Spatiotemporal Variation of Vegetation Coverage in Relation to Topographic Factors in the Upper Yellow River Basin of Gannan: Postprint

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Abstract

Vegetation cover in the upper Yellow River basin of Gannan plays a crucial role in maintaining the structural stability of alpine ecosystems and water conservation. Investigating the spatiotemporal variation of fractional vegetation cover and its relationship with topographic factors, and revealing the spatiotemporal distribution patterns of vegetation, can enhance our understanding of the dynamics and functions of alpine vegetation ecosystems, providing theoretical support for maintaining ecological balance and vegetation restoration. Based on four periods of Landsat imagery and Digital Elevation Model (DEM) data from 1990 to 2020 in the upper Yellow River basin of Gannan, this study employs methods including the dimidiate pixel model, overlay analysis, and Geodetector to investigate the spatiotemporal variation of fractional vegetation cover and its correlation with topographic factors in the study area. The results indicate that: (1) From 1990 to 2020, fractional vegetation cover in the upper Yellow River basin of Gannan experienced a process from degradation to recovery, and then to significant improvement; the proportion of medium-high vegetation cover (0.6–0.8) accounted for the largest share, representing 77.68% of the total area. (2) From 1990 to 2020, the study area exhibited a significant improving trend in fractional vegetation cover, with areas of improvement (Slope>0) accounting for approximately 91.26% of the total area, far exceeding the area of degraded regions (Slope<0). (3) The explanatory power of topographic factors on fractional vegetation cover varies significantly; elevation is the primary driving factor, and the interactive effects of topographic factors including slope, aspect, and elevation demonstrate greater explanatory power than individual factors. (4) Fractional vegetation cover in the study area exhibits a unimodal pattern of initially increasing and then decreasing with both elevation and slope; south-facing slopes have the highest vegetation cover, while northeast-facing slopes are relatively lower, and temporally, the area of vegetation cover from north to southwest directions shows a shrinking trend, whereas

areas in the southwest, west, and northwest directions are expanding. The research findings can provide scientific support for ecological protection and high-quality development in the upper Yellow River basin of Gannan.

Full Text

Abstract

Vegetation cover in the Upper Yellow River Basin of Gannan plays a crucial role in maintaining the structural stability of alpine ecosystems and conserving water sources. Investigating the spatiotemporal variation of vegetation coverage and its relationship with topographic factors, and revealing the patterns of vegetation distribution, can enhance our understanding of the dynamics and functions of alpine vegetation ecosystems, providing theoretical support for ecological balance maintenance and vegetation restoration. Based on four periods of Landsat imagery and Digital Elevation Model (DEM) data for the Upper Yellow River Basin in Gannan, this study employs the pixel dichotomy model, overlay analysis, and geographic detector methods to analyze the spatiotemporal changes in vegetation coverage and their correlation with topographic factors. The results indicate that: (1) From 1990 to 2020, vegetation coverage in the study area underwent a process from degradation to recovery, followed by significant improvement. Medium-high vegetation coverage (0.6-0.8) accounted for the largest proportion, representing 77.68% of the total area. (2) Between 1990 and 2020, the study area exhibited a significant improvement trend in vegetation coverage, with improved areas (Slope > 0) comprising 91.26% of the total area, far exceeding degraded regions (Slope < 0). (3) Topographic factors showed significant differences in their explanatory power for vegetation coverage. Elevation is the primary driving factor, while the interactive effects of slope, aspect, and elevation demonstrate stronger explanatory power than any single factor alone. (4) Vegetation coverage displayed a unimodal pattern of initially increasing then decreasing with both elevation and slope. Southern slopes exhibited the highest vegetation coverage, while northeastern slopes showed relatively lower values. Over the time series, vegetation coverage area from north to southwest directions presented a shrinking trend, whereas areas in southwest, west, and northwest directions expanded. These findings provide scientific support for ecological protection and high-quality development in the Upper Yellow River Basin of Gannan.

Keywords: vegetation coverage; geographic detector; spatiotemporal variation; topographic factor; Upper Yellow River Basin in Gannan

Introduction

Vegetation constitutes the foundation of terrestrial ecosystems and serves as a key participant in carbon and water cycling within watersheds. It plays a vital role in energy conversion, material cycling, and information exchange, making it indispensable for maintaining ecological balance and biodiversity. Fractional vegetation cover (FVC), defined as the percentage of vertical projection area of vegetation relative to total surface area, is commonly used to assess vegetation and land degradation status in ecological, soil conservation, and climate studies. FVC exerts significant influence on hydrological patterns, ecological stability, and regional development dynamics.

The Upper Yellow River Basin in Gannan, located on the northeastern edge of the Tibetan Plateau, features rich topographic and climatic diversity, serving as an important ecological barrier and water source replenishment area for the Yellow River. In recent years, excessive land resource development without scientific guidance has led to sharp declines in biodiversity and weakened water conservation capacity of wetlands, grasslands, and forests, resulting in soil erosion and vegetation degradation. Vegetation restoration represents the most effective measure for improving the ecosystem of the Tibetan Plateau and controlling soil erosion. Monitoring vegetation growth changes and conducting comprehensive planning can promote regional ecological protection and high-quality economic development.

With the development of remote sensing technology, spatiotemporal variation of vegetation coverage and its attribution have become research hotspots. Previous studies have applied long time-series remote sensing imagery to analyze vegetation dynamics. For instance, researchers have used MODIS NDVI data to identify positive correlations between vegetation coverage and precipitation in northwestern Ethiopia, while Landsat imagery and topographic data have revealed spatiotemporal vegetation changes under different terrain conditions in Duhok Governorate, Iraq. Other studies have examined the relationship between vegetation coverage and dust storms, demonstrated combined natural and anthropogenic influences on vegetation in the Urumqi River Basin, and quantified vegetation changes in the Yellow River Basin using statistical methods like the pixel model and Moran' s index. These applications of remote sensing technology have proven effective for monitoring vegetation changes and analyzing influencing factors.

The Upper Yellow River Basin in Gannan, known as the "Kidney of the Yellow River," contains extensive alpine grassland, wetland, and forest ecosystems that serve as crucial water source replenishment areas. Historical changes in vegetation status due to the unique alpine climate, topography, and complex human-environment relationships have caused ecological deterioration and increased ecological vulnerability in some areas. This study investigates spatiotemporal evolution of vegetation coverage from 1990 to 2020 in the Upper Yellow River Basin of Gannan using Google Earth Engine platform, Landsat imagery, the pixel dichotomy model, linear trend analysis, and geographic detector methods. We assess correlations between vegetation coverage and topographic factors, analyze detailed variations along topographic gradients, and aim to reveal vegetation growth and distribution patterns under different terrain conditions, thereby providing reliable data support for regional vegetation restoration and ecological rehabilitation.

1.1 Study Area

The Upper Yellow River Basin in Gannan is situated on the northeastern edge of the Tibetan Plateau, with geographic coordinates of 33°06 -36°10 N, 100°46 -104°44 E. The study area covers five counties: Hezuo City, Xiahe County, Luqu County, Maqu County, Lintan County, and Zhuoni County, spanning 30,570 km^2. The region features high elevation, with an average altitude above 3,000 m and relatively gentle relief. The climate is continental plateau climate, characterized by cold and humid conditions, with annual precipitation of 400–700 mm and mean annual temperature of approximately 1-3°C. Grassland types include alpine meadow, alpine shrub meadow, temperate meadow steppe, temperate steppe, lowland meadow, and warm temperate tussock, among which alpine meadow and alpine shrub meadow dominate.

1.2 Data Sources

This study utilized the Google Earth Engine (GEE) platform (https://code.earthengine.google.com/) to process Landsat 5/7/8/9 remote sensing data. Annual composites were generated by applying cloud and shadow masking to obtain all valid observations, followed by linear interpolation and NDVI calculation for each valid observation, combined with Savitzky-Golay smoothing to produce annual maximum NDVI composites. Landsat imagery with 30 m spatial resolution was selected as the primary data source.

Validation data were obtained from two sources: Landsat_5 TM imagery from the Geospatial Data Cloud platform (https://www.gscloud.cn/), and the China Vegetation Index Dataset from the Science Data Bank (https://www.scidb.cn/) with 12.5 m resolution. DEM data were extracted from the ALOS PALSAR RTC dataset (https://search.asf.alaska.edu/#/) with 12.5 m resolution. Elevation, slope, and aspect were derived using ArcGIS.

1.3 Methods

1.3.1 Pixel Dichotomy Model This model assumes each pixel comprises vegetation and non-vegetation components, with spectral data representing a linear combination of these components. Vegetation coverage represents the relative proportion of vegetation area. Based on this model, ENVI 5.3 software was used to quantitatively analyze annual vegetation coverage in the study area. Vegetation coverage was classified into five levels according to regional vegetation characteristics: low (0–0.2), medium-low (0.2-0.4), medium (0.4-0.6), medium-high (0.6-0.8), and high (0.8-1).

1.3.2 Confusion Matrix The confusion matrix evaluates classification accuracy, where diagonal elements represent correctly classified samples and off-diagonal elements represent misclassifications. Total classification accuracy (PC) is calculated as: PC = Σ(m Pkk)/N, where m is the number of categories, N is the total sample number, and Pkk is the number of correctly classified samples for category k.

1.3.3 Linear Trend Analysis Linear regression analysis was applied to examine spatiotemporal trends in vegetation coverage from 1990 to 2020. The F-test was used to assess trend significance, revealing interannual variation patterns.

1.3.4 Geographic Detector Geographic detector analyzes spatial heterogeneity and its causes through factor detection, interaction detection, risk assessment, and ecological analysis. This study employed factor and interaction detection to parse geographic influencing factors of vegetation coverage, identifying primary topographic drivers and their interactive effects.

1.3.5 Topographic Factor Classification The natural breaks method classified elevation into six levels: <2500 m, 2500-3000 m, 3000–3500 m, 3500-4000 m, 4000–4500 m, and >5000 m. Slope was classified according to the Soil Erosion Classification Standard into six categories: <5°, 5°-10°, 10°-15°, 15°-25°, 25°-35°, and >35°. Aspect was automatically classified into eight directions using ArcGIS. Zonal statistics were performed to analyze vegetation coverage variation across topographic units.

Results

2.1 Accuracy Validation

Using the GEE platform and pixel dichotomy model, vegetation coverage from 1990 to 2020 was retrieved. Accuracy was assessed through confusion matrix comparison with Landsat_5 TM imagery and China Vegetation Index Dataset. Random sample points yielded classification accuracies of 85.2% for 1990, 87.4% for 2000, 86.8% for 2010, and 88.1% for 2020, demonstrating the reliability of the GEE-based approach.

2.2 Spatiotemporal Variation Characteristics

2.2.1 Average Vegetation Coverage Distribution The study area is dominated by medium-high vegetation coverage (0.6–0.8), accounting for 77.68% of the total area. High vegetation coverage (0.8–1.0) represents only 0.46%, while low, medium-low, and medium coverage collectively comprise 21.86%.

2.2.2 Temporal Variation Trends Mean vegetation coverage values were 61.83% (1990), 60.96% (2000), 62.43% (2010), and 72.94% (2020), showing an initial decline followed by a consistent increase. Between 1990 and 2000, medium vegetation coverage increased significantly from 22.74% to 30.66%, while high and medium-high coverage decreased. From 2000 to 2020, vegetation coverage showed clear improvement, with medium-high and high coverage increasing to

67.75% of the total area, attributable to ecological protection and restoration projects such as Grain for Green and natural forest protection programs.

Most regions exhibited vegetation improvement, though localized degradation occurred in approximately 2,447.25 km^2 (8.74% of total area), primarily in southeastern Maqu County, likely due to special soil conditions and overgrazing. Southern Luqu County also showed degradation due to topographic characteristics and excessive disturbance.

2.2.3 Linear Trend Analysis Linear trend analysis and significance testing revealed widespread positive growth trends across the study area from 1990 to 2020. Improved areas covered 25,567.9 km^2 (91.26% of total area), with extremely significant, significant, and weakly significant increases accounting for 5,017.44 km^2 (17.91%), 8,290.53 km^2 (29.59%), and 12,200.71 km^2 (43.55%) respectively. Degraded areas totaled 2,506.43 km^2 (8.74%), with extremely significant, significant, and weakly significant decreases covering 407.36 km^2 (1.45%), 491.35 km^2 (1.75%), and 1,607.72 km^2 (5.74%) respectively.

Improvement was particularly notable in northwestern Maqu County, where pilot programs of grazing prohibition and afforestation were implemented. Xiahe County also showed substantial improvement through ecological monitoring and degraded grassland restoration. However, significant decreases occurred in southeastern Maqu County (anthropogenic pressure), central Luqu County (mountainous terrain and over-disturbance), eastern Hezuo City (severe grazing interference), and border areas between southern Luqu and northeastern Maqu (combined environmental stress and human activity).

2.3 Relationship with Topographic Factors

2.3.1 Correlation Strength Factor detection revealed that topographic factors differed significantly in their explanatory power for vegetation coverage, ranked as: elevation (0.347) > slope (0.089) > aspect (0.012). Elevation emerged as the primary driver, with slope and aspect as secondary factors. Interaction effects between elevation and other factors exceeded all other combinations, confirming elevation' s dominant control. Slope interactions showed enhanced explanatory power compared to single-factor effects, indicating slope' s indirect influence on vegetation coverage.

2.3.2 Elevation Gradient Variation Vegetation coverage exhibited a unimodal pattern with elevation, initially increasing then decreasing. Below 3,500 m, coverage increased with elevation as human disturbance decreased. Maximum coverage occurred at 3,500–4,000 m, where temperature and moisture provided optimal conditions. Above 4,000 m, coverage declined due to decreasing temperatures limiting vegetation growth.

2.3.3 Slope Gradient Variation Vegetation coverage also showed a unimodal pattern with slope. Below 5°, gentle terrain experienced frequent human activity, limiting vegetation growth. Maximum coverage occurred at 5°–10°, where optimal soil moisture and nutrient conditions supported vegetation development. Coverage decreased gradually at 10°–25° and declined sharply beyond 25° due to intensified soil erosion and deteriorating soil-water conditions.

2.3.4 Aspect Variation Aspect influences vegetation through differential soil moisture and solar radiation. Vegetation coverage varied significantly across aspects, ranking as: south > southwest > west > northwest > north > east > southeast > northeast. Southern slopes exhibited the best vegetation growth, while northeastern slopes showed the lowest coverage. Temporally, vegetation coverage area shrank from north to southwest directions while expanding in southwest, west, and northwest directions. Overall, sunny slopes supported higher vegetation coverage than shady slopes, reflecting the light-preferring characteristics of alpine meadow vegetation dominant in the study area.

Discussion

The Upper Yellow River Basin in Gannan, located on the northeastern edge of the Tibetan Plateau, is a critical watershed where vegetation condition directly impacts Yellow River water security and regional ecological balance. Using Landsat remote sensing data and the pixel dichotomy model offers simplicity and strong adaptability for estimating vegetation coverage in the Yellow River Basin.

3.1 Spatiotemporal Trends in Vegetation Coverage

From 1990 to 2020, vegetation coverage in the study area showed an overall upward trend, consistent with previous research. The period 1990–2000 experienced coverage decline due to overgrazing and unsustainable land use. From 2000 to 2020, vegetation showed continuous growth, primarily because the government strengthened ecological protection policies, consolidated Grain for Green achievements, and launched the second national round of the program in 2014, accelerating FVC growth.

The study area exhibited a gradient of higher vegetation coverage in the west and lower in the east, aligning with existing research. This pattern reflects comprehensive effects of grassland protection policies, land use conditions, and topography. Western Maqu County implemented grazing prohibition and desertification control projects, effectively promoting vegetation recovery. Xiahe County achieved success through ecological monitoring and degraded grassland restoration. Luqu County’ s livestock balance policy reduced grassland pressure and improved coverage. In contrast, eastern land use patterns and northern topography contributed to lower vegetation coverage.

3.2 Relationship Between Vegetation Coverage and Topographic Factors

Topography influences vegetation growth and evolution by altering habitats, causing significant regional differences in vegetation coverage distribution across watersheds, consistent with early research findings. Notably, vegetation coverage decreased with elevation due to cold climate at high altitudes. However, Figure 7 shows relatively low coverage in low-elevation areas with favorable hydrothermal conditions, likely due to dense population and intensive agricultural activities. Since the 1999 Grain for Green policy, urban population growth and expansion of urban land use, particularly in low-elevation valley areas, have further impacted vegetation.

Maximum vegetation coverage occurred at 5°–10° slopes, declining gradually beyond 10° and sharply after 25°, consistent with Zhang et al.'s findings. Increased slope reduces water pressure and heat accumulation, causing precipitation runoff and decreasing rainfall per unit area, thereby reducing vegetation coverage.

Aspect creates differences in solar radiation energy received by slopes, affecting vegetation growth. The light-preferring characteristic of alpine meadow vegetation in the study area aligns with research on the southern Qilian Mountains and upper Minjiang River. However, some studies report insignificant aspect effects, such as in Shanxi Province and the middle-upper Yangtze River Basin, reflecting regional differences in how aspect influences vegetation distribution. In arid and semi-arid regions, aspect-determined solar radiation and soil factors create unique conditions, sometimes resulting in shade-preferring vegetation characteristics.

This study provides an in-depth analysis of vegetation coverage spatiotemporal variation and its relationship with topographic factors. Future research will integrate climate, soil, land use, and socioeconomic data for comprehensive analysis to more accurately identify and quantify impacts of various factors on vegetation changes, providing references for scientifically sound vegetation protection and restoration strategies.

Conclusion

1. From 1990 to 2020, vegetation coverage in the Upper Yellow River Basin of Gannan showed overall improvement, dominated by medium-high coverage (0.6–0.8) accounting for 77.68% of the study area. High vegetation coverage (0.8–1.0) represented the smallest proportion at only 0.46%, with other types comprising 21.86%.

2. During the study period, improved vegetation coverage areas accounted for approximately 91.26% of the total area, far exceeding degraded areas. Localized degradation occurred in the northeastern region, while western areas showed more pronounced improvement than eastern areas.

3. Elevation was the primary driving factor influencing vegetation coverage,

with slope as a secondary factor. Interactive effects among topographic factors demonstrated synergistic enhancement.

4. Vegetation coverage showed a unimodal pattern with elevation, peaking at 3,500–4,000 m. Coverage also peaked at 5°–10° slopes. Northeastern slopes had relatively low vegetation coverage, while southern slopes had high coverage, reflecting the light-preferring characteristics of the region' s vegetation.

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