Research Article

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Spatiotemporal variation pattern and spatial coupling relationship between NDVI and LST in Mu Us Sandy Land

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Abstract: Normalized difference vegetation index (NDVI) and land surface temperature (LST) are important indicators of ecological changes, and their spatial and temporal variations and spatial coupling can provide a theoretical basis for the sustainable development of the ecological environment. Based on the MOD13A1 and MOD11A2 datasets, the spatial distribution characteristics of NDVI and LST from 2000 to 2020 were analyzed, and the trend change slope method and spatial coupling model were used to calculate the significant changes. Finally, the spatial coupling model was used to calculate the spatial coupling degree between NDVI and LST. The study shows that: (1) From 2000 to 2020, the annual NDVI value of the Mu Us Sandy Land was between 0.25 and 0.43, showing a stable upward trend overall, with an increase rate of 0.074/(10a). The proportion of improvement areas in the study area is 81.48%. (2) There are significant differences in the spatial distribution of surface temperature in Mu Us Sandy Land, showing an overall trend of decreasing from northwest to southeast and higher in the west than in the east. The LST of Mu Us Sandy Land is greatly affected by changes in land use types. The spatiotemporal variation trend of LST is different from the gradual warming trend of global climate change. The main reason is that human activities have changed land use types and increased local vegetation coverage. (3) There is a significant negative correlation between LST and NDVI in Mu Us Sandy Land, with an R^2 of 0.5073 and passing the significance test at the 0.01 level. This indicates that ecological engineering policies can effectively reduce LST in the study area, thereby achieving the effect of improving the environment. The overall spatial coupling between LST and NDVI is at a very high level, with an average coupling degree of 0.895 in the study area. The two mainly exhibit a state of mutual antagonism in space, reflecting the importance of green vegetation in regulating regional climate and LST. The vegetation index and spatiotemporal variation of LST in Mu Us Sandy Land are the result of the joint influence of human activities and climate change, and human activities dominated from 2000 to 2020.

Keywords: Mu Us sandy land, surface temperature, vegetation index, temporal and spatial changes, spatial coupling

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1 Introduction

Land surface temperature (LST) is an important parameter for studying energy and material exchange between the surface and atmosphere, playing an important role in regional and global surface ecosystems [1–3]. The variation of surface temperature at the regional scale is closely related to various environmental factors such as vegetation, hydrology, and climate [4–6]. It has been widely applied in urban heat island effects [7–10], ecological environment assessment [11,12], climate change [13–15], vegetation monitoring [16–18], and many other directions. The normalized difference vegetation index (NDVI) can be used to characterize the growth status of regional vegetation and is an important parameter for ecological environment assessment [19–22]. Among the environmental factors that affect surface temperature changes, vegetation is the most affected by human activities. Therefore, studying the response relationship between surface temperature and vegetation index is of great significance.

In recent years, due to the impact of global climate change and human activities, there have been significant changes in global biodiversity, ecosystems, and their services [23], and the ecological environment quality in arid and semi-arid areas has also fluctuated. The relationship between LST and NDVI, as important parameters in ecological environment change research, is one of the hot topics in ecology. The rapid development of remote sensing technology and the widespread application of satellite data provide abundant data sources for obtaining regional surface temperature and vegetation indices. At present, domestic and foreign scholars mainly use remote sensing technology to study the spatiotemporal variation characteristics of long-time series of LST and NDVI at the regional scale [24,25], influencing factors research [26], and correlation analysis [27,28]. Such as Ebrahim et al. [29] used Moderate Resolution Imaging Spectrometer (MODIS) data to analyze the spatiotemporal changes of LST in central Italy through Sen's slope and nonparametric Mann–Kendall trend test. The results showed that LST was significantly negatively correlated with altitude. Xuzhen et al. [30] used MODIS NDVI data and the Hurst index to study the temporal and spatial evolution trend and future sustainability of NDVI in the Lancang Mekong River Basin. The results showed that the NDVI in the study area generally showed a fluctuating upward trend, and there were differences in the growth rate of NDVI in different regions, with the highest growth rate in China. However, there is a relative lack of research on the coupling relationship between the two. LST and NDVI are the most important indicators in ecological environment research, and there is an interactive and coupled relationship between the two. On the one hand, surface temperature promotes or inhibits vegetation growth through the influence of solar radiation and underlying surface changes; on the other hand, vegetation can absorb solar radiation energy and release water vapor through transpiration to lower surface temperature. Therefore, studying the spatiotemporal variation patterns of LST and its spatial coupling relationship with NDVI can effectively reflect the trend of ecological environment change in the study area, which is of great significance in ecology and climate research. It can be used to analyze land use change, observe climate change, and evaluate the health status of ecosystems, which helps to provide a theoretical basis for improving regional ecological environment models.

The climate of Mu Us Sandy Land is arid, and the ecological environment is fragile, making it the most ecologically sensitive area in the agricultural pastoral ecotone of northwest China. Due to the influence of China's ecological policies and human activities, the vegetation coverage of Mu Us Sandy Land has undergone significant changes. The continuous monitoring of surface temperature and the analysis of its spatial coupling relationship with the vegetation index can provide theoretical support for the rational utilization of water resources and the restoration of the ecological environment in Mu Us Sandy Land. Therefore, the main contributions of this work are

- Through MODIS LST, NDVI products and Trend change slope method, analyze the spatiotemporal distribution characteristics of LST and NDVI in Mu Us sandy land from 2000 to 2020.
- Through the spatial coupling model, explore the spatial coupling relationship between land LST and NDVI.
- Estimate the correlation between LST and NDVI.
- Discuss the impact of meteorology, land use types, and vegetation changes on LST.

2 Materials and methods

2.1 Overview of the study area

Mu Us Sandy Land is located in the hinterland of the Loess Plateau, spanning the northern part of Yulin City, the southern part of Ordos City, and the northeastern part of Yanchi County (37.45°–39.37°N, 107.67°–110.67°E) (Figure 1). It covers an area of approximately 42,200 km^2, with an average elevation of around 1,300 m, gradually increasing from east to west and reaching a maximum of 1,900 m in the southern part. The Mu Us Sandy Land is located in the transitional zone between arid and semi-arid regions and is a transitional zone between desert grasslands, grasslands, and forest grasslands in China, with a very fragile ecological environment [31–33]. The research area is mainly characterized by a temperature continental climate, with drought and uneven distribution of rainfall. Rainfall is mainly concentrated from June to August, with an annual precipitation of 250–440 mm, increasing from west to southeast. There are differences in the spatial distribution of water resources in the Mu Us Sandy Land, with drought and water scarcity in the northwest and abundant surface and groundwater in the southeast. There are numerous rivers, including the Wuding River, Tuwei River, and Kuye River, which run through the southeast of the

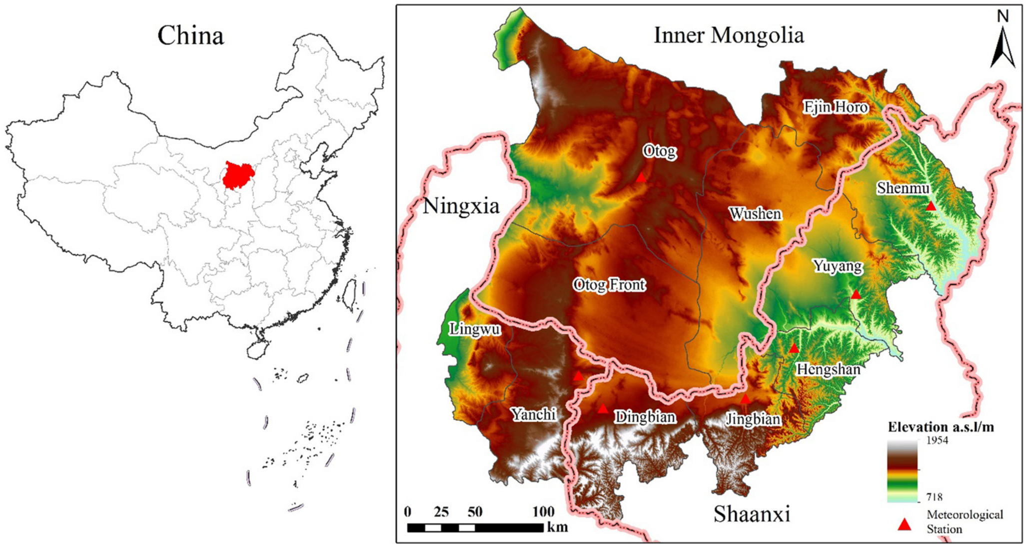

Figure 1: Geographic location and DEM of Mu Us Sandy Land.

sandy land, providing important guarantees for the ecological environment restoration and agricultural development in the southeast of Mu Us Sandy Land.

2.2 Data sources and processing

This study used data from the MODIS surface temperature product, sourced from the MODIS/TERRA satellite MOD11A2 surface temperature 8 days composite product provided by NASA from 2000 to 2020, with a spatial resolution of 1 km (Table 1). The image row numbers covering the research area are H26V04 and H26V05, totaling 1,820 images. Using format conversion, projection transformation, concatenation, and cropping to obtain the 8 days composite surface temperature data of the study area, and then using the weighted average method to obtain monthly and annual surface temperature data of the Mu Us Sandy Land from 2000 to 2020. The calculation of remote sensing data was completed under ENVI 5.3 software. The NDVI data are sourced from MODIS 16 d composite data, consisting of a total of 786 images with row and column numbers H26V04 and H26V05. The spatial resolution is 500 m, and the temporal resolution is 16 days. Two images can be obtained per month, and the average of the two is taken as the vegetation index for the current month. Convert HDF format to TIFF format data using ENVI5.3 software and perform projection conversion, stitching, cropping, and resampling.

The meteorological data are sourced from the China Meteorological Data Network (https://data.cma.cn/). There are a total of six national meteorological stations in the research area, namely Hengshan Station (53,740), Jingbian Station (53,735), Dingbian Station (53,725), Yanchi Station (53,723), Yulin Station (53,646), and Etuoqi Station (53,529).

Table 1: Source and description of research data

Name and description	Period	Spatial and temporal resolution	Data sources
LST: MOD11A2	2000–2020	1,000 m 8 days	National Aeronautics and Space Administration (https://search.earthdata.nasa.gov/)
NDVI: MOD13A1	2000–2020	500 m 16 days	National Aeronautics and Space Administration (https://search.earthdata.nasa.gov/)
Meteorological data: China Surface Climate Normals Dataset	2000–2020	— 1 days	China Meteorological Data Network (https://data.cma.cn/)
LULC: China Multi-Period Land Use Remote Sensing Monitoring Dataset	2000–2020	1,000 m 5 Year	Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/)

The meteorological data include eight types of daily data such as surface temperature, temperature, and precipitation. The monthly and annual average temperature data of each station are obtained through statistical analysis, and the average temperature of six meteorological stations in Mu Us Sandy Land is calculated as the temperature of the study area. Land use and land cover (LULC) grid data are provided by the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/). The data production is based on Landsat series satellite data as the data source and is completed through image classification and manual visual interpretation [34]. The spatial resolution of the dataset is 1 km, including six primary types: cropland, woodland, grassland, water area, built-up land, and unused land.

2.3 Research methods

2.3.1 Maximum value synthesis method

Maximum value compositions is an internationally recognized method for NDVI data statistics. The maximum value synthesis method can eliminate interference from factors such as air pollution, clouds, and solar altitude angle and obtain the best NDVI value for vegetation growth in the study area. This study selected the NDVI values of Mu Us Sandy Land from January to December every year from 2000 to 2020 and took the average of two data periods per month as the vegetation index data for that month. Then, using the maximum value synthesis method, the maximum value of each pixel was extracted as the NDVI value for that year. The formula is

$$\mathrm{NDVI}_i = \mathrm{Max}(\mathrm{NDVI}_{ij}), \tag{1}$$

where NDVI_i represents the NDVI value in the i-th year, with values ranging from 1 to 21, representing the years 2000–2020, respectively. NDVI_{ij} represents the NDVI value in the j-th month of the i-th year, with values ranging from 1 to 12, representing the months 1–12, respectively.

2.3.2 Trend change slope method

The trend change slope method is a pixel scale-based trend analysis method widely used in the analysis of spatiotemporal changes of large-scale surface parameters. This article uses the trend change slope method to simulate the trend of surface temperature changes at the pixel scale in the study area, analyzes the spatial variation patterns of surface temperature at different periods in the Mu Us Sandy Land, and obtains the change slope of each pixel during the study time period. The interannual change trend of the pixel is judged by the magnitude of the slope. The calculation formula is referenced in [35]:

$$\mathrm{Slope} = \frac{n * \sum_{i=1}^{n} i * \mathrm{NDVI}_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} \mathrm{NDVI}_i}{n * \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}, \tag{2}$$

where Slope is the slope of the NDVI change trend and N is the number of years during the monitoring period. This study was divided into two time periods, 2000–2010 and 2010–2020, with a value of 11; NDVI_i represents the vegetation index for the i-th year. When Slope >0, it indicates that vegetation growth tends to improve, while Slope <0 indicates that vegetation growth tends to deteriorate.

The significance of Slope will be further verified by the Mann–Kendall nonparametric statistical test [30], described as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} (S > 0) \\ 0 (S = 0) \\ \dfrac{S+1}{\sqrt{\mathrm{var}(S)}} (S < 0), \end{cases} \tag{3}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(\mathrm{NDVI}_i - \mathrm{NDVI}_j), \tag{4}$$

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

$$\mathrm{var}(S) = \frac{n(n-1)(2n-5)}{18}, \tag{6}$$

where n represents the time series length, sgn is a symbolic function, and the value range of the statistic Z can evaluate the significance of NDVI. In this study, the significance of the NDVI time series trend was judged at the 0.05 and 0.01 confidence levels. The definition of insignificant change is ($|Z| < 1.96$), the significant change is ($1.96 < |Z| < 2.58$), and the extremely significant change is $|Z| > 2.58$.

2.3.3 Spatial coupling model

Coupling is a concept in physics that refers to the phenomenon of two or more elements or systems interacting and influencing each other. The coupling degree is used to measure the degree of interaction between elements or systems. A spatial coupling model is selected to calculate the spatial coupling degree between NDVI and LST in Mu Us Sandy Land. The calculation formula is

$$C = \sqrt{\frac{f(x) \times g(x)}{\left[\frac{f(x) + g(x)}{2}\right]^2}}. \quad (3)$$

In equation (3), C is the coupling degree; $F(x)$ and $g(x)$ are the normalized values of NDVI and LST at x, respectively. Referring to the literature [3], the spatial coupling index is divided into four levels, with coupling degrees [0, 0.3], (0.3, 0.5], (0.5, 0.8], and (0.8, 1.0) indicating extremely poor, poor, good, and excellent coupling effects, respectively.

2.3.4 Pearson correlation coefficient

The Pearson correlation coefficient is a statistic that measures the strength and direction of the linear relationship between two continuous variables [36]. The values of the Pearson correlation coefficient range from −1 to 1. The calculation formula is

$$R = \frac{\sum_{i=1}(Y_i - \bar{Y})(X_i - \bar{X})}{\sqrt{\sum_{i=1}(Y_i - \bar{Y})^2 \sum_{i=1}(X_i - \bar{X})^2}},$$

where $\bar{X}$ and $\bar{Y}$ are the means of variables x and y, respectively.

3 Results and analysis

3.1 NDVI spatiotemporal distribution characteristics

3.1.1 NDVI time distribution characteristics

Figure 2 shows the interannual variation trend of NDVI in Mu Us Sandy Land. From Figure 2, it can be seen that from 2000 to 2020, the annual NDVI value of the Mu Us Sandy Land was between 0.25 and 0.43, showing a stable upward trend with an increase rate of 0.074/(10a). There were occasional fluctuations, with a significant downward trend observed from 2013 to 2015. Through meteorological data analysis, it was found that the precipitation in the study area decreased significantly in 2015, and insufficient water affected the growth of vegetation. Overall analysis shows that the NDVI value of the Mu Us Sandy Land showed a continuous upward trend from 2000 to 2020, mainly due to the implementation of ecological environment protection

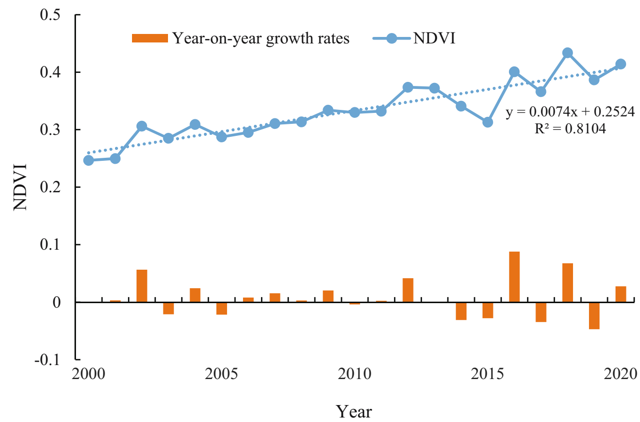

Figure 2: Interannual variation of NDVI in Mu Us Sandy Land from 2000 to 2020.

policies such as afforestation and wind and sand fixation in the study area, which maintained an overall upward trend in vegetation coverage of the Mu Us Sandy Land. The NDVI value in the study area fluctuates locally due to the uncertainty of water and heat changes.

3.1.2 Spatial distribution characteristics of NDVI

Figure 3 shows the spatial distribution of NDVI mean in Mu Us Sandy Land from 2000 to 2020. According to the changes in vegetation cover, the NDVI of the study area is divided into nonvegetation area (NDVI ≤ 0.2), extremely low vegetation area (0.2 < NDVI ≤ 0.3), low vegetation area (0.3 <

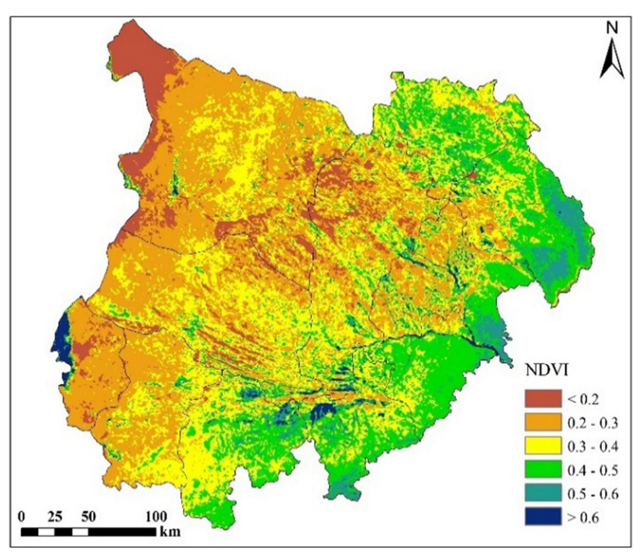

Figure 3: Annual mean spatial distribution of NDVI in Mu Us Sandy Land from 2000 to 2020.

NDVI ≤ 0.4), medium vegetation area (0.4 < NDVI ≤ 0.5), high vegetation area (0.5 < NDVI ≤ 0.6), and dense vegetation coverage area (0.6 < NDVI) [37]. The spatial distribution of NDVI in Mu Us Sandy Land shows significant differences, with an overall trend of gradually increasing from northwest to southeast. Dense vegetation areas are distributed on both sides of rivers in the study area and within the territory of Ningxia Hui Autonomous Region. High vegetation is mainly distributed in the southeast of Mu Us Sandy Land, located in Yulin City, Shaanxi Province. The terrain of this area is mainly low mountains and hills, with relatively abundant water resources and suitable water and thermal conditions for vegetation growth. The central vegetation area is distributed in the central and eastern part of the research area, which is located in the agricultural forestry transitional zone. The vegetation is mainly grassland, and the vegetation coverage is not high. The low vegetation area and no vegetation area are located in the northwest of the research area, which is the grassland area. The terrain is mostly eroded sand dunes and grassland between dunes, with low vegetation coverage and fragile ecological environment, which is easily affected by the natural environment and human activities.

3.2 NDVI dynamic change characteristics

Figure 4 shows the slope and significance distribution of NDVI trend changes in Mu Us Sandy Land from 2000 to 2020, and Table 2 shows the statistical table of different NDVI trend changes in Mu Us Sandy Land. The slope of NDVI variation in Mu Us Sandy Land from 2000 to 2020 was −0.0240–0.0389, with an average value of 0.0073. From 2000 to 2020, the NDVI of Mu Us Sandy Land was mainly improved and basically unchanged, with the proportion of basically unchanged areas accounting for 18.39% of the study area. It was mainly distributed in the windy and sandy areas in the northwest of the study area, where precipitation was sparse and vegetation was mainly sparse grasslands. The proportion of improvement areas in the study area is 81.48%, with the vast majority being extremely significant improvement areas, distributed in the

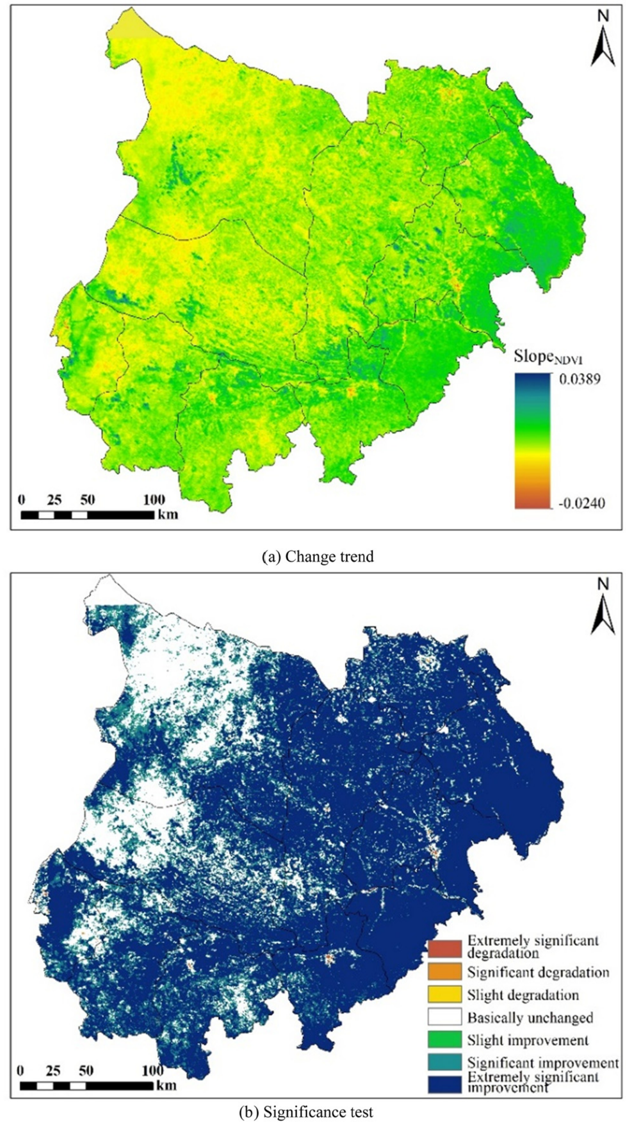

Figure 4: NDVI variation trend (a) and significance test (b) in Mu Us Sandy Land from 2000 to 2020.

Table 2: Statistical table of different trends in NDVI changes in Mu Us Sandy Land

Slope	Significance level *Z* value	Trend of change	Ratio (%)
<−0.0005	<0.01	Extremely significant degradation	0.04
<−0.0005	0.01–0.05	Significant degradation	0.05
<−0.0005	≥0.05	Slight degradation	0.04
−0.0005–0.0005	≥0.05	Basically unchanged	18.39
>0.0005	≥0.05	Slight improvement	4.97
>0.0005	0.01–0.05	Significant improvement	12.67
>0.0005	<0.01	Extremely significant improvement	63.84

central and eastern parts of the study area. The degraded area is relatively small, accounting for 0.12% of the study area.

3.3 Spatial and temporal distribution characteristics of surface temperature

Figure 5 and Table 3 show the spatial distribution of surface temperature in the Mu Us Sandy Land in 2000, 2010, and 2020, as well as the statistical table of the proportion of different surface temperatures. From the chart, it can be seen that the surface temperature of Mu Us Sandy Land has obvious spatial distribution characteristics, showing a gradually increasing trend from southeast to northwest. The distribution pattern of surface temperature in Mu Us Sandy Land varies in terms of time distribution, with surface temperature mainly concentrated at 32–36°C in 2000, accounting for 76.01%. In 2010, the surface temperature was concentrated at 30–34°C, accounting for 67.37%. The distribution of surface temperature in 2020 was relatively uniform between 28 and 36°C. From 2000 to 2020, the number of low-temperature areas continued to increase. The areas below 28°C in 2000 were relatively scattered in the study area, and the area continued to expand. In 2020, low-temperature areas were scattered throughout the eastern and southern parts of the study area. The main reason for the high distribution of surface temperature in the western region is that the human density is relatively low, the land use type is mainly unused land, and the density of surface vegetation coverage is relatively low. The low values are distributed in the eastern and southern regions, where water resources are relatively abundant, human activities are more frequent, agriculture and forestry development are relatively good, and land use types change significantly, mainly grassland, farmland, and forest land. The surface temperature shows a continuous downward trend.

Table 3: Proportion of different LST in Mu Us Sandy Land from 2000 to 2020

LST/°C	2000	2010	2020
<30	1.26	12.75	32.30
30–32	9.05	27.94	23.65
32–34	31.07	39.43	23.91
34–36	44.94	17.71	16.49
>36	13.68	2.17	3.64

In order to further analyze the variation pattern of surface temperature in Mu Us Sandy Land from 2000 to 2020, this study divided the trend of surface temperature change in Mu Us Sandy Land from 2000 to 2020 into seven levels based on trend analysis and significance analysis (Figure 6 and Table 4): extremely significant decrease, significant decrease, weak significant decrease, stable zone, weak significant increase, significant increase, and extremely significant increase. Among them, the extremely significant decrease zone, significant decrease zone, and weak significant decrease zone accounted for 20.33, 12.07, and 6.70% of the study area, while the stable zone accounted for 57.53% of the study area. The weak significant increase zone, significant increase zone, and extremely significant increase zone accounted for 1.01, 1.35, and 1.02% of the study area, respectively. The area of surface temperature rise is concentrated in the western part of the study area, with a relatively small proportion. The stable area of surface temperature is distributed in the west and scattered in the middle of the study area, which is the main dynamic change feature of surface temperature in the study area. The declining areas are mainly distributed in the central and eastern parts of the research area, with a wide area

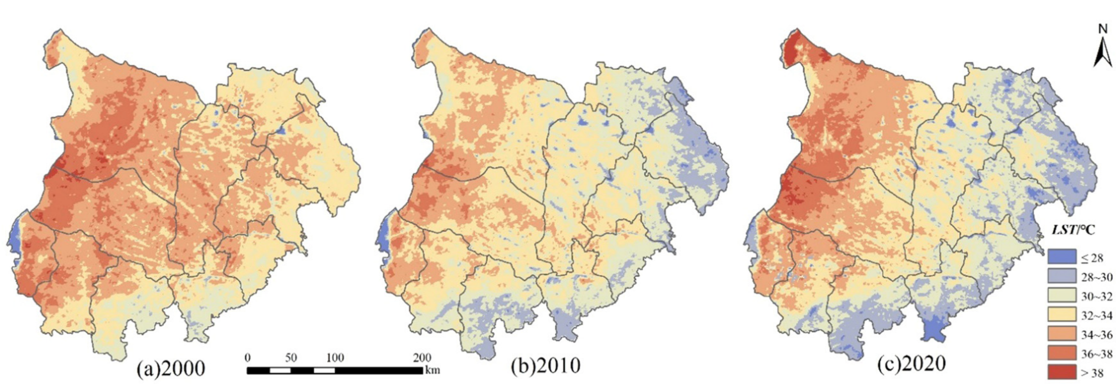

Figure 5: Spatial distribution map of annual LST in Mu Us Sandy Land from 2000 to 2020. (a) 2000, (b) 2010, and (c) 2020.

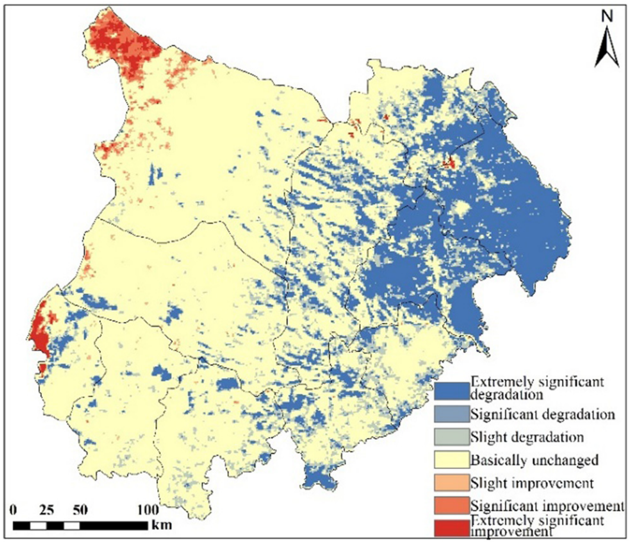

Figure 6: Interannual variation trend of LST in Mu Us Sandy Land.

distribution. The most significant decline is mainly concentrated in the northeast, distributed in Yuyang City and Shenmu City. The overall trend of surface temperature variation in Mu Us Sandy Land is similar to the distribution pattern of high and low temperatures in the study area, mainly due to the impact of human activities on land use types in the central and eastern regions.

From 2000 to 2020, the surface temperature of Mu Us Sandy Land fluctuated between 30.94 and 34.23°C, with an average surface temperature of 32.29°C, showing an overall downward trend. The change pattern of surface temperature is different from the gradual warming trend of global climate change. The main reason is that Mu Us Sandy Land is the main area for afforestation and returning farmland to forests and grasslands in China. Human activities have changed the land use type of the study area, reduced unused land area, and increased air humidity and surface evapotranspiration, thereby reducing the solar shortwave radiation received by the surface and maintaining a downward trend in surface temperature.

3.4 Annual LST variation characteristics of different land use type

Using overlay analysis to statistically analyze the average annual surface temperature of different land use types in Mu Us Sandy Land from 2000 to 2020 (Table 5). According to Table 5, there is a significant difference in annual surface temperature among different land use types. Construction land and unused land are the two land types with the highest surface temperature in the study area, at 33.25 and 33.20°C, respectively. Forest land and grassland are the second highest, with surface temperatures of 32.53 and 31.31°C, respectively. Farmland and water have the lowest surface temperatures, at 30.99 and 29.76°C, respectively. In cultivated land and water areas, water resources are relatively abundant, and higher evapotranspiration absorbs some of the solar radiation energy, resulting in lower surface temperatures. Construction land and unused land have no vegetation cover on their surfaces, and the surface temperature rises rapidly under the influence of solar radiation. The average surface temperature of each land use type showed a trend of first decreasing and then increasing. The decrease in surface temperature from 2000 to 2010 was related to national policies. From 1999 to 2010, the country implemented the project of returning farmland to forests and grasslands, which effectively prevented the process of land desertification, increased vegetation

Table 5: Average LST of different land use types in Mu Us Sandy Land from 2000 to 2020

LST (°C)	2000	2010	2020	Mean value
Cultivated land	32.18	30.33	30.29	30.99
Woodland	33.80	31.88	31.87	32.53
Meadow	32.43	30.50	31.46	31.31
Waters	30.60	29.41	30.45	29.76
Land used for building	34.19	32.47	33.05	33.25
Unutilized land	34.45	32.56	32.90	33.20

Table 4: Statistical table of different trends in LST Changes in Mu Us Sandy Land

Slope	Significance level *P*	Trend of change	Ratio (%)
<−0.05	<0.01	Extremely significant degradation	20.33
<−0.05	0.01–0.05	Significant degradation	12.07
<−0.05	≥0.05	Slight degradation	6.70
−0.05–0.05	≥0.05	Basically unchanged	57.53
>0.05	≥0.05	Slight improvement	1.01
>0.05	0.01–0.05	Significant improvement	1.35
>0.05	<0.01	Extremely significant improvement	1.02

coverage in the study area, and significantly improved the ecological environment quality of Mu Us Sandy Land. The surface temperature has rebounded again from 2010 to 2020, which is related to the continuous warming of the global climate.

3.5 Spatial coupling analysis of surface temperature and vegetation index

The 2D scatter plot tool of ENVI was used to obtain the scatter distribution maps and linear regression equations of LST and NDVI (Figure 7). R^2 of the two was 0.5073 and passed the significance test at the 0.01 level, indicating a significant negative correlation between LST and NDVI in the Mu Us Sandy Land. This indicates that ecological engineering policies such as afforestation and wind and sand fixation can effectively reduce surface temperature in the study area, thereby achieving the effect of improving the environment.

To further investigate the spatial correlation between LST and NDVI, a spatial coupling degree model was used to calculate the spatial coupling degree between LST and NDVI in the Mu Us Sandy Land. The results are shown in Figure 8. The overall spatial coupling between LST and NDVI is at a very high level, and the two mainly exhibit an antagonistic state in space. An increase in vegetation coverage can effectively reduce surface temperature, which occurs in most areas of the Mu Us sandy land. The increase in construction land has led to an increasingly prominent negative feedback effect of vegetation coverage on surface temperature, which is mainly affected by the urbanization process.

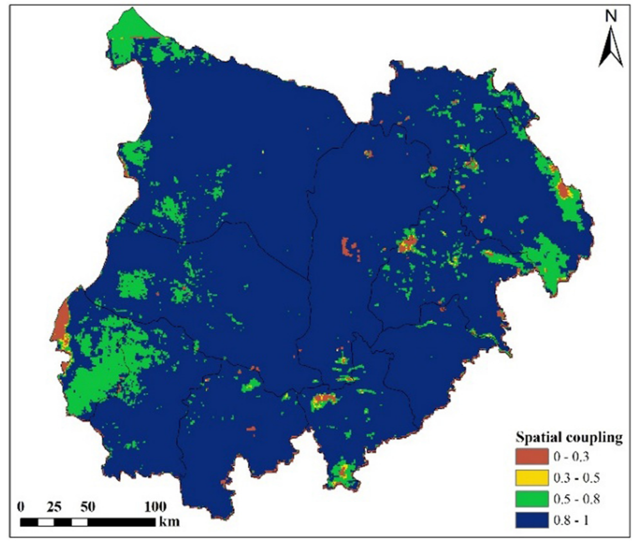

Figure 8: Spatial coupling distribution of LST and NDVI in Mu Us Sandy Land.

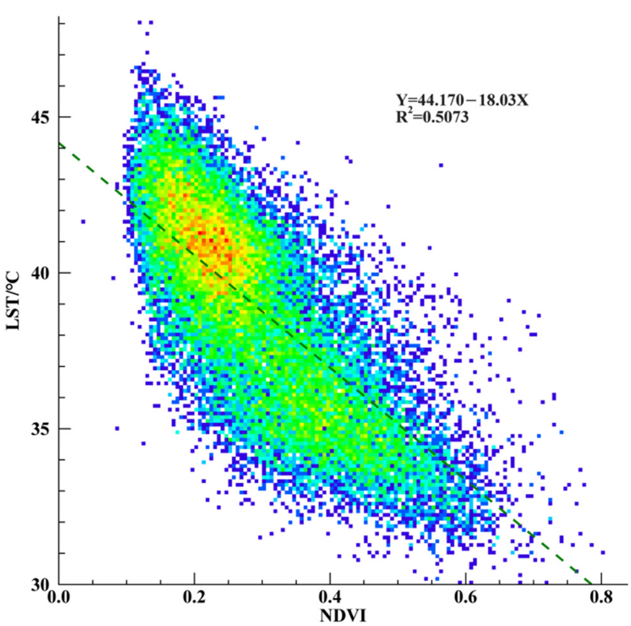

Figure 7: 2D scatter plot of LST and NDVI.

Statistical analysis was conducted on the coupling degree zones of the Mu Us Sandy Land, and the results are shown in Table 6. According to Table 6, the coupling degree of Mu Us Sandy Land in the range of (0.8, 1.0] has the highest number of grids, followed by (0.5, 0.8], [0, 0.3], and (0.3, 0.5]). The average coupling degree in the study area is 0.895, further proving the significant correlation between LST and NDVI and reflecting the importance of green vegetation in regulating regional climate and surface temperature.

Table 6: Statistical table of spatial coupling between LST and NDVI in Mu Us Sandy Land

Coupling degree	Coupling effect	Grid number	Proportion (%)	Mean coupling degree
[0, 0.3]	Range	2,359	2.58	0.895
(0.3, 0.5)	Poor	334	0.36	
(0.5, 0.8)	Preferably	8,551	9.34	
(0.8, 1.0)	Excellent	80,278	87.71	

4 Discussion

The Mu Us Sandy Land is located in the northwest arid and semi-arid areas, with a terrain mainly composed of wind-blown sand and grassland. The ecological environment is fragile, and it has a unique agricultural pastoral transitional zone. Based on MODIS data, studying the spatiotemporal distribution patterns of surface temperature and vegetation coverage, and further exploring the interrelationship between surface temperature and vegetation changes, evaluating the impact of vegetation on surface temperature, can provide a scientific basis for ecological environment protection and adaptation to climate change. According to the analysis of the interannual variation trend of NDVI in Mu Us sandy land, the overall NDVI showed a fluctuating upward trend from 2000 to 2020, indicating that the vegetation in the study area was generally developing in a good trend, which was consistent with the research results of Zuguang et al. [38] in the Yellow River Basin and Tong et al. [39] in the northern Loess Plateau. However, NDVI showed a relatively large downward trend in 2015. By reviewing the climate change in the study area, it is found that 2015 is the minimum point of temperature and precipitation in Mu Us sandy land [40–42], indicating that the main reason for the sudden change of NDVI in Mu Us sandy land in 2015 is the lack of hydrothermal conditions.

Vegetation index and surface temperature are important input parameters for studying water cycle, energy cycle, and ecological environment changes [29,43]. Clarifying the spatiotemporal evolution patterns of vegetation index and surface temperature in Mu Us Sandy Land is helpful for the rational allocation of water resources and the sustainable development of the ecological environment in the research area. Over the years, the average annual precipitation in Mu Us sandy land is 337.8 mm, the interannual fluctuation of precipitation is large, and the upward trend is not obvious [44]. However, the vegetation index of the Mu Us Sandy Land has steadily increased, indicating that China has made significant achievements in the implementation of large-scale projects such as returning farmland to forests and grasslands, diverting floods and silting land, constructing wind and sand prevention forests, and managing steep slopes under the leadership of the country and the government. In the context of global temperature rise, the surface temperature of the Mu Us Sandy Land has shown a downward trend, which is different from the change patterns in places such as the Yunnan-Kweichow Plateau [45]. The main reason is the implementation of ecological policies such as returning farmland to forests and grasslands, windbreak and sand fixation, and afforestation, which have changed the land use type and climate of Mu Us Sandy Land, increased vegetation coverage in the study area, and thus reduced surface temperature. Therefore, there is a close relationship between surface temperature and vegetation coverage, which is regulated through interactions: (1) Reflection and absorption: Vegetation can reflect solar radiation and reduce the area of direct sunlight shining on the surface, thereby reducing the absorption capacity of the surface. (2) Evapotranspiration: Vegetation evaporates soil moisture into the atmosphere through transpiration, which lowers surface temperature. Evapotranspiration uses water within plants to transfer heat, thereby reducing surface heat. (3) Climate regulation: The stomata of plants can be opened and closed for regulation, reducing water evaporation and preventing overheating. When the temperature rises, plants reduce the opening of stomata, reduce water evaporation, and thus lower the surface temperature. (4) Shadow effect: The growth of vegetation forms shadows, which can lower the temperature of the soil surface in direct contact with sunlight, thereby lowering the surface temperature. Overall, the higher the vegetation coverage, the lower the surface temperature, and the growth and protection of vegetation are important factors in reducing surface temperature.

The spatiotemporal variation of vegetation index and surface temperature is the result of the comprehensive influence of geographical factors, climate factors, and socio-economic factors. This study only analyzed the spatial variation and coupling relationship between the two, which has significant limitations in research. Moreover, the Mu Us Sandy Land has a large area that spans multiple administrative regions. There are significant differences in ecological and environmental policies among different administrative regions, resulting in different directions of vegetation index changes in the north-south and east–west regions of the Mu Us Sandy Land. This is also the main reason for the trend of surface temperature changes in the Mu Us Sandy Land to show an increase in the west and a decrease in the east. The quantification of the impact mechanism of ecological policies has always been a hot and difficult research topic in land science and ecological science, and it is also a key research direction in the future.

5 Conclusions

Using MOD13A1 and MOD11A2 as data sources, the spatial distribution characteristics of NDVI and LST in Mu Us Sandy Land from 2000 to 2020 were analyzed. ENVI and

MATLAB software were used to calculate the significant trend changes of NDVI and LST over the years. Finally, a spatial coupling model was used to calculate the spatial coupling degree between NDVI and LST in four seasons, and the spatial coupling differentiation characteristics of Mu Us Sandy Land were analyzed. The main conclusions are as follows:

(1) From 2000 to 2020, the annual NDVI value of Mu Us Sandy Land was between 0.25 and 0.43, showing a stable upward trend with an increase rate of 0.074/(10 a). The main reason for this was the implementation of ecological and environmental protection policies such as afforestation and wind and sand fixation in the study area, which had individual year fluctuations. The reason for this was the uncertainty of water and heat changes. The spatial distribution of NDVI in Mu Us Sandy Land shows significant differences, with an overall trend of gradually increasing from northwest to southeast. The slope of NDVI variation in Mu Us Sandy Land from 2000 to 2020 was −0.0240–0.0389, with an average value of 0.0073. The proportion of improvement areas in the study area is 81.48%, with the vast majority being extremely significant improvement areas, distributed in the central and eastern parts of the study area.

(2) There are significant differences in the spatial distribution of surface temperature in Mu Us Sandy Land, showing an overall trend of decreasing from northwest to southeast and higher in the west than in the east. The surface temperature of Mu Us Sandy Land is greatly affected by changes in land use types, and there is a significant difference in surface temperature among different land use types. Construction land and unused land have the highest surface temperature, followed by grasslands and forests, and finally, farmland and water bodies. The spatiotemporal variation trend of surface temperature in Mu Us Sandy Land is different from the gradual warming trend of global climate change. The main reason is that human activities have changed land use types and increased local vegetation coverage. Human activities have had a significant impact on surface temperature, reflecting the importance of green vegetation in regulating regional surface temperature. Therefore, the spatiotemporal variation of surface temperature in the Mu Us Sandy Land is the result of the joint influence of human activities and climate change, and human activities dominated from 2000 to 2020.

(3) The R^2 of LST and NDVI is 0.5073 and has passed the significance test at the 0.01 level, indicating a significant negative correlation between LST and NDVI in Mu Us Sandy Land. This indicates that ecological engineering policies such as afforestation and wind and sand fixation can effectively reduce surface temperature in the study area, thereby achieving the effect of improving the environment. Moreover, the overall spatial coupling degree between LST and NDVI is at a very high level, with an average coupling degree of 0.895 in the study area. The two mainly exhibit a state of mutual antagonism in space, further proving the significant correlation between LST and NDVI, and reflecting the importance of green vegetation in regulating regional climate and surface temperature.

It is hoped that the presented results could be used to analyze land-use change, observe climate change, and assess the health of the ecosystem, which will help to provide a theoretical basis for improving the regional ecological and environmental model. However, the interpretation of policies still needs to be deepened. In terms of research data, the lack of detailed socio-economic statistical data is a shortcoming of this study. In addition, the resolution of the surface temperature data used in this study is 1 km, and the spatial resolution is relatively coarse, which has caused certain limitations to this study. Therefore, the direction of future work is to provide more in-depth analysis for the study of the ecological environment of the Mu Us Sandy Land by utilizing higher-resolution satellite data, such as Landsat, Sentinel, and GaoFen, and more advanced data analysis models, and by taking into account socio-economic and policy documents.

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