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Spatiotemporal Variation of Vegetation Coverage and Its Driving Factors in the Beijing-Tianjin-Hebei Region Based on the Google Earth Engine Platform

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Abstract: Fractional Vegetation Cover (FVC) is an important indicator for evaluating the quality of regional ecological environments and sustainable development. As a core region of China's socio-economic development, the Beijing-Tianjin-Hebei area experiences vegetation dynamics that are significantly influenced by both intensive human activities and climate change. This study aims to reveal the spatiotemporal patterns of vegetation coverage in the Beijing-Tianjin-Hebei region from 2000 to 2023, and to identify the major climatic driving factors, with the goal of providing scientific support for regional ecological conservation and coordinated development policymaking. On this basis, a combination of methods including the Theil-Sen (Sen's) slope estimator, Mann-Kendall (MK) test, Hurst exponent analysis, and partial correlation analysis was comprehensively applied. An in-depth analysis was conducted on the spatiotemporal dynamics of FVC, its future persistence, and its relationships with temperature and precipitation. The results indicate that: (1) Spatially, the FVC in the Beijing-Tianjin-Hebei region exhibits a distinct "northwest-high, southeast-low" distribution pattern. Temporally, the region experienced three phases: rapid increase (2000–2010), significant decline (2010–2015), and restorative growth (2015–2023).(2) Vegetation improvement areas (47.90%) and degradation areas (41.68%) show strong spatial heterogeneity, and up to 59.83% of the region exhibits anti-persistent characteristics in vegetation dynamics.(3) Precipitation serves as a positive driving factor for improved FVC, while the influence of temperature exhibits spatial heterogeneity. The results of this study highlight the need for future regional ecological management to shift from solely pursuing increases in vegetation coverage toward enhancing ecosystem quality and resilience, and to develop adaptive strategies to address potential ecological risks.

Keywords: Fractional Vegetation Cover; Spatiotemporal Dynamics; Beijing-Tianjin-Hebei; Google Earth Engine.

1. Introduction

As a core component of terrestrial ecosystems, vegetation serves as a vital link connecting the soil, atmosphere, and hydrosphere, playing a crucial role in regulating the global carbon balance, conserving water resources, preventing soil erosion, maintaining biodiversity, and mitigating climate change [1]. Fractional Vegetation Cover (FVC) is a key parameter for quantifying surface vegetation conditions and assessing macro-scale ecological quality. Under the dual pressures of global climate change and intensive human activities, vegetation cover has become an "indicator" of ecosystem response and resilience at the regional scale [2]. Conducting long-term, large-scale precise monitoring and attribution analysis of FVC is of significant theoretical and practical importance for understanding ecosystem evolution, evaluating the effectiveness of ecological projects, and formulating regional sustainable development strategies[3].

The Beijing-Tianjin-Hebei region is one of the most densely populated areas in China, with the fastest urbanization process and the most intense human-environment interactions[4].Rapid industrialization and urban expansion have long posed a series of severe ecological and environmental challenges to the region, including water scarcity, land degradation, and air pollution.To address these issues and establish an ecological security barrier for the capital [5], China has initiated and continuously advanced multiple large-scale ecological restoration projects in the region since the early 21st century, including the "Three-North" Shelter Forest Program, management of sandstorm sources in Beijing and Tianjin, greening of the Taihang Mountains, and the conversion of farmland to forest and grassland [6–9].Against the complex backdrop of simultaneous development pressures and ecological conservation, the evolution of vegetation coverage and the effectiveness of ecological projects in the Beijing-Tianjin-Hebei region have become focal points in regional ecology, geography, and environmental science.

Traditional vegetation remote sensing studies are often constrained by bottlenecks in data acquisition, storage, and processing, making it difficult to efficiently perform long-term, large-scale dynamic analyses. In recent years, geospatial big data cloud platforms such as Google Earth Engine (GEE), with their vast online archives of remote sensing imagery (e.g., MODIS, Landsat) and powerful parallel computing capabilities, have provided revolutionary technical support for long-term analysis of ecological parameters [10].Currently, numerous studies have utilized the GEE cloud platform; for example, Song Menglai et al. [11] calculated annual FVC from Landsat imagery spanning 1990 to 2020 using GEE. Xu Mengchen et al. [12] used the GEE platform, integrating Landsat surface reflectance data and MODIS EVI products, to estimate the spatiotemporal dynamics of FVC in the Yangtze River Delta.In contrast, local computation of FVC is less efficient; for instance, Lu Junjing et al. [13] estimated FVC locally using only eight Landsat images from 1985 to 2020.These examples demonstrate that the GEE cloud platform enables researchers to rapidly and efficiently conduct in-depth studies of vegetation dynamics at regional and even global scales.

Therefore, this study relies on the GEE cloud platform, utilizing MODIS NDVI remote sensing data from 2000 to

2023, and applies the pixel dichotomy model to estimate vegetation coverage in the Beijing-Tianjin-Hebei region. Subsequently, multiple methods including Sen's slope, Mann-Kendall test, Hurst exponent, and partial correlation analysis are comprehensively applied to analyze the spatiotemporal evolution and driving forces of FVC. This research aims to: (1) characterize the spatial distribution of FVC in the Beijing-Tianjin-Hebei area during the last 24 years; (2) detect regions with significant vegetation changes and forecast the sustainability of future vegetation trends; and (3) examine how temperature and precipitation as major climatic factors drive changes in vegetation coverage.

2. Overview of the Study Area

The study area is the Beijing-Tianjin-Hebei region, which administratively includes the two municipalities of Beijing and Tianjin as well as the entire territory of Hebei Province (Fig. 1).The region lies between 113°27′E and 119°50′E longitude and 36°03′N and 42°40′N latitude, covering a total area of approximately 218,000 square kilometers. As the core of China's "Capital Economic Circle," the ecological status of the Beijing-Tianjin-Hebei region holds significant national strategic importance. The topography of the region generally exhibits a stepped pattern sloping from the northwest to the southeast. The northwest consists of mountainous and hilly areas surrounded by the Yanshan and Taihang Mountains, characterized by high elevation and complex terrain, serving as a crucial water conservation zone and ecological barrier. The southeast is dominated by the vast North China Plain, featuring flat and open terrain, which is the main population and urban concentration area as well as the primary agricultural production zone. The Beijing-Tianjin-Hebei region experiences a typical temperate monsoon climate, marked by hot and rainy summers and cold, dry winters. Under the influence of human activities, the land use patterns in the region have become highly complex. As shown in Figure 1, the main land cover types include forests, shrubs, and grasslands in the northwestern mountainous areas; croplands and water bodies in the southeastern plains; and impervious surfaces radiating outward from the cores of Beijing and Tianjin.

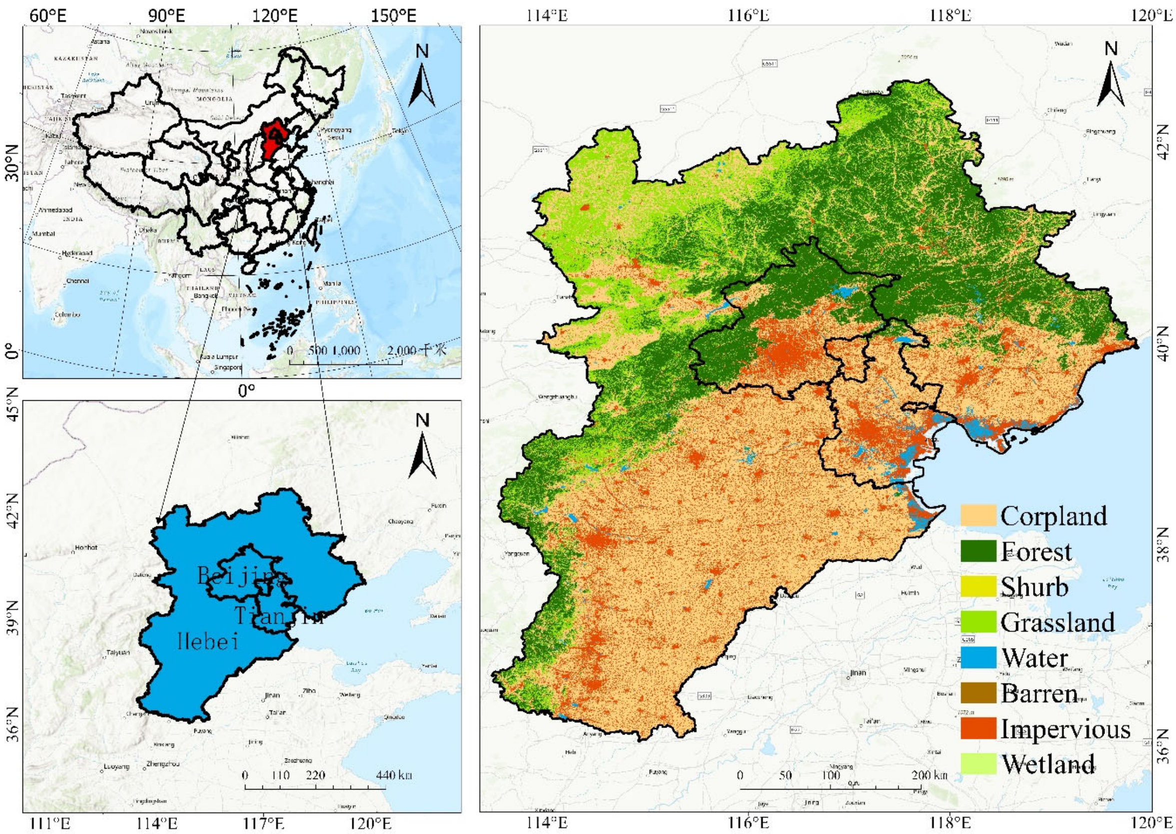

Figure 1. Overview of the Study Area

3. Materials and Methods

3.1. Data Sources and Processing

The data sources used in this study are listed in Table 1. The NDVI dataset was obtained from the MOD13Q1 product— a 16-day composite vegetation index generated from MODIS Terra daily surface reflectance—accessed through the GEE platform. The spatial resolution of this dataset is 250 meters. To minimize disturbances caused by clouds, atmospheric conditions, and solar elevation angle, this study employed the Maximum Value Composite (MVC) approach to process the 16-day NDVI data annually, generating yearly NDVI datasets from 2000 to 2023.The precipitation and temperature datasets were sourced from the National Tibetan Plateau Scientific Data Center [14][15], and their monthly records from 2000 to 2023 were processed into annual sums and means, respectively. Land cover data were obtained from the 30-meter resolution Chinese Annual Land Cover Dataset (CLCD) developed by Huang Xin's team at Wuhan University [16].All raster datasets were resampled to a spatial resolution of 250 meters using bilinear interpolation and standardized to the WGS-84 geographic coordinate system.

Table 1. Data Sources

Name	Data Source	Spatial Resolution	Temporal Resolution
MOD13Q1 NDVI	GEE Cloud Platform	250m	16 days
CLCD	GEE Cloud Platform	30m	Annual
Temperature	National Tibetan Plateau Data Center	1000m	Monthly
Precipitation	National Tibetan Plateau Data Center	1000m	Monthly

3.2. FVC Calculation Method

This study estimates fractional vegetation cover (FVC) using the pixel dichotomy model. The model assumes that the surface information of each pixel is a linear combination of pure vegetation and pure bare soil components, and that FVC is linearly related to the NDVI value of the pixel. The calculation formula is as follows:

$$F = \frac{\mathrm{NDVI} - \mathrm{NDVI_S}}{\mathrm{NDVI_V} - \mathrm{NDVI_S}} \quad (1)$$

In the formula, FVC denotes the fractional vegetation cover; NDVI represents the normalized difference vegetation index of the pixel; $NDVI_V$ and $NDVI_S$ correspond to the NDVI values of pure vegetation and pure bare soil pixels, respectively. In this study, to enhance the regional applicability and temporal stability of the model, $NDVI_V$ and $NDVI_S$ are not set as fixed empirical values. Instead, they are dynamically determined from the cumulative frequency histogram of all annual NDVI images from 2000 to 2023, with the 95th and 5th percentiles of NDVI values used as their respective approximations. To ensure the physical validity of FVC values, pixel values exceeding 1 are set to 1, and those below 0 are set to 0.

3.3. Methods for Spatiotemporal Evolution and Future Trend Analysis

This study estimates FVC using the pixel dichotomy model. The model assumes that the surface characteristics of each pixel are a linear combination of pure vegetation and pure bare soil, and that the FVC is linearly related to the NDVI value of the pixel. The calculation formula is as follows:

$$\mathrm{slope} = \mathrm{median}\left(\frac{\mathrm{FVC}_j - \mathrm{FVC}_i}{j - i}\right)(\forall j > i) \quad (2)$$

In the formula, FVC_i and FVC_j represent the FVC values for years i and j respectively (i < j); Median denotes the median function; slope indicates the trend.

The Mann-Kendall significance test is characterized by not requiring the data to follow a normal distribution and being robust to missing values and outliers. For a sequence $X_t=x_1$, x_2, $\cdots x_n$, the test statistic S is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}\,(x_j - x_i) \quad (3)$$

In the formula, n denotes the length of the time series; sgn is the sign function.

The test statistic Z is used to perform the trend test, with the specific procedure as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} & (S > 0) \\ 0 & (S = 0) \\ \dfrac{S+1}{\sqrt{\mathrm{var}\,(S)}} & (S < 0) \end{cases} \quad (4)$$

In the formula, the calculation of var(S) is given by:

$$\mathrm{var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (5)$$

In this study, the significance level is set at α=0.05, corresponding to a critical value Z1-α/2=±1.96. When the absolute value of Z exceeds 1.96, the trend passes the significance test at the 95% confidence level.

The Hurst exponent is a statistic that quantitatively describes the long-term correlation or persistence of a time series [19]. This study uses the Hurst exponent to quantitatively characterize the persistence of fractional vegetation cover in the Beijing-Tianjin-Hebei region over a long temporal sequence, and combines it with the slope trend to investigate the future trajectory of vegetation cover. The Hurst exponent HHH is interpreted as follows: when 0<H<0.50 < H < 0.50<H<0.5, future trends are negatively correlated with past trends; when H=0.5H = 0.5H=0.5, future trends are uncorrelated with past trends; and when 0.5<H<10.5 < H < 10.5<H<1, future trends are positively correlated with past trends.

3.4. Analysis of Driving Forces of FVC

Partial correlation analysis was conducted between temperature, precipitation, and fractional vegetation cover to investigate the driving effects of these two key climatic factors on vegetation cover changes in the Beijing-Tianjin-Hebei region over the past 24 years. The formula for calculating partial correlation is as follows:

$$R_{xy,z\lambda} = \frac{R_{xy,z} - R_{x\lambda,z} \times R_{y\lambda,z}}{\sqrt{(1 - R_{x\lambda,z}^2) \times (1 - R_{y\lambda,z}^2)}} \quad (6)$$

In the formula, $R_{xy,z\lambda}$ denotes the second-order partial correlation coefficient between variables x and y after removing the effects of factors z and λ; $R_{xy,z}$ represents the multiple correlation coefficient between x and y, with $R_{x\lambda,z}$ and $R_{y\lambda,z}$ defined similarly. A t-test is used to assess the significance of the correlation between the two variables. The sign of the contribution indicates whether the driving factor has a positive or negative effect on FVC, where a positive effect means the factor promotes FVC increase, and a negative effect means the factor inhibits FVC growth.

4. Results and Analysis

4.1. Analysis of Driving Forces of FVC

The multi-year average spatial distribution pattern of FVC in the Beijing-Tianjin-Hebei region from 2000 to 2023 (Fig. 3) exhibits a differentiated pattern of "high in the northwest and low in the southeast." The regions of high vegetation coverage are largely clustered in the northwestern Yanshan and Taihang Mountains. These areas serve as vital ecological barriers and water conservation zones for the Beijing-Tianjin-Hebei region, characterized mainly by mountainous and hilly terrain with relatively limited human disturbance. The dominant land cover types include extensive forests, shrubs, and dense grasslands, with well-preserved natural ecosystems, resulting in stable and high-level vegetation cover. High-coverage areas with FVC values exceeding 0.8 are primarily located in the deep mountainous regions of Yanshan and the central to northern parts of the Taihang Mountains, forming the core of the regional ecosystem. Conversely, low vegetation cover zones are primarily found in the southeastern North China Plain. This area features flat terrain and is one of the most densely populated and highly urbanized regions in China. The centers of low FVC values are mainly located in the core cities of Beijing and Tianjin and their surrounding towns, where impervious surfaces dominate. Additionally, some coastal areas around the Bohai Sea also exhibit low vegetation cover, potentially due to soil salinization or aquaculture activities. Table 3 indicates that the "moderate coverage" category occupies the largest proportion of FVC classes in the Beijing-Tianjin-Hebei region, accounting for 26.50%. Including the "relatively high coverage" (25.38%) and "high coverage" (18.10%) classes, the combined area proportion amounts to 69.98%, suggesting that the vegetation ecosystem in the study area has largely maintained a good status over the last twenty years. In contrast, the "low coverage" and "relatively low coverage" classes account for 12.58% and 17.44% of the area, respectively, totaling 30.02% of the study region.

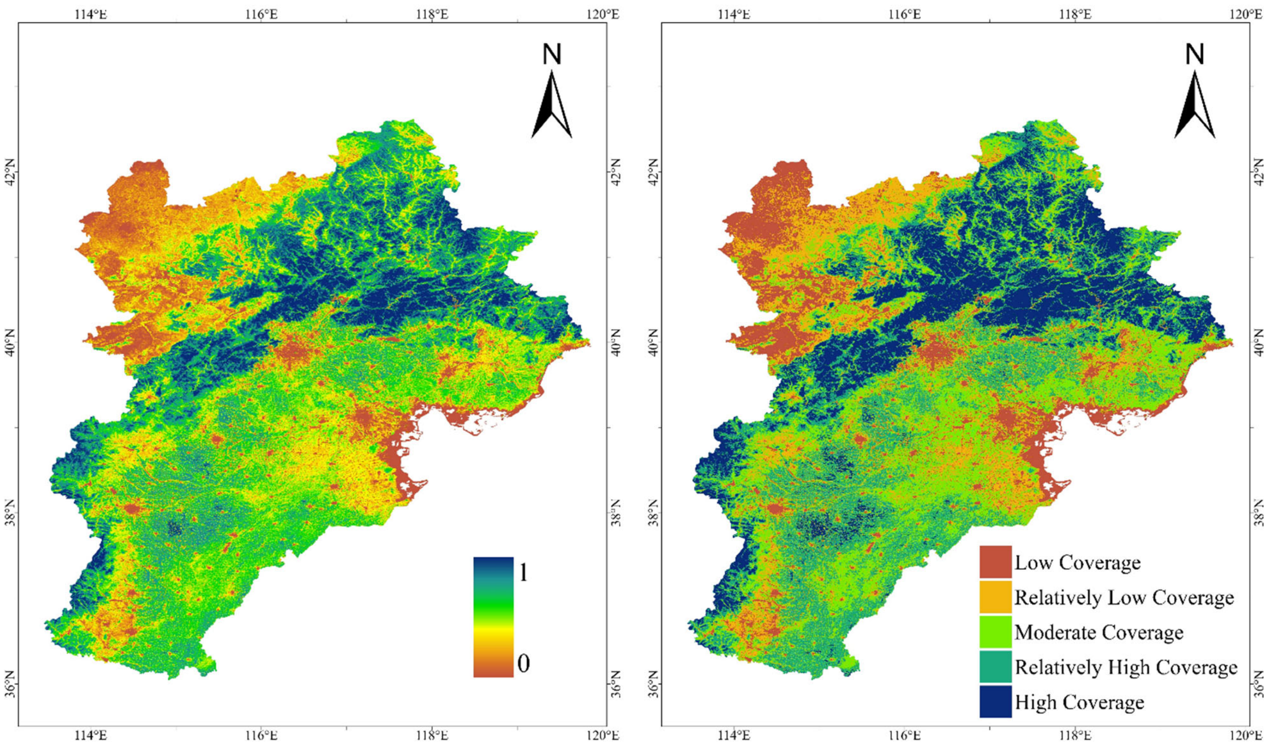

Figure 2. Multi-year Average Spatial Distribution of Fractional Vegetation Cover in the Beijing-Tianjin-Hebei Region from 2000 to 2023

Table 2. Area Proportions of Vegetation Cover Classes in the Beijing-Tianjin-Hebei Region from 2000 to 2023

FVC	Category	Number of Pixels (10,000s)	Percentage (%)
0-0.2	Low Coverage	56.6039	12.58
0.2-0.4	Lower Coverage	78.4861	17.44
0.4-0.6	Moderate Coverage	119.2527	26.50
0.6-0.8	Higher Coverage	114.2247	25.38
0.8-1	High Coverage	81.432	18.10

4.2. Temporal Variation Characteristics of Vegetation Cover

As shown in Figure 3 and Table 3, the annual mean FVC in the Beijing-Tianjin-Hebei region exhibits a fluctuating upward trend over time. The region's annual average FVC increased markedly from 0.5050 in 2000 to 0.5353 in 2023, indicating an overall improvement in vegetation conditions over nearly a quarter-century. However, this process was not a linear increase but underwent three distinct phases. The first phase was a rapid growth period (2000–2010), during which the FVC growth rate reached 0.0032 per year and peaked at 0.5603 in 2008. This greening trend likely relates to the national initiatives such as the "Beijing-Tianjin Sandstorm Source Control Project" and the ongoing "Three-North Shelter Forest Program" implemented during that time. The second phase was a significant decline period (2010–2015), during which the region's FVC sharply reversed after a decade of improvement, decreasing at a rate of -0.0079 per year. The coefficient of determination ($R^2 = 0.7638$) indicates that this degradation trend was highly significant, with the lowest values recorded in 2014 and 2015. This vegetation decline may be related to a series of extreme climate events, such as regional droughts. The third phase was a recovery growth period (2015–2023). Following the low point in 2015, the FVC in the Beijing-Tianjin-Hebei region began a new recovery phase, with an increasing slope of 0.0032 per year, reaching the highest value of 0.5589 in 2022, surpassing the pre-2010 peak. This indicates that with the deepening implementation of China's "ecological civilization" strategy, the cumulative effects of long-term ecological protection and restoration policies have continually manifested, effectively supporting vegetation improvement.

Table 3. Annual Mean Fractional Vegetation Cover Trends in the Beijing-Tianjin-Hebei Region from 2000 to 2023

Year	Mean FVC	Year	Mean FVC	Year	Mean FVC
2000	0.5050	2008	0.5603	2016	0.5268
2001	0.5612	2009	0.5523	2017	0.5320
2002	0.5400	2010	0.5576	2018	0.5369
2003	0.5311	2011	0.5350	2019	0.5208
2004	0.5366	2012	0.5454	2020	0.5395
2005	0.5386	2013	0.5310	2021	0.5494
2006	0.5426	2014	0.5201	2022	0.5589
2007	0.5533	2015	0.5207	2023	0.5353

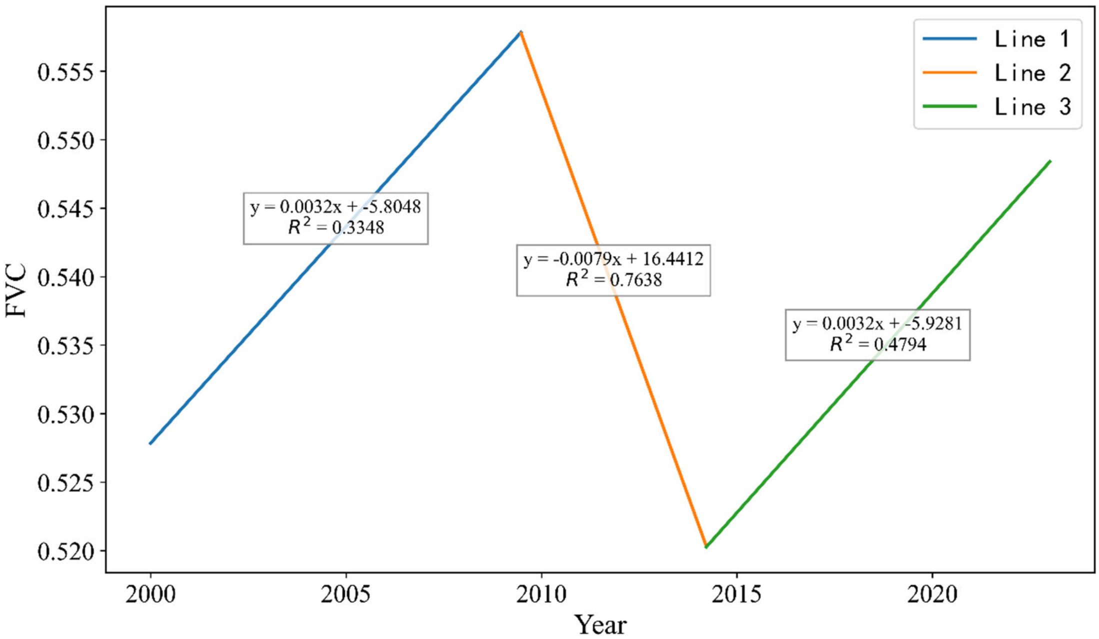

Figure 3. Temporal Changes in FVC in the Beijing-Tianjin-Hebei Region from 2000 to 2023

4.3. Spatial Variation Characteristics of FVC

Figure 4 clearly demonstrates that the overall spatial pattern of vegetation change in the region is characterized by sustained ecological improvement in the northwest and localized degradation in the southeastern plains. Table 4 indicates that regions with a trend of vegetation cover improvement comprise 47.90% of the total area, marginally higher than those experiencing degradation. The area with essentially unchanged vegetation cover is the smallest, accounting for only 10.42%. This suggests that over the past 24 years, vegetation conditions in the Beijing-Tianjin-Hebei region have been predominantly characterized by improvement. Spatially, areas with significant increases in vegetation cover (accounting for 20.38% of the area) are highly concentrated in the northwest, particularly in the Yanshan and Taihang mountain ranges. These areas serve as core implementation zones for major national ecological projects such as the "Beijing-Tianjin Sandstorm Source Control Project" and the "Three-North Shelter Forest Program," with remarkable vegetation restoration results, highlighting the decisive positive role of long-term, large-scale ecological restoration policies in improving mountainous ecosystems. In contrast, regions showing marked declines in vegetation cover (comprising 19.43% of the area) are primarily located in the southeastern part of the North China Plain, notably in urban clusters centered on Beijing and Tianjin and their outward expansion areas. This is likely due to rapid urbanization and industrialization processes, which have replaced substantial amounts of original vegetation (such as cropland and forests/grasslands) with impervious surfaces, causing significant negative impacts on local ecosystems.

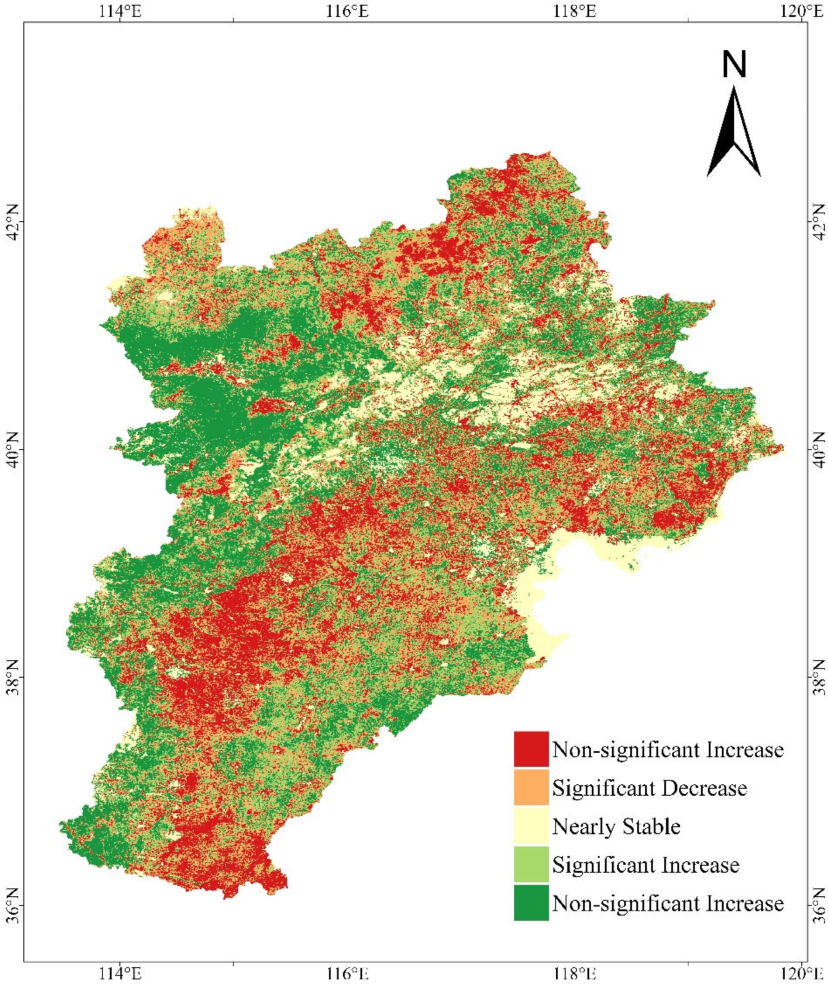

Figure 4. Spatial Distribution of Interannual Trends in Fractional Vegetation Cover in the Beijing-Tianjin-Hebei Region from 2000 to 2023

Table 4. Percentage Distribution of Vegetation Cover Change Trends in the Beijing-Tianjin-Hebei Area from 2000 to 2023

slope	Z	Trend of Change	Percentage of Area (%)
>0.0001	>1.96	Significant Increase	20.38
>0.0001	-1.96~1.96	Non-significant Increase	27.52
-0.0001~0.0001	~	Nearly Stable	10.42
<-0.0001	-1.96~1.96	Significant Decrease	19.43
<-0.0001	<-1.96	Non-significant Decrease	22.25

4.4. Future Characteristics of FVC Change

Figure 5 illustrates that the future spatial pattern of FVC change in the Beijing-Tianjin-Hebei area reveals an overall lack of persistence in vegetation trends. According to the statistics in Table 5, areas exhibiting anti-persistence (H < 0.5) account for as much as 59.83%, including 32.23% classified as "increase-to-decrease" and 27.60% as "decrease-to-increase" regions. In contrast, persistent regions (H > 0.5), namely "continuous increase" and "continuous decrease," together account for only 29.95% of the total area. The largest category, "increase-to-decrease" (32.23%), is widely distributed across the Yanshan and Taihang mountain ranges. Although these areas have achieved notable ecological restoration over the past two decades, they face a significant risk of future degradation, potentially due to the diminishing marginal effects of ecological projects, shifts in climatic conditions, or increased human disturbances. Additionally, the second-largest category, "decrease-to-increase" (27.60%), is primarily concentrated in the southeastern plains, where vegetation degradation was historically severe, particularly in peri-urban expansion zones. This trend may be attributed to the implementation of urban greening policies and industrial restructuring, which allowed certain lands to recover. The spatial distribution of these categories carries significant implications as an early warning for regional ecological management and policy-making.

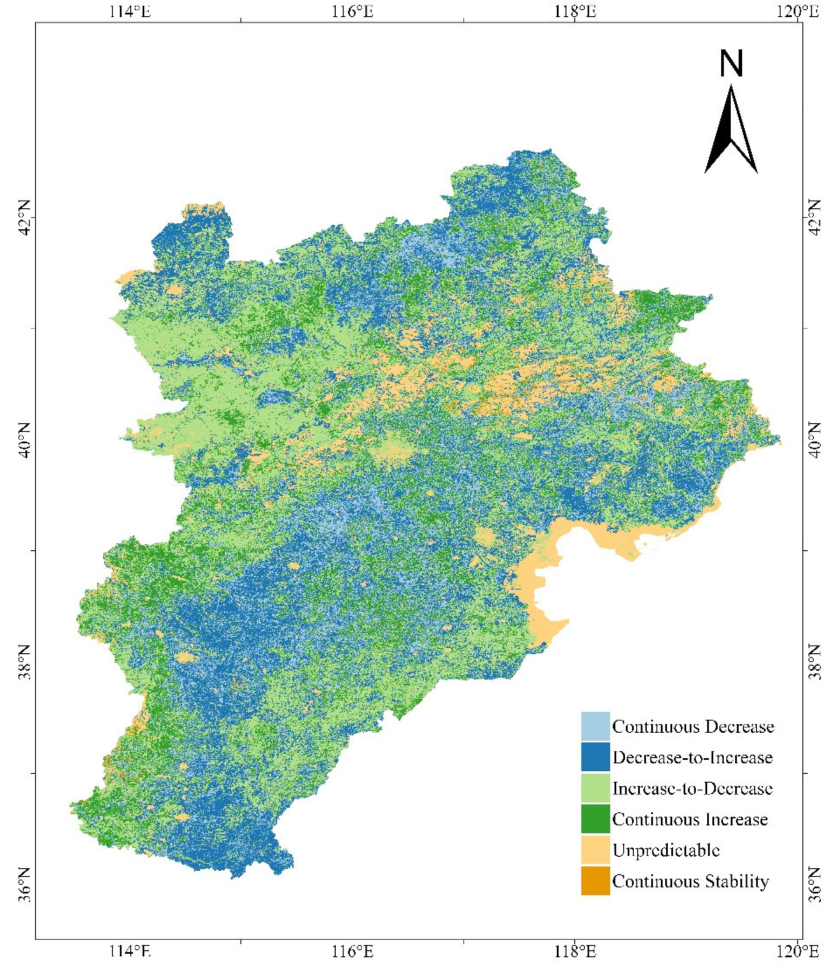

Figure 5. Hurst Index-Based Spatial Pattern of Future Vegetation Change in the Beijing-Tianjin-Hebei Area during 2000 to 2023

Table 5. Hurst Index-Based Classification of Fractional Vegetation Cover in the Beijing-Tianjin-Hebei Area from 2000 to 2023

slope	HI	Future Change Trends	Percentage of Area (%)
>0.0001	0~0.5	Increase-to-Decrease	32.23
>0.0001	0.5~1	Continuous Increase	15.67
-0.0001~0.0001	0~0.5	Unpredictable	9.45
-0.0001~0.0001	0.5~1	Continuous Stability	0.96
<-0.0001	0~0.5	Decrease-to-Increase	27.60
<-0.0001	0.5~1	Continuous Decrease	14.28

4.5. Driving Forces of FVC

Figure 6 illustrates that rainfall acts as a broadly significant positive driver throughout the study region, with the majority of areas displaying positive correlations, especially in the Yanshan and Taihang mountain ranges to the northwest and the North China Plain to the southeast. The significance test map (Fig. 6, right) shows that most of the positively correlated regions achieve significance at $p < 0.05$, suggesting that enhanced rainfall substantially facilitates vegetation development within the study area. This outcome aligns with the natural geographic context of the Beijing-Tianjin-Hebei region as a transitional zone between semi-humid and semi-arid climates, where water availability is a critical limiting factor for vegetation growth and ecosystem productivity; thus, abundant precipitation effectively alleviates water stress and positively influences FVC. In contrast, the effect of temperature (Fig. 7) displays a complex spatial heterogeneity. In the northwest regions of the Yanshan and Taihang Mountains, there is generally a significant negative correlation between temperature and FVC, indicating that in these higher-altitude and relatively cooler mountainous areas, increased temperature inhibits vegetation growth. The primary reason may be that rising temperatures intensify soil evaporation and plant transpiration, leading to more severe moisture deficits under limited precipitation supply; this water stress negatively outweighs any positive effects from improved thermal conditions. In contrast, temperature and fractional vegetation cover in the flat southeastern North China Plain mainly exhibit a positive relationship, which may be attributed to moderate temperature increases satisfying thermal requirements for crops and other vegetation, lengthening the growing season and thereby enhancing vegetation growth and cover.

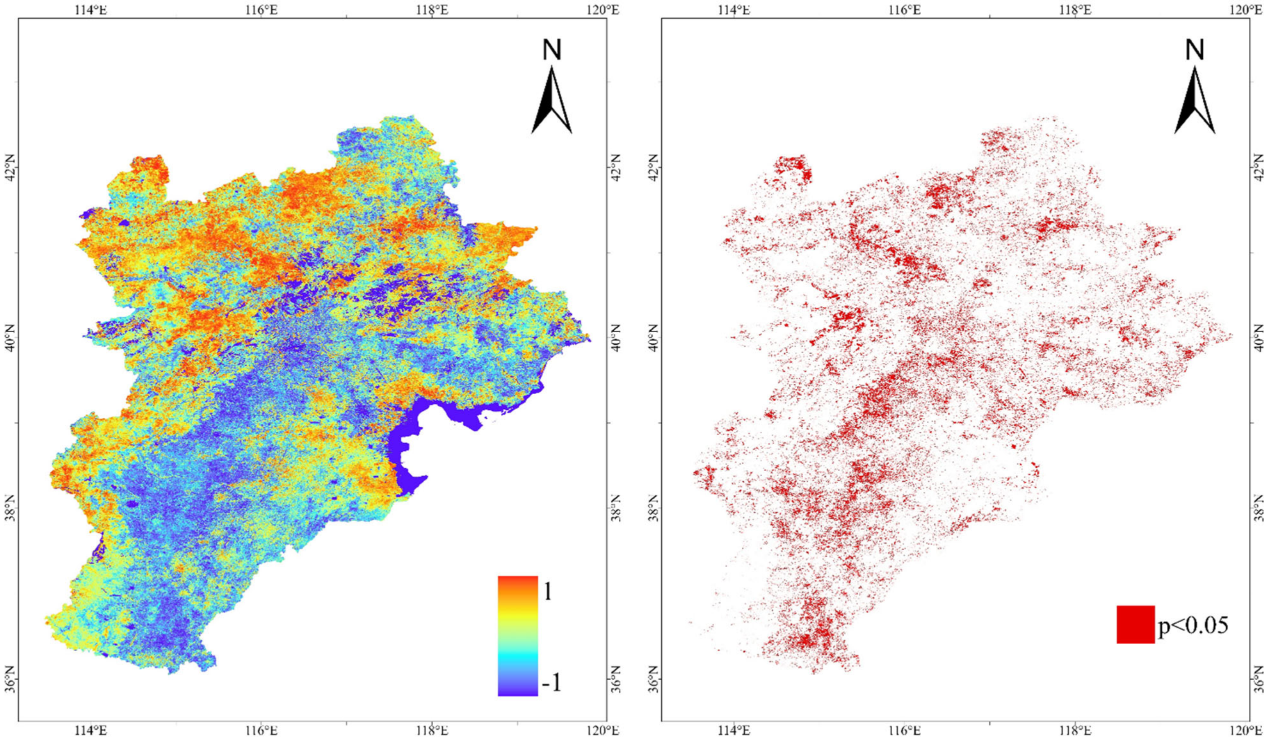

Figure 6. Spatial Distribution of Partial Correlation between Precipitation and FVC

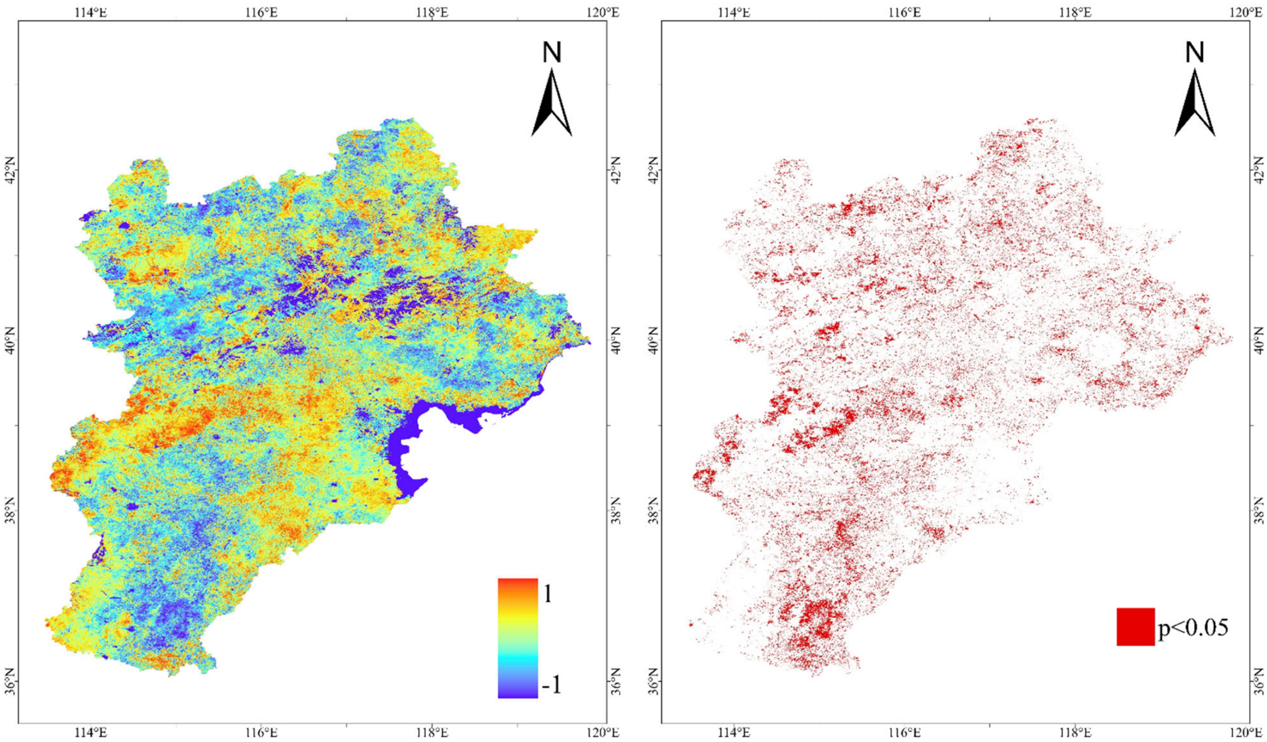

Figure 7. Spatial Distribution of Partial Correlation between Temperature and FVC

5. Conclusion

This study conducted a spatiotemporal evolution and driving factor analysis of FVC in the Beijing-Tianjin-Hebei region from 2000 to 2023. The main conclusions are as follows: (1) Vegetation cover in the study area exhibits a spatial pattern of "high in the northwest and low in the southeast," with high-coverage zones concentrated mainly in the Yanshan and Taihang Mountains in the northwest; (2) The temporal evolution shows three phases, including rapid growth from 2000 to 2010, a sharp decline from 2010 to 2015, and a recovery after 2015. Nearly 60% of the vegetation change trends display anti-persistence; (3) Increased precipitation acts as a favorable driver for vegetation growth in the region, while rising temperature promotes vegetation growth in the southeastern plains with relatively sufficient moisture and heat conditions but inhibits vegetation growth in the water-limited northwestern mountainous areas.

6. Discussion

The results of this study provide strong evidence for the significant achievements of national ecological projects such as the "Three-North Shelter Forest Program" and the "Beijing-Tianjin Sandstorm Source Control." However, the study also reveals the continuous degradation of vegetation in the southeastern plains, highlighting the encroachment of ecological space amid rapid urbanization in China. Future ecological management strategies in the Beijing-Tianjin-Hebei region should be adjusted with targeted measures. In the northwestern mountainous areas, the policy focus should shift from merely "increasing greenery" to "maintaining vitality," by implementing scientific forest management and tending to enhance the health and resilience of forest ecosystems, enabling them to better adapt to future climate change. For the southeastern plains, the core policy should emphasize "preserving greenery," through delineating and strictly enforcing ecological protection redlines, integrating urban green spaces, parks, and river corridors to form ecological networks, and vigorously promoting green infrastructure such as "sponge cities" to mitigate the negative impacts of urbanization on ecosystems and achieve harmonious coexistence between humans and nature.

Furthermore, although this study reveals the dynamics of vegetation changes in the Beijing-Tianjin-Hebei region, some limitations remain. The partial correlation analysis used for driving factor identification can only uncover linear relationships, whereas in reality, the influences of driving factors are often complex and nonlinear. Additionally, this research mainly focuses on climatic factors, while the impacts of human activities and their interactions with natural factors require further investigation to provide a more comprehensive and in-depth assessment of the actual state and sustainability of regional ecosystems.

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