Research on Vegetation Cover Change in Sanmenxia City Based on NDVI from 1990 to 2020

Yaqiu Yin[1,2,3,4][a], Tingting Wang[5][b] and Peiyong He[6,*][c]
[1]*Land Consolidation and Rehabilitation Center, Ministry of Natural Resources, Beijing 100035, China*
[2]*Land Science and Technology Innovation Center, Ministry of Natural Resources, Beijing 100035, China*
[3]*Technology Innovation Center for Land Engineering, Ministry of Natural Resources, Beijing 100035, China*
[4]*Key Laboratory of Land Consolidation and Rehabilitation, Ministry of Natural Resources, Beijing 10035, China*
[5]*Shandong Yellow River Ecological Development Group Co., Ltd., Jinan 250014, Shandong, China*
[6]*China Academy of Natural Resources Economics, Beijing 101149, China*
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Keywords: NDVI, Vegetation Cover, Spatiotemporal Change Characteristics, Sanmenxia City.

Abstract: This study examines the spatiotemporal distribution and change characteristics of forest and grassland vegetation cover in Sanmenxia City from 1990 to 2020, predicting the future trend of forest and grassland vegetation cover to provide a reference for the establishment of a reference system for ecological restoration in bauxite mining in Sanmenxia City. Utilizing NDVI time series data from 1990 to 2020, the study employs annual mean, Theil-Sen median trend analysis, and Mann-Kendall test methods to investigate the spatiotemporal distribution characteristics of forest and grassland vegetation cover in Sanmenxia City. The Hurst index is used for predicting the future changes in vegetation cover in the area. Overall, the vegetation cover in Sanmenxia City mainly shows a pattern of being higher in the south and lower in the north, with the area of vegetation cover improvement significantly exceeding the area of degradation from 1990 to 2020. The future outlook for vegetation cover in Sanmenxia City is promising, with areas predicted to have positive development trends exceeding those with negative trends. Regions with negative trends are primarily located in the central and northern parts of Sanmenxia City along the Yellow River, expected to shift from improvement to degradation trends. This calls for significant attention in ecological protection and management processes.

1 INTRODUCTION

Research on vegetation cover change is an important aspect of mine ecological restoration studies (Ju, 2022; Yu, 2022; Zhang, Z. Q., 2022; Yin, 2022; Li, B., 2022; Jin, 2022; Shi, 2022; Zhou, 2022). Degradation of surface vegetation cover can lead to a series of severe issues, such as soil erosion, desertification, shrinkage of lakes and rivers, and imbalance of carbon sink functions. Currently, remote sensing technology has become the main means of monitoring vegetation changes in mining areas and watersheds during the ecological restoration process, allowing for macro-scale acquisition of vegetation change data caused by mining. Vegetation cover change is usually characterized by vegetation cover degree and rate. Vegetation cover (NDVI) generally refers to the ratio of forest area to total land area, reflecting the area ratio of vegetation cover. It is an important indicator for measuring surface vegetation, an essential basis for describing ecosystems, and a significant manifestation of regional ecosystem environmental changes (Bao, 2022; Gao, 2022; Wang, 2021; Dang, 2022; Guan, 2023; Kang, 2023; Ye, 2023; Li, 2023).

Sanmenxia City, rich in mineral resources, serves as an important base for high-quality bauxite resources in Henan Province. Due to previous intense and disorderly mining activities, widespread surface vegetation cover damage has occurred, necessitating

[a] https://orcid.org/0009-0008-1270-153X
[b] https://orcid.org/0009-0006-7683-189X
[c] https://orcid.org/0009-0004-6504-0449

Yin, Y., Wang, T., He and P.
Research on Vegetation Cover Change in Sanmenxia City Based on NDVI from 1990 to 2020.
DOI: 10.5220/0013572700004671
In *Proceedings of the 7th International Conference on Environmental Science and Civil Engineering (ICESCE 2024)*, pages 10-16
ISBN: 978-989-758-764-1; ISSN: 3051-701X

urgent resolution. Protecting and restoring surface vegetation cover has become a current research hotspot. The changes in vegetation cover and the resulting ecological environment changes in Sanmenxia City have a significant impact on regional sustainable development (Zhang, Y., 2022; Xu, 2023; Li, X. R., 2022; Liao, 2022; Ye, 2019; Hou, 2023; Xie, 2023; Ma, 2023). Therefore, it is necessary to study the spatiotemporal change characteristics of vegetation cover in Sanmenxia City. Accordingly, this study uses GEE NDVI time series data from 1980 to 2020, employing Theil-Sen median trend analysis and Mann-Kendall test methods to only research the spatiotemporal distribution and change characteristics of forest and grassland vegetation cover, and uses the Hurst index method to analyze and predict future development trends, aiming to provide references for scientific protection and ecological restoration of bauxite mining in Sanmenxia City and promote positive succession of the ecosystem.

2 STUDY AREA

The project area is located in the northern part of Sanmenxia, mainly covering the Hubei District and Shan State District. The area stretches approximately 16km from east to west and 6.9km from north to south, covering an area of about 110.84km^2. Its geographical coordinates range from 111°17′0.06″E to 111°27′43.91″E and from 34°44′40.96″N to 34°50′18.56″N. The terrain is high on both the eastern and western sides and low in the middle, with most areas at an elevation of 300m to 500m. The project area is situated in the Yellow River basin between the mountains of western Henan and the Taihang Mountains, featuring a unique geomorphology – the loess landform, which shares similarities and differences with the Loess Plateau. Based on genesis and morphology, the main geomorphological types in the project area include eroded and accumulated loess areas, fluvial erosion-accumulation floodplains, and river valley terraces. Sanmenxia City has a warm temperate continental monsoon climate, with an average annual temperature of 13.9°C and annual rainfall ranging from 530 to 850mm, unevenly distributed across seasons, primarily concentrated in July, August, and September. The location of Sanmenxia City is shown in Figure 1.

3 RESEARCH METHODS

3.1 Data Sources

The NDVI dataset is based on GEE satellite remote sensing data from continuous time series, with annual averages used to generate data for the years 1990, 1995, 2000, 2005, 2011, 2015, and 2020, resulting in a total of seven images with a spatial resolution of 30m. The forest and grassland vector data were obtained from the 2020 Sanmenxia City land use data, which was integrated to generate vector data for the forest and grassland areas of Sanmenxia City.

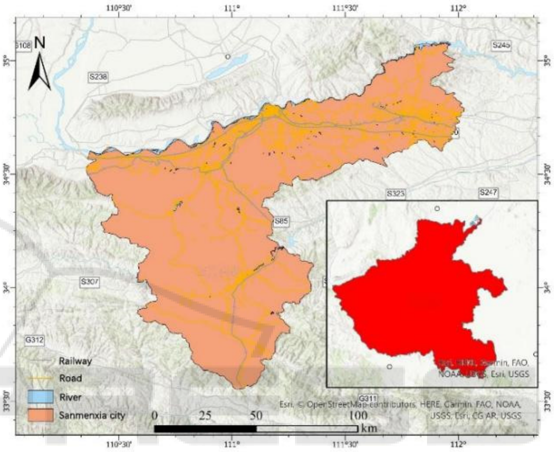

Figure 1: Location of the Sanmenxia City.

3.2 Inter-Annual Variation and Spatial Pattern Analysis

The annual mean NDVI for forest and grassland in Sanmenxia City from 1990 to 2020 was calculated step by step to obtain data for seven years, analyzing its temporal change characteristics. The average NDVI for forest and grassland in Sanmenxia City was calculated per pixel to obtain the spatial distribution of the average NDVI over seven years, analyzing its spatial pattern characteristics.

3.3 Trend Change Analysis

The Sen's slope trend analysis combined with the Mann-Kendall trend significance test method was adopted for analyzing the trend of vegetation cover change in forest and grassland areas.

The Theil-Sen Median trend analysis is a robust non-parametric statistical method for calculating trends, which can reduce the impact of outliers in the data. The calculation formula is as follows: For the time series $\{x_t\}$, t=1, 2, 3, …, n, define the slope Q:

$$Q = Median\left(\frac{x_b - x_a}{b - a}\right), 1 \le a < b \le n. \quad (1)$$

In the formula, x_a and x_b are the time series data; Median represents the median value; when $Q>0$, the time series $\{x_t\}$ shows an increasing trend, otherwise, the time series $\{x_t\}$ shows a decreasing trend.

The Mann-Kendall non-parametric test method is used to assess the significance of trends, with the advantage of not requiring the sample to follow a normal distribution, and it is not affected by missing values and outliers. The calculation formula is as follows: For the time series $\{x_t\}$, $t=1,2,3, \ldots, n$, define the statistic S:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i). \quad (2)$$

S follows a normal distribution with variance V_s:

$$V_S = [n(n-1)(2n+5)]/18. \quad (3)$$

Define the statistic Z:

$$Z = \begin{cases} \frac{S-1}{\sqrt{V_S}} & S>0 \\ 0 & S=0 \\ \frac{S+1}{\sqrt{V_S}} & S<0 \end{cases} \quad (4)$$

In the formula: x_j and x_i are time series data; sgn is the sign function; Z's value range is (-∞，+∞). At a given significance level α, critical value $u_{1-2/2}$ is determined from the normal distribution table. When $|Z|>u_{1-a2}$, it indicates that the time series $\{x_t\}$ has a significant change at the $\{x_t\}$ level. The trend change of the time series $\{x_t\}$ is judged through a significance test at a 0.05 confidence level; when $Z>1.96$, it indicates that the time series $\{x_t\}$ significantly increases; when $0<Z\le1.96$, it indicates that the time series $\{x_t\}$ does not significantly increase; when Z=0, it indicates that the time series $\{x_t\}$ remains unchanged; when $-1.96\le Z<0$, it indicates that the time series $\{x_t\}$ does not significantly decrease; when Z<-1.96, it indicates that the time series $\{x_t\}$ significantly decreases.

3.4 Future Evolution Analysis

The Hurst exponent is an effective method to quantitatively describe the long-term dependence of a time series. The calculation method is as follows:

For the time series $\{x_t\}$, $t=1,2,3, \ldots, n$; for a positive integer τ, define the mean series $\bar{x_\tau}$:

$$\bar{x_\tau} = \frac{1}{\tau}\sum_{t=1}^{\tau} x_t \quad (\tau=1,2,\ldots,n); \quad (5)$$

Cumulative deviation sequence $X_{t,\tau}$:

$$X_{t,\tau} = \sum_{t=1}^{t}(x_t - \bar{x_\tau}) \ (1 \le t \le \tau); \quad (6)$$

Range sequence R_τ:

$$R_\tau = maxX_{t,\tau} = minX_{t,\tau}(1 \le t \le \tau;\ \tau = 1, 2, \ldots, n); \quad (7)$$

Standard deviation sequence S_τ:

$$S_\tau = \sqrt[2]{[\frac{1}{\tau}\sum_{t=1}^{\tau}(x_t - x_\tau)^2]} \quad (\tau=1,2,\ldots,n) \quad (8)$$

If $R_\tau/S_\tau \propto \tau^H$ holds true, it indicates the presence of Hurst phenomenon in the time series $\{x_t\}$. The Hurst exponent (H) can be derived using least squares regression in the double logarithmic coordinate system $[in\tau, \text{in}(R_\tau/S_\tau)]$.

Based on the value of H, the time series $\{x_t\}$ can be identified as either completely random or exhibiting persistence. The Hurst exponent values encompass three scenarios: if $0.5<H<1$, it indicates that the time series $\{x_t\}$ is persistent, meaning future changes are consistent with past trends, and the closer H is to 1, the stronger the persistence. If $H = 0.5$, it implies that the time series $\{x_t\}$ is random with no long-term correlation. If $0<H<0.5$, it signifies that the time series $\{x_t\}$ has anti-persistence, meaning future trends will be opposite to past trends, and the closer H is to 0, the stronger the anti-persistence.

4 RESULTS AND ANALYSIS

4.1 NDVI Spatial Pattern Analysis

Based on the NDVI time series data from 1990 to 2020, the average values over seven years were calculated to obtain the spatial distribution map of NDVI average values in Sanmenxia City (Figure 2), which was then classified into six levels for statistical analysis. The results show that the area with high vegetation cover (NDVI ≥ 0.7) in Sanmenxia City is 3595.42 square kilometers, accounting for 62.12% of the total forest and grassland area, predominantly consisting of forested land, shrubland, and sparse forest, clustering in the southern region of Sanmenxia City with some distribution in the northernmost areas. The area with moderate vegetation cover (0.3 ≤ NDVI < 0.7) covers 2190.37 square kilometers, representing 37.84% of the total forest and grassland area, mainly distributed around cities and villages within the region. The area with low vegetation cover (NDVI <

0.3) spans 2.32 square kilometers, merely constituting 0.04% of the forest and grassland area, predominantly comprising paddy fields and dry land, with sparse distribution mainly around the areas of medium vegetation cover in the northern part of Sanmenxia City.

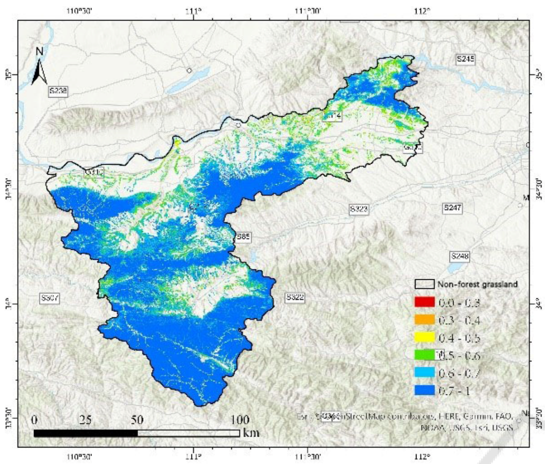

Figure 2: NDVI mean value in forestland and grassland in 1990-2020.

4.2 Inter-Annual NDVI Variation Analysis

From 1990 to 2020, the annual average NDVI of forest and grassland in Sanmenxia City fluctuated but overall showed an increasing trend, with a growth rate of approximately 0.187 per annum. The minimum and maximum values occurred in 1995 and 2020, respectively, with values of 0.4866 and 0.8258 (Figure 3). The analysis revealed a fluctuating increase trend from 1990 to 2005 and a stable growth trend from 2005 to 2020. Overall, the vegetation cover condition of forest and grassland in Sanmenxia City significantly improved over these 30 years.

4.3 NDVI Spatial Variation Analysis

Based on Theil-Sen trend analysis results and adopting the criteria of $Q > 0.0005$, $-0.0005 < Q \leq 0.0005$, and $Q \leq -0.0005$, the vegetation change of forest and grassland in Sanmenxia City was classified into three specific conditions: improvement, stability, and degradation. The results of the Mann-Kendall test were divided into significant change and non-significant change according to $|Z| > 1.96$ and $|Z| \leq 1.96$. Combining both results spatially, the trend of vegetation cover change of forest and grassland can be categorized into five major types: significant improvement, slight improvement, stable, slight degradation, and significant degradation, with their respective area proportions calculated (Figure 4).

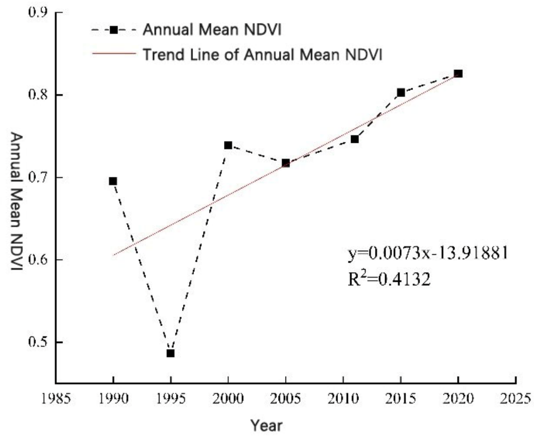

Figure 3: Inter-annual variation of NDVI in forestland and grassland in 1990-2020.

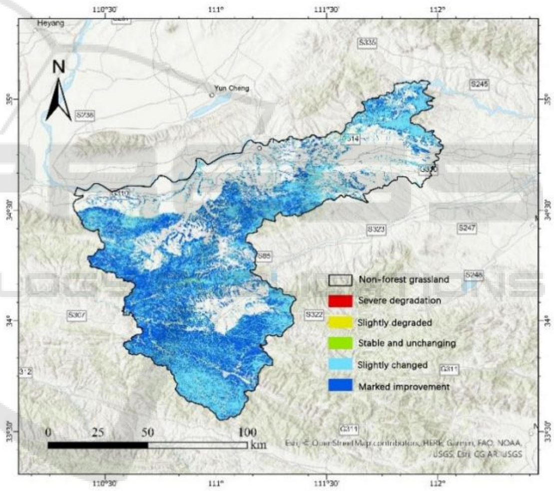

Figure 4: Change trend of forestry and grass coverage in the Sanmenxia City during 1990-2020.

From 1990 to 2020, the trend of vegetation cover change in forest and grassland in Sanmenxia City was predominantly improvement, covering an area of 5711.81 square kilometers, accounting for 98.68% of the total forest and grassland area, with significantly improved areas covering 2823.89 square kilometers, accounting for 48.79%, mainly distributed on the southwestern side of Sanmenxia City. The degraded area covered 69.02 square kilometers, accounting for 1.19% of the total area, primarily slight degradation. The area with a stable trend in vegetation change covered 6.21 square kilometers, accounting for 0.13% of the total area. In summary, the trend of high cover change in forest and grassland in Sanmenxia City from 1990 to 2020 was characterized by improved vegetation cover, with slight improvement in low cover areas.

4.4 Future Evolution Analysis of NDVI

4.4.1 NDVI Spatial Sustainability

Through R/S analysis, the average Hurst exponent for Sanmenxia City was obtained, indicating the presence of persistent series in the vegetation cover of forest and grassland. According to the classification results, areas with $0.5 < H < 1$, accounting for a certain percentage of the total area, exhibit unidirectional persistence characteristics, meaning the current trend of change will continue beyond 2020. Areas with $0 < H < 0.5$, covering a certain area and accounting for a certain percentage of the total area, show reverse direction persistence characteristics, indicating the future trend of vegetation cover change will be opposite to the current trend.

4.4.2 Future Development Trends of NDVI

Overlaying the spatial sustainability characteristics of NDVI with the spatial change trends reveals the future development directions of vegetation cover in forest and grassland areas of Sanmenxia City. The results are divided into four development directions: benign, malignant, stable, and uncertain. Areas with a benign development trend account for 71.401% of the total forest and grassland area, with their spatial distribution largely coinciding with the areas showing vegetation cover improvement, among which, areas of persistent slight improvement account for 33.308%, and areas of persistent significant improvement also contribute significantly; areas showing antipersistent degradation account for 0.263%, indicating that these areas will transition from degradation to benign development in the future. The area showing a malignant development trend accounts for 28.522% of the total forest and grassland area, with its spatial distribution largely aligning with the vegetation degradation areas, among which, areas of slight and significant degradation account for 0.92% and 0.012% respectively; antipersistent improvement areas account for 27.59%, primarily located in the central and northern parts of Sanmenxia City along the Yellow River, predicted to transition from improvement to degradation. Areas with stable and uncertain trends in vegetation cover change constitute 0.107% of the total area (Figure 5 and Table 1).

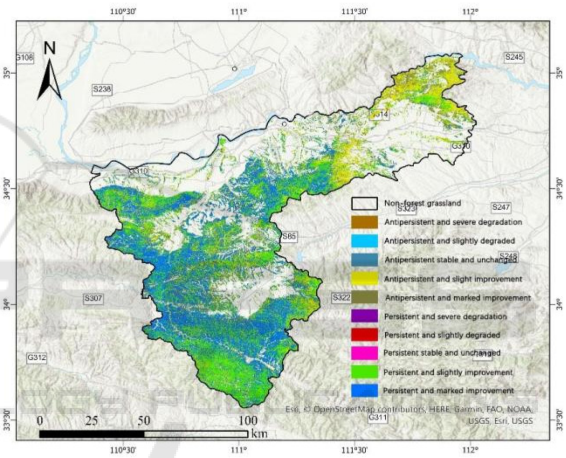

Figure 5: Future development trend of forestry and grass coverage.

Table 1: Future development direction of forestry and grass coverage.

Development Direction	Overlay Results	Area/km^2	Proportion/%
Benign Direction	Persistent & Slight Improvement	1926.11	33.308
	Persistent & Significant Improvement	2189.15	37.83
	Antipersistent & Severe Degradation	0.17	0.003
	Antipersistent & Slight Degradation	14.96	0.26
Malignant Direction	Persistent & Severe Degradation	0.72	0.012
	Persistent & Slight Degradation	53.17	0.92
	Antipersistent & Slight Improvement	961.81	16.62
	Antipersistent & Significant Improvement	634.74	10.97
Stable	Persistent & Stable Unchanged	1.54	0.027
Uncertain	Antipersistent & Stable Unchanged	4.67	0.08

5 CONCLUSION

This paper, based on NDVI time series data from 1990 to 2020 and employing Theil-Sen Median trend analysis, Mann-Kendall test, and Hurst index methods, analyzes the spatiotemporal characteristics and predicts future trends of vegetation cover change in forest and grassland in Sanmenxia City from 1990 to 2020. The main conclusions are as follows:

Overall, the vegetation cover of forest and grassland in Sanmenxia City primarily exhibits high coverage in the south and low coverage in the north. High coverage areas are mainly located in the southwestern regions such as Panhe Township, Xujiawan Township, and Wayaogou Township, while low coverage areas are predominantly found in the northern parts of Sanmenxia City, such as Gongqian Township.

From 1990 to 2020, the annual average NDVI of forest and grassland in Sanmenxia City fluctuated but showed an overall increasing trend, with a growth rate of approximately 0.187 per annum. The improved areas span 5711.81 square kilometers, accounting for 98.68% of the total forest and grassland area, significantly exceeding the degraded areas.

The future prospects for vegetation cover in forest and grassland areas of Sanmenxia City are promising. Areas with a benign development trend account for 71.401% of the total area, while those showing a malignant trend account for 28.522%, mainly distributed in the central and northern parts of the city along the Yellow River. The shift from improvement to degradation trends in these areas should be highly regarded in the process of ecological protection and management.

ACKNOWLEDGMENTS

Correspondence should be addressed Yang Yaohong; ecorestoration2023@163.com.

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