatial statistics of NDVI spatiotemporal change in each district and county of Dingxi City from 2001 to 2020 are shown in Fig. 2c. Tongwei County had the highest proportion of area with increased annual maximum NDVI (99.56%), followed by Longxi County (98.44%); however, Anding District had the highest proportion of area with significantly increased annual maximum NDVI (94.26%). Min County had the highest proportion of area with decreased annual maximum NDVI (3.65%), while Tongwei County had the lowest proportion of area with decreased annual maximum NDVI (0.43%).

3.1.2 Interannual variation trend of NDVI

The annual temporal variation trends of the annual maximum NDVI in Dingxi City and its districts and counties from 2001 to 2020 are shown in Fig. 3. From 2001 to 2020, the annual maximum NDVI in Dingxi City showed a fluctuating upward trend, with a growth rate of 0.0078 per year; it was lowest in 2001 (0.54) and reached its maximum value in 2020 (0.72). From 2001 to 2020, the annual maximum NDVI values of all seven districts and counties in Dingxi City showed increasing trends. The growth rates, from high to low, were Anding District, Tongwei County, Longxi County, Lintao County, Weiyuan County, Zhang County, and Min County.

Figure 2 visible subfigure labels and legends

(a) Mean NDVI. Scale: 0–80 km. Legend values: 0.4, 0.5, 0.6, 0.7, 0.8.

(b) Area proportion under different NDVI change trends. Scale: 0–80 km. Legend: significantly increased area proportion 89.02%; slightly decreased area proportion 1.17%; slightly increased area proportion 9.24%; significantly decreased area proportion 0.57%.

(c) NDVI change trends by district/county. Scale: 0–80 km. County/district labels: Lintao County, Weiyuan County, Min County, Zhang County, Longxi County, Anding District, Tongwei County. Legend: significant decrease; slight decrease; slight increase; significant increase.

Fig. 2 Annual mean NDVI and change trend in Dingxi City from 2001 to 2020

- (a) Dingxi City –NDVI; Year; NDVI interannual variation trend; $y = -15.00 + 0.0079x,\ R^2 = 0.71$
- (b) Anding District –NDVI; Year; NDVI interannual variation trend; $y = -19.65 + 0.0100x,\ R^2 = 0.70$
- (c) Longxi County –NDVI; Year; NDVI interannual variation trend; $y = -18.32 + 0.0093x,\ R^2 = 0.63$

- (d) Min County –NDVI; Year; NDVI interannual variation trend; $y = -7.86 + 0.0042x,\ R^2 = 0.76$
- (e) Zhang County –NDVI; Year; NDVI interannual variation trend; $y = -9.54 + 0.0051x,\ R^2 = 0.71$
- (f) Weiyuan County –NDVI; Year; NDVI interannual variation trend; $y = -11.49 + 0.0061x,\ R^2 = 0.57$
- (g) Tongwei County –NDVI; Year; NDVI interannual variation trend; $y = -18.40 + 0.0094x,\ R^2 = 0.65$
- (h) Lintao County –NDVI; Year; NDVI interannual variation trend; $y = -14.91 + 0.0077x,\ R^2 = 0.66$

Fig. 3 Temporal trends of annual maximum NDVI in Dingxi City and its districts/counties from 2001 to 2020

3.2 Habitat Quality

3.2.1 Evolution of the Spatiotemporal Pattern of Habitat Quality

As shown in Fig. 4, from 2000 to 2020, habitat quality in Dingxi City was dominated by the "relatively poor" and "relatively good" categories, whose combined area accounted for more than 99.55%. Among them, the area with relatively poor habitat quality accounted for the largest proportion (91.71%), followed by the area with relatively good habitat quality (6.55%), which was mainly distributed in Min County and Zhang County; this is related to the high coverage of woodland vegetation types. In 2000, 2005, 2010, 2015, and 2020, the average habitat quality index values in Dingxi City were 0.3329, 0.3346, 0.3363, 0.3369, and 0.3376, respectively. Overall, habitat quality was relatively poor, but showed a slowly increasing trend. From 2000 to 2020, the area share of regions classified as having good habitat quality was the smallest in Dingxi City (Table 3), increasing from 0.05% in 2000 to 0.06% in 2005, then to 0.08% in 2010, and remaining unchanged at 0.08% in subsequent years. The area shares of regions with relatively good, moderate, and poor habitat quality showed increasing trends, whereas the area share of regions with relatively poor habitat quality showed a continuous decreasing trend. During 2000–2020, habitat quality change in Dingxi City was dominated by degradation, accounting for approximately 72.03% of the city' s area, of which slight degradation accounted for approximately 68.95%.

3.2.2 Spatiotemporal Changes in the Degree of Habitat Degradation

As shown in Fig. 5, the degree of habitat degradation in Dingxi City was dominated by severe degradation, with the corresponding area accounting for more than 53.56% of the city' s area; areas with low degradation ranked second (34.66%). In 2000, 2005, 2010, 2015, and 2020, the average habitat degradation values in Dingxi City were 0.3478,

(a) 2000

Legend: habitat quality index —0~0.2; 0.2~0.4; 0.4~0.6; 0.6~0.8; 0.8~1.
Scale bar: 0–80 km; N.

(b) 2005

Legend: habitat quality index —0~0.2; 0.2~0.4; 0.4~0.6; 0.6~0.8; 0.8~1.
Scale bar: 0–80 km; N.

(c) 2010

Legend: habitat quality index —0~0.2; 0.2~0.4; 0.4~0.6; 0.6~0.8; 0.8~1.
Scale bar: 0–80 km; N.

(d) 2015

Legend: habitat quality index —0~0.2; 0.2~0.4; 0.4~0.6; 0.6~0.8; 0.8~1.
Scale bar: 0–80 km; N.

(e) 2020

Legend: habitat quality index —0~0.2; 0.2~0.4; 0.4~0.6; 0.6~0.8; 0.8~1.
Scale bar: 0–80 km; N.

(f) 2000–2020 change trend

Legend: significantly decreased area accounted for 3.18%; slightly decreased area accounted for 68.95%; slightly increased area accounted for 22.62%; significantly increased area accounted for 5.25%.
Scale bar: 0–80 km; N.

Fig. 4 Habitat quality in Dingxi City from 2000 to 2020

Table 3 Percentage distribution, mean, and standard deviation of habitat quality in Dingxi City from 2000 to 2020

Grade	Value interval	2000 Proportion/%	2000 Mean	2000 Standard deviation	2005 Proportion/%	2005 Mean	2005 Standard deviation	2010 Proportion/%	2010 Mean	2010 Standard deviation	2015 Proportion/%	2015 Mean	2015 Standard deviation	2020 Proportion/%	2020 Mean	2020 Standard deviation
Poor	0~0.2	0.12	0.3329	0.09	0.13	0.3346	0.09	0.16	0.3363	0.09	0.21	0.3369	0.1	0.28	0.3376	0.1
Relatively poor	0.2~0.4	93.19	0.3329	0.09	92.91	0.3346	0.09	92.48	0.3363	0.09	92.13	0.3369	0.1	91.74	0.3376	0.1
Moderate	0.4~0.6	0.05	0.3329	0.09	0.09	0.3346	0.09	0.07	0.3363	0.09	0.06	0.3369	0.1	0.09	0.3376	0.1
Relatively good	0.6~0.8	6.59	0.3329	0.09	6.81	0.3346	0.09	7.21	0.3363	0.09	7.52	0.3369	0.1	7.81	0.3376	0.1
Good	0.8~1.0	0.05	0.3329	0.09	0.06	0.3346	0.09	0.08	0.3363	0.09	0.08	0.3369	0.1	0.08	0.3376	0.1

0.3629, 0.3699, 0.3628, and 0.3586; the degree of habitat degradation was relatively high and, overall, showed a trend of first increasing and then decreasing. Compared with the degree of habitat degradation in Dingxi City in 2000, in 2010 the area proportions of highly degraded and moderately degraded zones in Dingxi City increased by 4.55% and 0.62%, respectively. During 2000–2010, habitat degradation was relatively severe, and the highly degraded areas were mainly concentrated in the northern and southern parts of Dingxi City. Compared with the degree of habitat degradation in Dingxi City in 2010, by 2020 the area proportion of highly degraded zones in Dingxi City had decreased by 2.9%, the area of slightly degraded zones had increased by 2.3%, and the area of moderately degraded zones showed a slight increasing trend. From 2000 to 2020, the degree of habitat degradation in Dingxi City showed a trend of first rising and then falling: it reached a peak in 2010, with a mean value of 0.3699; compared with 2000, the highly degraded zones increased by 4.55%. Thereafter, by 2020, the highly degraded zones decreased by 2.9%, while the slightly degraded zones increased by 2.3% (Table 4). During 2000–2020, the degree of habitat degradation in Dingxi City was dominated by increases, accounting for approximately 74.38% of the area of Dingxi City, of which the area with a significant increase accounted for approximately 10.74%.

4 Discussion

The spatiotemporal variation characteristics of NDVI in Dingxi City from 2001 to 2020 reflect the dynamic coupling relationship between vegetation cover and natural environmental factors. The patterns of its spatial differentiation and temporal evolution are consistent with the Longzhong Loess Hilly···

(a) 2000
Legend: degradation level—0–0.2; 0.2–0.4; 0.4–0.6. Scale: 0–80 km.

(b) 2005
Legend: degradation level—0–0.2; 0.2–0.4; 0.4–0.6. Scale: 0–80 km.

(c) 2010
Legend: degradation level—0–0.2; 0.2–0.4; 0.4–0.6. Scale: 0–80 km.

(d) 2015
Legend: degradation level—0–0.2; 0.2–0.4; 0.4–0.6. Scale: 0–80 km.

(e) 2020
Legend: degradation level—0–0.2; 0.2–0.4; 0.4–0.6. Scale: 0–80 km.

(f) 2000–2020 change trend
Legend: area with significant decrease, 8.31%; area with slight decrease, 17.31%; area with slight increase, 63.64%; area with significant increase, 10.74%. Scale: 0–80 km.

Fig. 5 Habitat degradation levels in Dingxi City from 2000 to 2020

Tab. 4 Percentage, mean value, and standard deviation of habitat degradation levels in Dingxi City from 2000 to 2020

Level	Score grade	2000 Percentage/%	2000 Mean value	2000 Standard deviation	2005 Percentage/%	2005 Mean value	2005 Standard deviation	2010 Percentage/%	2010 Mean value	2010 Standard deviation	2015 Percentage/%	2015 Mean value	2015 Standard deviation	2020 Percentage/%	2020 Mean value	2020 Standard deviation
Low	0–0.2	39.84	0.3478	0.21	36.38	0.3629	0.21	34.67	0.3699	0.21	36.14	0.3628	0.21	36.97	0.3586	0.21
Medium	0.2–0.4	6.59	0.3478	0.21	6.80	0.3629	0.21	7.21	0.3699	0.21	7.52	0.3628	0.21	7.81	0.3586	0.21
High	0.4–0.6	53.57	0.3478	0.21	56.82	0.3629	0.21	58.12	0.3699	0.21	56.34	0.3628	0.21	55.22	0.3586	0.21

…the ecological background characteristics of the region, and also reflects the response mechanism of vegetation restoration under ecological-engineering intervention. The spatial distribution of the multi-year mean of the annual maximum NDVI in Dingxi City shows pronounced heterogeneity characterized by "higher in the south and lower in the north," which is highly related to regional topography and vegetation types. In Min County and Zhang County in the southwest, the annual maximum NDVI values are 0.76 and 0.74, respectively. Because these areas are located in the West Qinling and Minshan mountains, with crisscrossing mountains and dense forests, the high coverage of deciduous and evergreen trees becomes the core factor increasing the regional vegetation index. This positive role of forest vegetation is also an important feature distinguishing the mountainous ecosystems of the southern Loess Plateau from the northern gully areas. Anding District and Tongwei County in the northeast belong to the gully region of the Loess Plateau, with annual maximum NDVI values of 0.51 and 0.54, respectively. They are dominated by farmland and grassland, and, under the combined conditions of scarce annual precipitation and abundant sunshine[6], the vegetation growth potential of farmland and grassland ecosystems is constrained. The low-coverage vegetation pattern is not only a direct manifestation of regional ecological fragility, but is also more likely to trigger a chain reaction of intensified soil erosion[22], which is consistent with the spatial heterogeneity pattern of the loess hilly region of central Gansu[23]. The annual maximum NDVI in Dingxi City fluctuated upward at a rate of 0.0078, and 98.26% of the area showed an improving trend; this is closely related to the sustained implementation of the policy of returning farmland to forest and grassland[24]. The long-term increase in NDVI is not only a direct indication of improved vegetation conditions, but will also exert far-reaching positive impacts on ecosystem services such as regional water and soil conservation, carbon-sink capacity, and biodiversity protection, providing practical reference for vegetation restoration and ecological management and control in the loess hilly region of central Gansu[25].

Habitat quality in Dingxi City is closely associated with the regional land-use pattern, the intensity of human activities, and the characteristics of habitat degradation. From 2000 to 2020, although the citywide mean habitat quality showed a slow upward change, more than 91.74% of the area remained at the "relatively poor" grade (0.2–0.4),

Only 7.81% of the area reached the "relatively good" or higher grade (habitat-quality index > 0.6). This grade differentiation further highlights the imbalance of the spatial distribution. In areas with relatively low habitat quality, the land-use types are dominated by farmland and grassland, with urban–rural settlements and large-scale cultivated areas widely distributed[26–27]. According to the threat factors and their weights for the study area in the InVEST model, farmland and impervious surfaces, as core threat factors, exert a broader stress effect across such areas. Meanwhile, in 2020 these districts and counties had proportions of highly degraded habitat areas significantly higher than the citywide average. The single land-use type also weakened the ecosystem's resistance to disturbance, causing habitat stability to decline continuously and ultimately forming concentrated areas of low-quality habitat[28–30]. Areas with relatively high habitat quality are mainly distributed in Min County and Zhang County. These two counties are not only the main carriers of "relatively good" habitat in the city, but also contain Lianhua Mountain National Nature Reserve and Zhang County Guiqing Mountain Provincial Nature Reserve, among others. In these areas, land-use types are diverse and interference from human activities is relatively weak; the proportion of slightly degraded areas is higher than the citywide average of 36.97%, and habitat-system stability is stronger, which is similar to the findings of other scholars[31].

5 Conclusions

This study systematically analyzed the spatiotemporal evolution characteristics of vegetation cover and habitat quality in Dingxi City from 2000 to 2020, and comprehensively explored the multi-factor driving mechanisms. The main conclusions are as follows:

(1) From 2001 to 2020, the multi-year mean of the annual maximum NDVI in Dingxi City showed a spatial distribution pattern of "high in the southwest and low in the northeast." The annual maximum NDVI values in the southwestern Min County and Zhang County were relatively high, at 0.76 and 0.74, respectively; whereas Anding District and Tongwei County in the northeast are dominated by loess gullies, and their multi-year mean annual maximum NDVI values were relatively low, at 0.51 and 0.54, respectively.

(2) The area in which the annual maximum NDVI increased accounted for approximately 98.26% of the total area of Dingxi City, among which the

area with a significant increase accounted for approximately 89.02%. The annual maximum NDVI in Dingxi City fluctuated upward at a rate of 0.0078, and the annual maximum NDVI values of all seven districts and counties in Dingxi City showed increasing trends.

(3) The mean habitat quality in Dingxi City increased from 0.3329 in 2000 to 0.3376 in 2020, but more than 91.74% of the area remained at the "relatively poor" grade. High-quality areas (habitat-quality index > 0.6) were concentrated in forestland in the southwest, accounting for approximately 7.81% of the total area, whereas low-quality areas were distributed in farmland- and grassland-dominated areas in the northeast where human activities are intensive. Habitat degradation showed a pattern of "rising first and then declining," reaching a peak value of 0.3699 in 2010, when highly degraded areas accounted for 58.12%; by 2020 it had declined to 0.3586, and highly degraded areas had decreased by 2.9%.

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Spatiotemporal variation of vegetation cover and habitat quality in the central loess hilly region of Gansu Province: A case study of Dingxi City

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Abstract: The central loess hilly region of Gansu Province—a typical ecologically fragile zone—is located in the central part of the Loess Plateau. The terrain is fragmented, soil erosion is severe, and vegetation restoration has always been a major challenge for ecological protection. This study focuses on the spatiotemporal evolution of vegetation and the ecological environment, considering Dingxi City in Gansu Province as a case study. Based on land use and normalized difference vegetation index (NDVI) data from 2000 to 2020, Sen+Mann-Kendall trend analysis and the InVEST model were employed to investigate the dynamic evolution of vegetation cover and the ecological environment in the area. The results indicate that the annual maximum NDVI values of Dingxi City exhibit a spatial distribution pattern of "high in the southwest and low in the northeast," with a fluctuation increase at a rate of 0.0078 each year. A total of 98.26% of the area showed an improvement trend, among which 89.02% exhibited a marked improvement trend. The mean habitat quality increased from 0.3329 in 2000 to 0.3376 in 2020, but over 91.74% of the area remains in the "poor" category. High-quality areas (NDVI>0.6) are concentrated in the southwestern forest areas, covering approximately 7.81% of the total area, whereas low-quality areas are mainly distributed in the northeastern agricultural and grassland areas with intensive human activities. This study reveals the evolution patterns of NDVI and habitat quality in Dingxi City, providing quantitative evidence for ecological protection, land use planning, and policy formulation in the central loess hilly region of Gansu Province.

Keywords: central loess hilly region of Gansu Province; NDVI; habitat quality; InVEST model