

Postprint of Vegetation-Topography Coupling Effects in the Pisha Sandstone Area of the Yellow River Based on Landsat Imagery

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Abstract

The Pisha sandstone area of the Yellow River is characterized by a fragile ecological environment and severe soil erosion. Deciphering the coupling mechanism between vegetation cover dynamics and topographic factors in this region holds significant theoretical value for promoting ecological restoration. Based on Landsat remote sensing data from 2000 to 2024, this study employs linear regression methods to analyze the spatiotemporal trends of vegetation cover. Combined with a Digital Elevation Model (DEM), the correlation characteristics between fractional vegetation cover (FVC) and topographic factors—including elevation, slope, aspect, and topographic niche index (TNI)—are systematically explored. Furthermore, Geodetector is utilized to reveal the driving effects of topographic factors on the spatial differentiation of vegetation cover.

The results indicate that: (1) Over the past 25 years, the FVC in the study area has shown an overall upward trend, with mean values ranging between 0.34 and 0.52; (2) Soil-covered and sand-covered areas are dominated by high vegetation cover, while bare Pisha sandstone areas are characterized primarily by low vegetation cover; (3) Vegetation cover exhibits a “rise then fall” trend with increasing elevation and slope, reaching peaks in the ranges of 1200–1300 m and 5°–15°, respectively; differences between aspects are not significant; vegetation is mainly distributed in the middle topographic niche levels with a TNI of 0.38–0.7; (4) The degree of influence of each factor on vegetation cover follows the order: elevation > slope > TNI > aspect. The interaction between any two factors manifests as non-linear enhancement, with the interaction between elevation and TNI showing the strongest explanatory power (q-value of 0.22). Vegetation cover in the Pisha sandstone area of the Yellow River is continuously improving and shows a significant coupling relationship with topographic factors. These research findings provide scientific support for the precise configuration

of vegetation in the Pisha sandstone area and the high-quality development of the Yellow River Basin.

Full Text

Vegetation-Topography Coupling Effects in the Pisha Sandstone Region of the Yellow River Based on Landsat Imagery

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Abstract

The Pisha sandstone area of the Yellow River is characterized by a fragile ecological environment and severe soil erosion. Researching the coupling mechanism between vegetation cover dynamics and topographic factors in this region is of great significance for promoting ecological restoration and sustainable development. This study utilizes multi-temporal Landsat remote sensing data (2000–2024) and high-resolution Digital Elevation Models (DEM) to analyze the spatio-temporal evolution of Fractional Vegetation Cover (FVC) and its response to topographic variables. By employing linear regression and Geographical Detectors (GeoDetector), the research quantifies the individual and interactive influences of factors such as elevation, slope, aspect, and the Topographic Position Index (TPI). The results indicate that: (1) Over the past 25 years, vegetation coverage has shown an overall upward trend, with mean values increasing from 0.34 to 0.52; (2) Soil-covered and sand-covered areas are dominated by high vegetation coverage, whereas bare Pisha sandstone areas are characterized primarily by low coverage; (3) Vegetation coverage follows a “unimodal” pattern with increasing elevation and slope, peaking within the ranges of 1200–1300 m and 5°–15°, respectively; (4) The degree of influence is ranked as elevation > slope > TPI > aspect. The interaction between elevation and TPI possesses the strongest explanatory power ($q = 0.22$). These findings provide scientific support for the precision allocation of vegetation and high-quality development in the Yellow River Basin.

1. Introduction

The Pisha sandstone area, located in the middle reaches of the Yellow River, is one of the most concentrated areas of soil erosion in the world. Due to its unique lithological characteristics—low cementation and high susceptibility to weathering—the region faces significant challenges in vegetation establishment. Topography is a fundamental determinant of spatial patterns in terrestrial ecosystems,

as it redistributes solar radiation and water resources. Understanding how vegetation responds to topographic gradients is essential for ecological conservation. While previous studies have explored the general ecological characteristics of the Loess Plateau, specific research on the vegetation-topography coupling effects within the unique Pisha sandstone geological formations remains limited.

2. Materials and Methods

2.1 Study Area

The study area is situated in the transition zone between the Loess Plateau and the Mu Us Desert (108°45' to 111°31'E, 38°10' to 40°10'N). It features a semi-arid continental climate with an annual average precipitation of 250-400 mm. The Pisha sandstone area is classified into three types: soil-covered, sand-covered, and bare rock areas.

2.2 Data Sources and Processing

Landsat series imagery (Landsat 7, 8, and 9) was utilized for the years 2000, 2005, 2010, 2015, 2020, and 2024. Preprocessing included radiometric calibration, atmospheric correction, and mosaicking. Topographic factors were extracted from SRTM DEM data (30 m resolution).

2.3 Methodology

Vegetation cover was estimated using the dimidiate pixel model:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$$

where $NDVI_{soil}$ and $NDVI_{veg}$ represent the NDVI values of bare soil and fully covered vegetation, respectively, determined using a 5%-95% confidence interval.

Linear regression was used to calculate the trend slope (θ_{Slope}):

$$\theta_{Slope} = \frac{n \times \sum_{i=1}^n (i \times FVC_i) - \sum_{i=1}^n i \times \sum_{i=1}^n FVC_i}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2}$$

The Topographic Position Index (TPI) was calculated to represent relative terrain position:

$$TPI = \ln \left[\left(\frac{E}{\bar{E}} + 1 \right) \times \left(\frac{S}{\bar{S}} + 1 \right) \right]$$

where E and S represent elevation and slope.

Figure 1

Figure 1: Figure 1

3. Results and Analysis

3.1 Spatio-temporal Dynamics of FVC

Over the past 25 years, FVC in the Pisha sandstone area has shown a consistent upward trend, increasing from 34.47% to 51.51%. This improvement is closely related to ecological projects such as the “Sea Buckthorn Ecological Engineering” initiated in 1998. High vegetation coverage increased from 15.39% to 31.42% by 2024, while low coverage decreased from 39.42% to 10.59%.

3.2 Influence of Topographic Factors

Vegetation coverage exhibits a distinct “unimodal” distribution with elevation and slope. - **Elevation:** FVC peaks in the 1200–1300 m range (27.62% coverage). Above 1400 m, adverse conditions such as low temperatures and thin soil layers limit growth. - **Slope:** The maximum FVC occurs within the 5°–15° range (56.29%). On steep slopes (>25°), high runoff and erosion lead to fragmented vegetation patches. - **Aspect:** Differences across various slope aspects were not statistically significant, likely due to the highly fragmented “slope-gully” system masking individual aspect effects. - **TPI:** Vegetation is primarily concentrated in the middle terrain niche (0.38–0.7). Low TPI areas (valleys) often suffer from poor aeration, while high TPI areas (ridges) face intense wind erosion.

[FIGURE:2]

3.3 Interaction Analysis

GeoDetector results indicate that the interaction between any two topographic factors exhibits non-linear enhancement. The interaction between elevation and TPI showed the highest explanatory power ($q = 0.217$), followed by elevation and slope ($q = 0.216$). This suggests that the vertical differentiation of hydrothermal conditions is the primary driver of vegetation patterns.

4. Discussion and Conclusion

4.1 Ecological Thresholds and Management

The study identifies critical topographic thresholds for vegetation restoration. Slopes <15° are suitable for agronomic conservation measures, while slopes >25° require mandatory ecological engineering. In low-altitude zones (<1300 m), composite configurations of shrubs and grasses are effective. In high-altitude

Figure 3

Figure 2: Figure 3

Figure 4

Figure 3: Figure 4

or high-TPI zones (>0.7), focus should shift toward natural restoration and stress-tolerant species.

4.2 Conclusion

1. Vegetation coverage in the Pisha sandstone area has significantly improved since 2000, transitioning from a state of nearly bare soil to comprehensive cover.
2. Topography significantly modulates FVC distribution, with elevation and slope acting as the dominant constraints.
3. The coupling effect between terrain and vegetation is non-linear and enhanced by factor interactions.
4. Future restoration should adopt a “spatially differentiated governance” model, tailoring species selection and engineering measures to specific topographic units to ensure the sustainability of the Yellow River’s ecological barrier.

Keywords

Pisha sandstone (Soft Rock); Vegetation Coverage; Spatio-temporal Differentiation; Topographic Effects; Geographical Detector

Figures

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Figure 5

Figure 4: Figure 5

Figure 6

Figure 5: Figure 6

Figure 7

Figure 6: Figure 7

Figure 8

Figure 7: Figure 8