Postprint: Analysis of Vegetation Cover Characteristics in Different Landforms and Terrains of the Ten Major Kongdui on the Ordos Plateau

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Abstract

Artificial grass planting and afforestation have effectively improved soil and water erosion in the Ten Great Kongdui of the Ordos Plateau, but vegetation degradation has occurred in some areas. A thorough understanding of topographic influences on vegetation holds important practical significance for soil and water conservation in this region. Based on ZY3-01 satellite elevation data and MODIS Normalized Difference Vegetation Index (NDVI) data, vegetation changes across different landform types in the Ten Great Kongdui from 2000 to 2022 were analyzed. The results indicate: (1) Vegetation in the Ten Great Kongdui has improved overall, with NDVI showing an upward trend across different landform types. The multi-year average NDVI values for plain, hill, and desert regions are 0.591, 0.337, and 0.325, respectively, with the desert region exhibiting the greatest increasing trend. Vegetation degradation in the plain region is mainly distributed along the Yellow River coast, accounting for 16.28% of the plain area; degradation in the desert region is mainly distributed in the middle reaches of the Haoqing River, accounting for 0.64% of the desert area; degradation in the hill region is mainly distributed in the upper reaches of the Xiliugou, Hantaichuan, and Hashilachuan rivers, accounting for 1.88% of the hill area. (2) Under different slope conditions, vegetation on gentle slopes and moderate slopes in the plain region is generally better than that on level ground and flat land. NDVI in the desert region shows the pattern: level ground > flat land > gentle slope > moderate slope > steep slope. NDVI in the hill region is almost identical to that in the desert region, but steep slopes performed better than gentle and moderate slopes, yet worse than level ground and flat land during 2000–2022. (3) Under different aspect conditions, NDVI in the plain region during 2000–2022 shows the pattern: sunny slope > semi-shaded slope > shady slope. The desert region generally shows: shady slope > sunny slope > semi-shaded slope. The hill region shows: shady slope > semi-shaded slope > sunny slope. Therefore, desert and hill regions should plant more vegetation on

level ground or flat land, and in slope areas, shady slopes with smaller gradients should be prioritized for planting.

Full Text

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Analysis of Vegetation Coverage Characteristics Across Different Topographies and Landforms in the Ten Tributaries of the Ordos Plateau

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Abstract: Artificial grass and tree planting have effectively mitigated soil erosion in the ten tributaries of the Ordos Plateau, Inner Mongolia, China. However, some regions have experienced vegetation degradation. Understanding the influence of topography on vegetation is critical for soil and water conservation efforts in this area. This study analyzed vegetation changes across different topographies and landforms in the ten tributaries from 2000 to 2022, utilizing digital elevation model (DEM) data from the ZY3-01 satellite and normalized difference vegetation index (NDVI) data from MODIS. The findings are as follows: (1) The overall vegetation in the ten tributaries improved, with the NDVI of different landform types showing an upward trend. The multi-year average NDVI values for plain, hilly, and desert areas were 0.591, 0.337, and 0.325, respectively. The most pronounced improvement occurred in the desert area. Vegetation degradation accounted for 16.28% of the plain area (mainly along the Yellow River), 0.64% of the desert area (predominantly in the middle reaches of the Haoqing River), and 1.88% of the hilly area (primarily in the upper reaches of Xiliugou, Hantaichuan, and Hashilachuan). (2) In the plain area, NDVI on flat gentle slopes and gentle slopes exceeded that on horizontal and flat land. In the desert area, NDVI followed the trend: horizontal land > flat land > flat gentle slope > gentle slope > steep slope. Similarly, in the hilly area, NDVI trends mirrored those of the desert area; however, from 2000 to 2022, NDVI on steep slopes surpassed that on flat gentle slopes and gentle slopes but remained lower than that on horizontal and flat land. (3) From 2000 to 2022, in the plain area, NDVI followed the trend: sunny slope > half-sunny slope > shady slope. Conversely, in the desert area, NDVI followed the trend: shady slope > sunny slope > half-sunny slope. In the hilly area, the trend was shady slope > half-sunny slope > sunny slope. These findings suggest that desert and hilly areas would benefit from planting vegetation on horizontal or flat land and on shady slopes with lower gradients for sloping areas.

Keywords: ZY3-01 satellite; sand forest plantation; temporal and spatial changes of vegetation; slope; slope aspect; ten tributaries; Ordos Plateau

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The ten tributaries of the Ordos Plateau experience active wind-water erosion, with crisscrossing gullies in the upper reaches and an east-west desert corridor in the middle reaches, serving as a major source of sediment deposition in the Inner Mongolia section of the Yellow River. To reduce sediment input to the Yellow River, large-scale vegetation has been planted in the upper and middle reaches through artificial greening. Although the ecological environment of the ten tributaries has improved and sediment discharge has decreased, rapid expansion of forest and grass vegetation, coupled with irrational planting and limited water resources, has led to widespread decline in many key artificial forests. Large-scale vegetation distribution is constrained by hydrothermal conditions, while small-scale distribution is limited by topographic conditions. Different slopes and aspects significantly influence soil moisture, heat, and nutrient distribution, making their impact on vegetation non-negligible. Peng et al. studied *Salix matsudana* at different slope positions in the Liudaogou watershed of the Loess Plateau and found that slope-grown willow tends to become "small old trees." Wang et al. demonstrated that vegetation growth is greatly affected by slope, with flat and gentle slopes suitable for crops and steep slopes appropriate for trees, shrubs, and grasses. Wang et al. monitored *Larix principis-rupprechtii* in the Liupan Mountains and showed that slope position significantly affects transpiration, which is closely related to vegetation indices. Pei et al. monitored *Salix psammophila* in the Mu Us Desert and found that sap flow of willows with the same diameter at breast height was greater on flat land than on mid-slope and hilltop positions, with micro-topographic differences in vegetation landscapes primarily caused by variations in hydrothermal conditions and nutrient status. Some scholars have used remote sensing to analyze relationships between vegetation distribution and elevation, slope, and aspect, with most studies indicating correlations among all three factors, though some found relationships only with aspect and slope, or elevation and slope. However, these studies used elevation data with resolutions coarser than 100 m. Guan et al. and Zhu et al. analyzed vegetation change characteristics in the ten tributaries but their temporal coverage was discontinuous, making it difficult to reflect true vegetation change patterns, and they did not consider topographic effects—a research gap this study addresses. Therefore, this paper uses high-resolution ZY3-01 satellite DEM data, MODIS NDVI data, and surveyed tree species data to investigate relationships between topography and vegetation coverage across different landforms in the ten tributaries, to better understand vegetation change characteristics in the upper and middle reaches, which is crucial for assessing regional vegetation restoration status and providing theoretical guidance for artificial forest construction and ecological protection.

1.1 Study Area Overview

The ten tributaries (39°50 ~40°30 N, 108°45 ~110°55 E) are seasonal rivers crossing the Kubuqi Desert and flowing through alluvial plains before joining the Yellow River in northern Ordos Plateau. From west to east, they are: Mabula Kongdui, Borse Tai Gully, Heilai Gully, Xiliugou, Hantaichuan, Haoqing River, Hashilachuan, Muhaer River, Dongliugou, and Husitai River, covering a total area of 10,767 km^2. The terrain slopes from south to north and west to east, with elevations between 888–1,627 m. Three typical landform types are distributed from south to north: a hilly-gully region in the upper reaches dominated by water erosion with severe soil loss; a wind-sand region in the middle reaches where the Kubuqi Desert crosses east-west with severe wind erosion; and an alluvial fan plain in the lower reaches with extensive cropland and intensive human activity. The watershed has a typical temperate continental monsoon climate, with windy days concentrated in March–May, averaging 17 $m \cdot s^{-1}$; annual average temperature is 6–9°C; evaporation is intense at about 10 times precipitation; annual precipitation is 200-350 mm, decreasing from southeast to northwest, often occurring as storms concentrated in June–September, accounting for ~70% of annual precipitation. Vegetation transitions from typical steppe in the east-south to desert steppe and steppe desert in the northwest. The ratio of trees, shrubs, and grass in major artificial forests is approximately 1:6:3.

1.2 Data and Processing

NDVI data were obtained from the MODIS MOD13Q1 product with 250 m spatial resolution and 16-day temporal resolution from 2000 to 2022. Data preprocessing included format conversion, image mosaicking, reprojection, and gap filling. Invalid values in MODIS images were processed and interpolated, then resampled to match the resolution of DEM data. Elevation data were derived from ZY3-01 satellite, which offers strong timeliness and currency, with image plane accuracy better than 5 m and elevation accuracy better than 2 m without ground control points. ArcGIS Pro spatial analysis tools were used to extract slope and aspect from DEM data.

Slope affects the scale and intensity of surface material flow and energy conversion, playing an important role in vegetation distribution. Based on the land slope classification standard for Fuxian County on the Loess Plateau proposed by Zhang et al. and combined with slope conditions in the ten tributaries, slopes were classified as: horizontal land (0°), flat land (1°–3°), flat gentle slope (3°–7°), gentle slope (7°–15°), and steep slope (>15°). Following Lei Siyue' s research on slope aspect division in the Loess Plateau and considering the terrain of the ten tributaries, aspect was divided into four categories: starting from true north (0°) and rotating clockwise 0°–360°, shady slope is (0°–67.5°, 337.5°–360°), half-shady/half-sunny slope is (67.5°–157.5°, 247.5°–337.5°), and sunny slope is (157.5°–247.5°), where 0° refers to true north (Figure [Figure 247: see original paper].5°).

Tree species survey data came from the most recent survey (2014) by the Ordos Forestry Bureau, obtained through Landsat data interpretation and field surveys, covering four counties (Dongsheng District, Zhungeer Banner, Dalate Banner, Hangjin Banner) with 28 tree species (Figure 4). Major species include *Caragana* (including *C. microphylla* and *C. intermedia*), *Salix psammophila*, poplar, *Hedysarum mongolicum*, *C. korshinskii*, and *Pinus tabuliformis*.

1.3 Research Methods

The Theil-Sen median trend analysis method was applied pixel-by-pixel to calculate the change rate and reflect regional vegetation trends:

$$b = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \quad 2000 \leq i < j \leq 2022$$

where b is the Theil-Sen median; $b > 0$ indicates vegetation improvement and $b < 0$ indicates degradation; x_j and x_i are NDVI values in years j and i, respectively.

The Mann-Kendall non-parametric statistical test was used for significance testing. The test statistic S is calculated as:

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases}$$

where n is the time series length. The test statistic Z is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases}$$

At significance level $\alpha = 0.05$, if $|Z| \geq 1.96$, the trend passes the 95% significance test and is considered significant change; if $|Z| < 1.96$, it is non-significant. Trends were classified as: significant improvement ($b > 0.0005$, $|Z| \geq 1.96$), slight improvement ($b > 0.0005$, $|Z| < 1.96$), slight degradation ($b < -0.0005$, $|Z| < 1.96$), significant degradation ($b < -0.0005$, $|Z| \geq 1.96$), and basically stable ($-0.0005 \leq b \leq 0.0005$, $|Z| < 1.96$).

Results and Analysis

2.1.1 Spatial Variation Characteristics of Vegetation

NDVI values differed significantly across the three landform types, ranging 0.096–0.883. In the hilly area, NDVI ranged 0.122–0.822, with better vegetation growth in the upper reaches of Hashilachuan, Hantaichuan, Xiliugou, and various gullies, while other areas showed poorer growth. In the desert area, NDVI ranged 0.103–0.870, with particularly poor and concentrated vegetation in the narrow central belt west of Hantaichuan, while better growth occurred east of Hantaichuan and in the upper and lower reaches of Heilai Gully and Borse Tai Gully. The plain area generally showed good vegetation growth, with NDVI ranging 0.096–0.883.

Trend analysis and Mann-Kendall testing revealed that vegetation in the ten tributaries improved overall, but degradation was concentrated in certain areas accounting for 4.04% of the total region (Figure 6). In plain cropland, degradation occurred mainly along the Yellow River, representing 16.28% of the plain area. The main crops in the lower Yellow River floodplain are wheat and rapeseed, harvested from early June and early July respectively, which is the primary cause of vegetation degradation along the river. In the middle and upper cropland, the main crop is corn, harvested from early October, coinciding with withering of trees and herbs. Desert area degradation was mainly distributed in the lower reaches of the Haoqing River, accounting for 0.64% of the desert area. Hilly area degradation was mainly distributed in the upper reaches of Xiliugou, Hantaichuan, and Hashilachuan as patchy distributions, representing 1.88% of the hilly area. Except for areas along the Yellow River and urban expansion zones, vegetation degradation was relatively concentrated and small in area, likely caused by uneven soil moisture distribution due to topographic differences.

Overlay analysis of degraded vegetation with tree species (Figure 7) yielded Table 1. In 87.21% of the region, forest land showed significant improvement. Except for *Platycladus orientalis*, *Juniperus rigida*, and *Sophora japonica*, all other species accounted for high proportions in significantly improved areas, exceeding 70%, with some species showing no degradation at all, such as *Prunus armeniaca*, *Prunus davidiana*, *Syringa*, *Pyrus*, and *Acer*. This indicates that selected tree species grew well in these areas. However, some species showed large-scale degradation, such as *Juniperus chinensis*, *Sophora japonica*, and *Platycladus orientalis*, suggesting these species are unsuitable for local plantations. Some widely planted species also showed patchy degradation, such as *Caragana*, *Pinus tabuliformis*, *Caragana korshinskii*, and poplar in the upper reaches of Hantaichuan and Hashilachuan. Degraded species in the upper reaches of Xiliugou, Borse Tai Gully, and Mabula Kongdui were mainly *Caragana*, with some *Salix psammophila* and willow degradation. Compared with the upper hilly area, degradation in the middle desert area was less extensive, concentrated mainly along the Haoqing River and Dongliugou, with degraded species including *Caragana*, poplar, *Caragana korshinskii*, *Hedysarum mongolicum*, and *Salix psammophila*. In the lower plain cropland, degradation was minimal, with only a few point distributions, as the lower reaches are dominated by cropland with relatively small artificial forest areas.

2.1.2 Temporal Variation Characteristics of Vegetation Across Different Landform Types

The three landform types showed fluctuating upward NDVI trends, with multi-year averages of 0.591, 0.337, and 0.325 for plain, hilly, and desert areas respectively, decreasing in that order. The plain area showed a gentle trend, the hilly area was intermediate, and the desert area showed the most obvious increase. Besides topographic factors, under the same climate conditions, plain area NDVI may be more influenced by cropland area and crop species, while hilly and desert areas are more affected by artificial planting and soil moisture stress.

Except for 2000, hilly area NDVI was greater than desert area before 2010, but the opposite occurred after 2010, suggesting that soil erosion may still cause vegetation degradation in the hilly area. The three landform types showed different NDVI patterns in individual periods but consistent patterns in other periods. NDVI was identical between plain and desert areas in 2000–2002, 2004–2005, and 2007–2008, and between plain and hilly areas in 2016–2017 (Figure 9). Inconsistencies may be caused by climate change and human activities.

The multi-year average NDVI of the three landform types peaked in August and then declined until October, indicating that the main growing season for most plants in the study area is June–September.

2.2.1 Relationship Between Vegetation and Slope

NDVI trends were generally consistent across different slopes for all landform types, though some differences existed before 2010. In the plain area, flat gentle slopes and gentle slopes showed better vegetation growth than horizontal and flat land, likely because the former are dominated by grassland and forest while the latter are dominated by wheat and corn, with harvesting affecting vegetation characteristics. Steep slopes showed the poorest vegetation growth, especially before 2010 in plain and hilly areas. During the growing season (June–September), NDVI trends in the plain area exceeded those in the desert area, indicating this is the peak growth period for crops. After 2010, steep slope vegetation degradation may be caused by soil moisture stress and human disturbance as vegetation matures.

Desert area NDVI trends remained consistent across different slopes, particularly after 2010, with minimal differences from other landform types. Desert and hilly areas showed similar temporal patterns, with only minor differences. Before 2010, vegetation growth followed the trend: horizontal land > flat land > flat gentle slope > gentle slope > steep slope, because sandy soil has uniform texture, poor water retention, and soil moisture decreases with increasing slope, leading to poorer vegetation growth on steeper slopes. After 2010, steep slope vegetation growth in some years exceeded that on flat gentle and gentle slopes but remained poorer than on horizontal and flat land. This occurred because trees were smaller before 2010 and soil moisture on steep slopes could meet growth requirements, but later soil moisture stress caused decline, followed by artificial replanting that improved growth after 2010.

Hilly area NDVI trends across different slopes almost completely mirrored those of the desert area, also showing horizontal land > flat land > flat gentle slope > gentle slope. However, steep slope vegetation growth was better than flat gentle and gentle slopes throughout the entire period, though still poorer than on horizontal and flat land. This differs substantially from the desert area, likely because check dams built in the upper hilly-gully region reduced water and nutrient loss, improving vegetation growth. Some differences existed between the plain area and other landform types before 2010, possibly due to stronger human activity impacts.

2.2.2 Relationship Between Vegetation and Slope Aspect

NDVI trends were generally consistent across different slope aspects for all landform types. In the plain area, NDVI followed the trend: sunny slope > half-sunny slope > shady slope throughout the entire period, with differences less than 0.05. In the desert area, NDVI followed the trend: shady slope > sunny slope > half-sunny slope, also with differences less than 0.05. In the hilly area, NDVI followed the trend: shady slope > half-sunny slope > sunny slope, with differences less than 0.05. Therefore, in plain areas, vegetation grows better and has higher survival rates on sunny slopes, while desert and hilly areas are more suitable for planting vegetation on shady slopes with smaller gradients.

Conclusions

(1) Vegetation in the ten tributaries improved overall, but degradation was concentrated in certain areas accounting for 4.04% of the total region. Plain cropland degradation occurred mainly along the Yellow River (16.28% of the plain area). Middle reaches degradation was mainly distributed in the lower Haoqing River (0.64% of the desert area). Upper hilly area degradation occurred patchily in the upper reaches of Xiliugou, Hantaichuan, and Hashilachuan (1.88% of the hilly area). In 87.21% of the region, artificial forest land showed significant improvement. Except for *Platycladus orientalis*, *Juniperus rigida*, and *Sophora japonica*, all other species accounted for high proportions in significantly improved areas. *Caragana*, *Pinus tabuliformis*, *Caragana korshinskii*, and poplar in the upper reaches of Hantaichuan and Hashilachuan showed concentrated degradation. Degraded species in the upper reaches of Xiliugou, Borse Tai Gully, and Mabula Kongdui were mainly *Caragana*, with some *Salix psammophila* and willow. Desert area degradation was concentrated along the Haoqing River and Dongliugou, with degraded species including *Caragana*, poplar, *Caragana korshinskii*, *Hedysarum mongolicum*, and *Salix psammophila*. Lower plain cropland showed minimal degradation with only a few point distributions.

(2) NDVI showed fluctuating upward trends across all landform types, with multi-year averages of 0.591, 0.337, and 0.325 for plain, hilly, and desert areas respectively, decreasing in that order. The plain area showed a gentle trend, the hilly area was intermediate, and the desert area showed the most obvious increase. NDVI peaked in August for all landform types.

(3) NDVI trends were generally consistent across different slopes. In the plain area, flat gentle slopes and gentle slopes showed better NDVI than horizontal and flat land. In the desert area, NDVI followed the trend: horizontal land > flat land > flat gentle slope > gentle slope > steep slope. Hilly area NDVI trends almost completely mirrored those of the desert area, but steep slope vegetation growth was better than flat gentle and gentle slopes throughout the entire period, though still poorer than on horizontal and flat land. Therefore, more vegetation should be planted on horizontal and flat land in desert and hilly areas.

(4) NDVI trends were generally consistent across different slope aspects. In the plain area, NDVI followed the trend: sunny slope > half-sunny slope > shady slope. In the desert area, NDVI followed the trend: shady slope > sunny slope > half-sunny slope. In the hilly area, the trend was shady slope > half-sunny slope > sunny slope. Therefore, desert and hilly areas should plant more vegetation on shady slopes with smaller gradients.

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