Vegetation Cover Change and Its Influencing Factors in Typical Counties of the Loess Plateau from 1990 to 2020 (Postprint)

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Abstract

To investigate the dynamic evolution patterns of vegetation and their influencing factors in Ji County over the past 30 years, this study, based on Landsat imagery and combined with meteorological, land use, nighttime light, and other data, employed methods such as trend analysis, partial correlation analysis, random forest, and residual analysis to investigate the spatiotemporal variation characteristics of vegetation coverage in Ji County and the impacts of climatic and anthropogenic factors on vegetation change. The results show: (1) From 1990 to 2020, the vegetation coverage (FVC) in the study area showed a significant overall increasing trend, with an average annual growth rate of approximately 0.49%, indicating a clear improvement in vegetation quality. (2) The FVC in Ji County exhibited a distinct spatial characteristic of interlaced distribution of 'low-value-high-value' areas. From 1990 to 2020, areas with significant FVC increase accounted for 51%, while areas with significant FVC decrease accounted for 7%. (3) Climatic factors exerted an inhibitory effect on vegetation growth in some high-FVC areas and built-up areas, while promoting vegetation coverage in other regions. When human activities were considered as a global influencing factor, the contribution rates of climate and human activities to vegetation dynamics were 53.43% and 46.57%, respectively; when treated as a local variable, the relative contribution rate decreased to 13.07%. Human activities were an important influencing factor of vegetation degradation in specific areas such as central and eastern Ji County, and were also associated with vegetation restoration in the western and southern regions. The research results can provide a scientific basis for further implementation of regional ecological restoration efforts.

Full Text

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Abstract

To explore the dynamic evolution of vegetation and its influencing factors in Ji County over the past 30 years, this study utilized Landsat imagery integrated with meteorological, land use, and nighttime light data. Trend analysis, partial correlation analysis, random forest modeling, and residual analysis were employed to investigate the spatiotemporal variation characteristics of fractional vegetation cover (FVC) and the impacts of climatic and anthropogenic factors on vegetation changes. The results revealed: (1) From 1990 to 2020, FVC in the study area exhibited a significant upward trend with an average annual growth rate of approximately 0.49%, indicating a clear improvement in vegetation quality. (2) The spatial distribution of FVC displayed a distinct "low-high" interlaced pattern. Areas with significant FVC increase accounted for 53.43% of the total, while those with significant decrease comprised 46.57%. (3) Climatic factors inhibited vegetation growth in high-FVC zones and built-up areas, while promoting vegetation cover elsewhere. When human activities were considered as a global influencing factor, their contribution to vegetation dynamics was comparable to that of climate factors. However, when treated as a local variable, the relative contribution of human activities decreased to 13.07%. Human activities represented a critical factor driving vegetation degradation in specific regions such as central and eastern Ji County, while also being associated with vegetation restoration in the western and southern areas. These findings provide a scientific basis for advancing regional ecological restoration efforts.

Keywords: fractional vegetation cover; Google Earth Engine; climate change; human activity; Loess Plateau

Introduction

Vegetation constitutes a core component of terrestrial ecosystems, playing vital roles in carbon cycling, water balance, and energy conversion processes. Surface vegetation effectively intercepts rainfall, reduces runoff, prevents sand encroachment, and stabilizes soils. China has contributed the most to global forest resource growth worldwide, accounting for a significant portion of increased leaf area. However, vegetation change results from the combined effects of natural factors and human activities. Climate change directly affects vegetation growth, potentially exerting either positive or negative influences with spatial heterogeneity. Human activities also have dual effects: while large-scale ecological restoration projects implemented since the 1990s have promoted vegetation recovery, urban expansion, deforestation, and other anthropogenic disturbances have destroyed surface vegetation.

Current academic research on vegetation change attribution has achieved substantial progress across different regions. Studies in Southwest China indicate that climate change and human activities primarily promote vegetation growth, with human contributions lower than climatic factors. In Northwest China, vegetation cover increased across 55.77% of the region, with natural factors showing higher contribution rates. On the Loess Plateau, the positive effects of human activities intensified after 2000. In the Huai River Basin, human activities dominated vegetation changes in most cities, with average contributions of 56.0% and 44.0% from human activities and climate factors, respectively. However, these studies generally treat human activities as a global influencing factor, which may overestimate their impact since anthropogenic influences weaken or disappear in areas far from human settlements. This uncertainty in attribution can be reduced by distinguishing between human-activity and non-human-activity zones based on land use data from before and after the Grain-for-Green Program.

Ji County, adjacent to the Yellow River, represents an important ecological conservation area characterized by loess hilly and gully landforms with steep slopes, deep gullies, and fragmented terrain. The county' s soil erosion area reaches 9.53$×10^{4}$ hm^2, accounting for 53.6% of its total area. To combat ecological degradation, Ji County pioneered the implementation of the Grain-for-Green Program in 1999, with cumulative afforestation of 2.77$×10^{4}$ hm^2. While forest coverage has significantly improved, the relative contributions of natural and anthropogenic factors to vegetation changes remain unclear. County-level administrative units represent relatively independent basic units that can provide theoretical foundations for coordinating socioeconomic development and ecological protection. This study selected FVC as the quantitative index for vegetation change, analyzing its long-term trends from 1990 to 2020 and investigating the relative contributions of climate and human activities using random forest modeling and residual analysis to provide scientific support for regional ecological restoration and coordinated human-environment relationships on the Loess Plateau.

1.1 Study Area Overview

Ji County (35°53 19 -36°21 5 N, 110°26 29 -111°7 34 E) is located in the southeastern Loess Plateau, covering an area of approximately 1,777 km^2. It was among the first counties on the Loess Plateau to implement the Grain-for-Green Program. The elevation ranges from 383 m to 1,812 m, exhibiting a characteristic pattern of alternating low and high elevations from west to east [Figure 1:

see original paper]. The region has a mean annual temperature of 10.38°C, mean annual precipitation of 524.87 mm concentrated in July–August, and mean annual evaporation of 1,723.80 mm. Vegetation shows clear spatial distribution patterns, with natural secondary forests primarily in high-altitude areas and artificial forests (mainly *Pinus tabuliformis*, *Robinia pseudoacacia*, and *Quercus wutaishanica*) mostly in the west. The main land use types in 2020 were grassland (21.79%), forestland (46.94%), cropland (30.24%), construction land (0.44%), and water bodies (0.59%).

1.2 Data Sources

1.2.1 Fractional Vegetation Cover Landsat Collection 2 Tier 1 surface reflectance imagery, available on the Google Earth Engine platform, has undergone radiometric correction, atmospheric correction, and high-precision geometric correction, making it suitable for long-term time series analysis. Images from June to September were screened by year, and cloud masking was applied. The normalized difference vegetation index (NDVI) was calculated using the formula:

$$NDVI = \frac{NIR - R}{NIR + R}$$

where NIR represents the near-infrared band and R represents the red band. To eliminate interference from clouds and other factors, maximum value compositing was applied to generate annual NDVI images. The pixel dichotomy model was then used to estimate FVC:

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

where $NDVI_{veg}$ represents the NDVI value for pure vegetation cover and $NDVI_{soil}$ represents the NDVI value for bare soil. The 5% and 95% cumulative frequency values of NDVI were selected as $NDVI_{soil}$ and $NDVI_{veg}$, respectively. FVC was classified into five categories: low ($0 \leq$ FVC < 0.2), relatively low ($0.2 \leq$ FVC < 0.4), moderate ($0.4 \leq$ FVC < 0.6), relatively high ($0.6 \leq$ FVC < 0.8), and high ($0.8 \leq$ FVC < 1). All processes were completed through scripting on the Google Earth Engine platform.

1.2.2 Influencing Factors Following previous research on the Loess Plateau, mean annual temperature and annual precipitation were selected as climatic factors affecting FVC. Nighttime light remote sensing data and land use data were chosen to represent human activities, as nighttime lights can monitor urban development dynamics while land use changes directly reflect human disturbances. Data sources and processing details are listed in . Processing included reprojection, clipping, mosaicking, and resampling to 30 m resolution using ArcGIS Pro 3.0.

1.3 Methods

1.3.1 Partial Correlation Analysis The partial correlation coefficient quantifies the effect of a specific variable on FVC under multivariate interactions using the formula:

$$R_{xy,z} = \frac{R_{xy} - R_{xz}R_{yz}}{\sqrt{(1 - R_{xz}^2)(1 - R_{yz}^2)}}$$

where $R_{xy,z}$ is the partial correlation coefficient between variables x and y after controlling for variable z; R_{xy}, R_{xz}, and R_{yz} are the correlation coefficients between variables x and y, x and z, and y and z, respectively. Calculations were performed in Matlab R2022b.

1.3.2 Random Forest Random forest regression is an ensemble algorithm composed of decision trees. Assuming sample data contain K features, k features (k < K) are randomly selected to establish m classification and regression trees, with final results obtained by averaging the decision tree models. This process includes ranking feature importance, which reflects the influence magnitude of different environmental factors on FVC. To further explore factor interactions, influencing factors were paired as input data for random forest modeling, and validation set R^2 values were used to quantify the explanatory power of different factor combinations on FVC spatial distribution.

1.3.3 Contribution Analysis **Residual Analysis.** Linear regression was applied to fit the relationships between temperature, precipitation, and FVC. The difference between observed FVC values and fitted values (residuals) represents FVC changes under human activity impacts:

$$FVC_{res} = FVC_{obs} - FVC_{cc}$$

$$FVC_{cc} = a \times Tem + b \times Pre + c$$

where FVC_{obs} is the observed FVC value; FVC_{cc} is the FVC value under climate change impacts; Tem and Pre represent mean annual temperature and annual precipitation, respectively; and a, b, and c are regression coefficients.

Relative Contribution Calculation. The method proposed by Li et al. was used to classify driver contributions . Slope values of FVC_{obs}, FVC_{cc}, and FVC_{res} represent the trend values of actual FVC, climate-impacted FVC, and human-activity-impacted FVC, respectively.

Human Activity and Non-Human Activity Zones. Based on land use data from 1999 and 2020, areas with changed land use types before and after the Grain-for-Green Program, as well as cropland and construction land, were classified as human activity zones. Areas with unchanged land use types, including forestland, grassland, and water bodies, were classified as non-human activity zones.

2 Results

2.1 Temporal Variation Characteristics of FVC

From 1990 to 2020, FVC showed an average increasing trend of 0.49% per year, with the growth rate slowing after 2013 [Figure 2: see original paper]. The change was statistically significant ($P < 0.01$). Based on vegetation cover variation characteristics, the study period was divided into three stages: 1990–1999, characterized by natural vegetation growth with slow increases; 2000–2013, featuring rapid FVC increases with an annual growth rate of 0.57% ($P < 0.05$); and 2014–2020, showing stabilized vegetation cover with slowed growth rates.

The area of low and relatively low FVC grades continuously decreased from 1990 to 2020 [Figure 3: see original paper]. Before the Grain-for-Green Program (1990–1999), most areas exhibited low FVC values with insignificant change trends. After program implementation, the proportion of high and relatively high FVC areas increased significantly ($P < 0.01$), indicating substantially improved vegetation quality.

2.2 Spatial Distribution and Variation Characteristics of FVC

The multi-year average FVC value was 0.49, showing an interlaced spatial distribution pattern of "low in the west, high in the east" [Figure 4: see original paper]. High-FVC zones were located in the northwestern and eastern high-altitude areas with complex terrain, representing the main distribution areas of natural secondary forests. Low-FVC zones were distributed in the western and central regions, where cropland and grassland dominated.

Trend analysis revealed that 53.43% of the study area showed significant FVC increases, while 46.57% showed significant decreases ($P < 0.05$) [Figure 5: see original paper]. Significant decreases were mainly distributed at the edges of high-FVC zones and near construction land. The spatial distribution exhibited significant positive autocorrelation. Getis-Ord Gi* hot spot analysis identified two low-value clusters and two high-value clusters [Figure 4: see original paper]. High-value cluster vegetation showed non-significant increases, while low-value clusters in the central built-up areas decreased significantly and those in western agricultural and grassland areas increased significantly.

2.3 Attribution of FVC Changes

2.3.1 Factor Analysis Partial correlation analysis indicated that temperature promoted vegetation cover in 76.6% of the area, with significant promotion in 33.2% ($P < 0.05$), primarily distributed in the east. Precipitation showed positive correlations with FVC in 71.2% of the area, with 54.5% significantly affected ($P < 0.05$), concentrated in western cropland and grassland areas. Areas significantly inhibited by precipitation accounted for 16.7%, mainly in high-FVC zones and near construction land.

Random forest importance ranking showed that factors influencing FVC, in descending order, were temperature, precipitation, and nighttime light index . The explanatory power of combined factors on FVC spatial distribution exceeded that of single factors, with the temperature-precipitation combination showing the highest explanatory power.

2.3.2 Climate Change Impacts on FVC Both temperature and precipitation in the study area showed increasing trends from 1990 to 2020, with rates of 0.25% and 0.24% per year, respectively, indicating overall warming and wetting trends [Figure 6: see original paper]. Climate change was favorable for vegetation restoration, with 79.0% of the area showing positive FVC trends under climate impacts. Before the Grain-for-Green Program, 57.7% of the area experienced increased FVC due to climate factors, mainly distributed in cropland and grassland areas. After program implementation, 58.9% of the area showed elevated FVC under climate influences.

2.3.3 Relative Contributions of Climate Change and Human Activities Residual analysis revealed that under climate change impacts, FVC increased at an average annual rate of 0.25%, while under human activity impacts, the rate was 0.24% [Figure 7: see original paper]. Before separating the factors, climate and human activities contributed 53.43% and 46.57% respectively. After separation, the relative contribution of human activities decreased to 13.07%, indicating that previous studies may have overestimated human activity contributions.

Vegetation cover significantly decreased in built-up areas and some high-FVC zones due to human activities. In areas with frequent human activities (cropland and construction land), FVC showed decreasing trends, with adjacent cropland areas also experiencing reductions. Urban expansion and other human activities from 1990 to 1999 caused FVC decline in cropland and built-up areas. After the Grain-for-Green Program, most regions (91.8%) showed increased vegetation cover due to human activities, including farmland cultivation, grassland restoration, and afforestation.

3 Discussion

3.1 Dynamic Changes of FVC in Ji County from 1990 to 2020

The overall increasing trend of FVC in Ji County from 1990 to 2020 aligns with findings from Zhao et al. The highest growth rate occurred after 2000, demonstrating that China' s ecological restoration projects since the 1990s have promoted vegetation recovery. Before the Grain-for-Green Program, agricultural and grassland areas were dominated by low and relatively low FVC grades. After program implementation and agricultural activities, vegetation quality improved significantly ($P < 0.05$), consistent with results from Yang et al. The significant increase in low-FVC zones and slight degradation at the edges of high-FVC zones were mainly related to climate change and road construction. These results suggest that ecological restoration strategies should not only improve vegetation quality in low-cover areas but also consider ecological protection in high-cover natural secondary forest regions.

3.2 Relative Contributions of Climate Change and Human Activities to FVC Changes

Previous studies have confirmed that Loess Plateau vegetation cover is primarily related to temperature and precipitation. Temperature promotes photosynthesis and extends growing seasons, while precipitation provides essential water for biochemical reactions. Climate change has had long-term positive effects on overall vegetation dynamics in the study area, though with spatial heterogeneity. Climate change negatively impacted vegetation at the edges of high-FVC zones and in construction land areas. High-FVC zone vegetation degradation occurred mainly in forest-grassland transition areas with low cover, rugged terrain, and steep slopes, where increased precipitation intensifies soil erosion and is unfavorable for vegetation growth. In these areas, higher temperatures increase evapotranspiration, limiting vegetation growth. Construction land FVC reduction was primarily related to human alteration of the natural environment: residential expansion increased impervious surfaces, reduced infiltration, and elevated surface temperatures, causing significant FVC decline. Vegetation restoration in other areas was associated with increased temperature and precipitation.

Ji County shows clear spatial differentiation between human activity and non-human activity zones. After separation, human activity zones accounted for 26.2% of the area, while non-human activity zones comprised 73.8%. Non-human activity zones feature high elevations, dense forests, and minimal anthropogenic disturbance. This study considered climate factors as global influences and human activities as local factors. Before separation, climate and human activity contributions were comparable, but after separation, human activity contribution to FVC change decreased to 13.07%, indicating that vegetation change in the study area was primarily driven by natural factors, consistent with findings from Xie et al. Although the proportion of human activity contribution was relatively small, it represented a critical factor causing vegetation degradation in central and eastern Ji County while also promoting vegetation restoration in the western and southern areas.

Research demonstrates the dual nature of human activities in Ji County. On one hand, urban expansion encroached on vegetation growth areas, significantly reducing FVC. On the other hand, vegetation restoration zones were mainly distributed in cropland and grassland areas, where crop growth and grassland recovery increased surface vegetation cover. Afforestation, water detention dams, and reservoir construction also promoted vegetation growth and improved vegetation coverage.

4 Conclusion

This study analyzed the spatiotemporal evolution characteristics of FVC in Ji County from 1990 to 2020 and quantified the relative contributions of climate change and human activities. The main conclusions are:

1) Vegetation cover in Ji County was generally good and showed an increasing trend from 1990 to 2020, with an average annual growth rate of 0.49%. The spatial distribution exhibited an interlaced pattern of low and high values from west to east. Construction land areas and some high-FVC zones experienced significant FVC reduction.

2) The explanatory power of combined factors on FVC spatial distribution exceeded that of single factors, with the temperature-precipitation combination showing the highest explanatory power. Temperature and precipitation promoted vegetation cover in 76.6% and 71.2% of the study area, respectively, demonstrating spatial heterogeneity in their effects.

3) Before separating climate change and human activities, their contributions were comparable. After separation, the contribution of human activities to FVC change decreased to 13.07%. FVC changes in Ji County resulted from combined climate and anthropogenic influences, with climate as the primary driver. Human activities caused vegetation degradation in central and eastern areas while promoting restoration in western and southern regions.

This study has certain limitations. Land use and nighttime light data were used to represent human activities, but the representativeness of selected driving factors could be improved. Future research should incorporate more multidimensional raster data to more accurately reflect spatiotemporal variations in human activities.

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