Spatiotemporal Variation and Driving Force Analysis of Forest-Grass Vegetation Coverage in Hetao Irrigation District Based on Geodetector (Postprint)

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Date: 2023-05-30T00:00:00+00:00

Abstract

Based on forest and grass vegetation coverage data from 2000–2019, this study analyzed the spatiotemporal variation characteristics of forest and grass vegetation in the Hetao Irrigation District over the past 20 years, and quantitatively examined the influence of various driving factors on forest and grass vegetation coverage using the geographical detector. The results indicate that: (1) Over the past 20 years, the forest and grassland area in the Hetao Irrigation District exhibited an overall decreasing trend, with a reduction of 966.15 km^2; the forest and grass vegetation coverage grade showed an overall increasing trend, with a multi-year average coverage of 28.3%; spatially, the forest and grass vegetation coverage exhibited a spatial variation characteristic of decreasing from northeast to southwest; (2) Over the past 20 years, the centroids of low and medium forest and grass vegetation coverage were primarily located on the northeast side of the Yongji Irrigation Subdistrict and the southwest side of the Yichang Irrigation Subdistrict; the centroids of forest and grass vegetation coverage at all levels demonstrated a decreasing gradient from northeast to southwest, and all exhibited a migration trend toward the southwest, with migration distances ranging from 0.71 to 15.46 km across various periods; (3) Distance to water bodies, groundwater depth, temperature, and precipitation are the dominant environmental factors affecting forest and grass vegetation coverage in the region, with explanatory powers of 0.427, 0.439, 0.318, and 0.368, respectively; the interaction effects between distance to water bodies, groundwater depth, annual average precipitation and other factors are generally high; the magnitude of regional water content is the main driving force affecting the growth status of forest and grassland in the Hetao Irrigation District; the research results can provide a scientific basis for the protection and restoration of natural vegetation in irrigation districts.

Full Text

Spatiotemporal Change and Driving Force Analysis of Forest-Grass Vegetation Coverage in Hetao Irrigation District Based on Geographical Detector

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Abstract

Based on forest-grass vegetation coverage data from 2000 to 2019, this study analyzed the spatiotemporal variation characteristics of forest-grass vegetation in Hetao Irrigation District over the past 20 years, and quantitatively examined the influence of various driving factors on forest-grass vegetation coverage using a geographical detector. The results showed that: (1) The area of forest and grassland in Hetao Irrigation District showed an overall decreasing trend, with a reduction of 966.15 km^2, while the vegetation coverage level of forest-grassland showed an overall upward trend. The multi-year average forest-grass vegetation coverage was 28.3%. Spatially, forest-grass vegetation coverage in Hetao Irrigation District exhibited a spatial pattern of decreasing from northeast to southwest. (2) The centers of gravity for low and medium forest-grass vegetation coverage were mainly located in the northeast of Yongji irrigation area and the southwest of Yichang irrigation area, respectively. The centers of gravity for all levels of forest-grass vegetation coverage showed a decreasing trend from northeast to southwest, and all exhibited a migration trend toward the southwest, with migration distances ranging from 0.71 to 15.46 km in each period. (3) Distance to water bodies, groundwater depth, temperature, and precipitation were the dominant environmental factors affecting forest-grass vegetation coverage in the region, with explanatory powers of 0.427, 0.439, 0.318, and 0.368, respectively. The interactions between distance to water bodies, groundwater depth, annual average precipitation, and other factors were generally high, indicating that regional water content is the main driving force affecting the growth status of forest-grassland in Hetao Irrigation District. These research results can provide a scientific basis for the protection and restoration of natural vegetation in irrigation districts.

Keywords: Hetao Irrigation District; forest-grass vegetation coverage; spatiotemporal change; driving factor; geographical detector

1. Introduction

Forest and grass vegetation constitutes an important component of terrestrial ecosystems, playing a crucial role in global material cycling and energy flow, and providing significant ecological benefits for mitigating regional soil erosion. Vegetation coverage (Fractional Vegetation Cover, FVC) serves as an important indicator for measuring vegetation growth status, reflecting various environmental problems such as vegetation degradation in regional natural ecosystems, and representing a critical parameter for estimating and monitoring regional ecosystem stability and function. Many scholars have analyzed regional vegetation growth changes and their driving forces based on vegetation coverage data using different methods, with numerous studies finding that meteorological factors (temperature, precipitation) have strong explanatory power for vegetation growth changes. For example, Ma Xiaoni et al. conducted a quantitative analysis of environmental driving factors for vegetation coverage in the Pisha sandstone area of the Loess Plateau, demonstrating that precipitation, temperature, and soil moisture were the dominant environmental factors influencing the spatial distribution of vegetation coverage in this region.

In recent years, more scholars have quantitatively analyzed and evaluated the impact of natural environmental factors on vegetation growth, while fewer have explored the response relationship between vegetation growth and human activities. In reality, the influence of human activities on vegetation growth and change cannot be ignored. The geographical detector is a spatial statistical method based on a set of statistical approaches for detecting spatial differentiation and revealing its underlying driving forces. Through geographical detector analysis of spatiotemporal changes in vegetation coverage in the upper reaches of the Minjiang River, it was found that vegetation coverage in the upper Minjiang River was mainly affected by four factors: altitude, temperature, soil type, and precipitation. Many studies on the driving force analysis of spatiotemporal changes in regional vegetation coverage are significant, but most only quantitatively analyze the explanatory power of driving factors on vegetation coverage, lacking analysis of the suitable conditions for driving factors that affect vegetation growth.

Most areas of Hetao Irrigation District are located on the edge of desertification, causing natural vegetation such as grassland and forest in this region to be on the verge of degradation. As a large farming-pastoral ecotone in China, year-round cultivation and irrigation have led to declining groundwater levels and intensified soil salinization, thereby increasing the complexity and fragility of the ecosystem. Without effective protection, it is prone to evolve toward desertification. In recent years, many scholars have studied vegetation coverage in the Yellow River Basin and the Inner Mongolia-Shaanxi-Gansu region, including Hetao Irrigation District. Among them, Zhang Zhiqiang et al. analyzed the spatiotemporal distribution pattern of vegetation coverage in the Yellow River Basin from 2000 to 2019, providing data support for ecological protection planning in the Yellow River Basin. Su Lide et al. analyzed desertification dynamics in Urat Rear Banner from 1986 to 2019, finding that Urat Rear Banner was in a state of desertification. However, previous studies on vegetation coverage generally analyzed regional overall vegetation, making it difficult for conclusions about regional overall vegetation coverage to reflect the growth status of natural vegetation in farming-dominated irrigation districts. Therefore, this study takes this as an entry point to investigate the interannual dynamic changes of forest-grass vegetation in Hetao Irrigation District.

2. Materials and Methods

2.1 Study Area Overview Hetao Irrigation District is located in Bayannur City, Inner Mongolia Autonomous Region, China. It is one of the three major irrigation districts in China and the largest irrigation district in Asia [Figure 1: see original paper]. The irrigation district has a temperate continental monsoon climate with low annual precipitation of about 135–225 mm, concentrated mainly in July–September. The average annual evaporation is about 1,750 mm, and the multi-year average temperature is about 5.6 °C. The irrigation district is bordered by the Yinshan Mountains to the north, the Yellow River to the south, the suburbs of Baotou City to the east, and the Ulan Buh Desert to the west. The east-west span is about 250–260 km, and the north-south span is about 45–60 km. The terrain is flat, with overall elevation ranging between 911–1,167 m. The annual Yellow River water diversion is about 5×10^{9} m^3, accounting for one-sixth of the Yellow River's transit flow, representing an important water resource for the irrigation district.

2.2 Data Sources and Preprocessing This study used five types of basic data related to the research, including: remote sensing data for extracting vegetation coverage; land use vector data for extracting forest and grass vegetation; and topographic data, meteorological data, groundwater data, GDP and population data, and distance data from water bodies, roads, residential areas, and cultivated land (Table 1). All datasets underwent geometric correction, atmospheric correction, and other preprocessing. Combined with regional phenological patterns, the data were processed using ArcGIS software for seamless mosaic, projection, and clipping to obtain the land use vector data for Hetao Irrigation District. The data were processed during the peak vegetation growth season (July–September).

2.3 Methods

2.3.1 Forest-Grass Vegetation Coverage The pixel dichotomy model was used to estimate vegetation coverage. The calculation formula is as follows:

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

where FVC represents vegetation coverage. Following the method of Li Miaomiao et al., the maximum and minimum values were taken from the NDVI frequency cumulative table within a given confidence interval. Therefore, this study combined the actual situation of Hetao Irrigation District with previous research and adopted the 5%–95% confidence interval to estimate vegetation coverage. Forest-grass vegetation coverage in Hetao Irrigation District was extracted through forest-grassland vector data.

Referring to the "Standard for Classification and Gradation of Soil Erosion" issued by the Ministry of Water Resources of the People's Republic of China in 2008 and relevant literature on vegetation coverage classification requirements, combined with field investigations, vegetation coverage was divided into five levels through density segmentation (Table 2).

2.3.2 Trend Analysis The annual variation trend was expressed as follows:

$$slope = \frac{n\sum_{i=1}^{n} ix_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} x_i}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where $slope$ represents the trend slope of forest-grass vegetation coverage; n represents the length of the study time series; variable i represents the year number; and x_i represents the vegetation coverage in year i. A positive $slope$ value indicates an increasing trend in vegetation coverage during the study period, while a negative value indicates a decreasing trend.

2.3.3 Gravity Center Migration Model The gravity center migration model is one of the important models for analyzing landscape pattern changes, which can intuitively show the migration pattern and aggregation of a certain element in space. The calculation formula is as follows:

$$X_r = \frac{\sum_{i=1}^{n} F_{is} \times x_i}{\sum_{i=1}^{n} F_{is}}, \quad Y_r = \frac{\sum_{i=1}^{n} F_{is} \times y_i}{\sum_{i=1}^{n} F_{is}}$$

where X_r and Y_r represent the longitude and latitude coordinates of the gravity center of each vegetation coverage level; F_{is} represents the value of the i-th vegetation coverage pixel in year s; and x_i, y_i are the gravity center coordinates of vegetation coverage on the i-th grid in year s.

2.3.4 Quantitative Analysis of Driving Factors **Factor Detection**: This detects the spatial differentiation of vegetation coverage and the degree to which each driving factor explains the spatial differentiation of forest-grass vegetation coverage, measured by the q value. The calculation formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST}$$

where h represents the classification or zoning of forest-grass vegetation coverage or driving factors; N_h and N are the number of units in zone h and the entire region, respectively; σ_h^2 and σ^2 are the variances of y values in zone h and the entire region, respectively; SSW and SST are the sum of within-layer variance and total variance of the entire region, respectively. The value range of q is [0,1]. A larger q value indicates stronger explanatory power of driving factor x on vegetation coverage y, and vice versa.

Interaction Detection: This identifies the interaction between different driving factors, i.e., whether the explanatory power is enhanced or weakened when factor X_1 and factor X_2 act together on vegetation coverage. The differences in interaction between different factors mainly show five results: $q(X_1 \cap X_2) < \mathrm{Min}(q(X_1), q(X_2))$ indicates nonlinear weakening; $\mathrm{Min}(q(X_1), q(X_2)) < q(X_1 \cap X_2) < \mathrm{Max}(q(X_1), q(X_2))$ indicates single-factor nonlinear weakening; $q(X_1 \cap X_2) > \mathrm{Max}(q(X_1), q(X_2))$ indicates dual-factor enhancement; $q(X_1 \cap X_2) = q(X_1)+q(X_2)$ indicates independent interaction; and $q(X_1 \cap X_2) > q(X_1)+q(X_2)$ indicates nonlinear enhancement.

Risk Zone Detection: This determines whether there are significant differences in the mean values of attributes among subregions of each driving factor and can identify the suitable range for forest-grass vegetation growth. Risk detection uses the t statistic for testing, expressed as:

$$t = \frac{\bar{Y}_{h1} - \bar{Y}_{h2}}{\sqrt{\frac{Var_{h1}}{n_{h1}} + \frac{Var_{h2}}{n_{h2}}}}$$

where $\bar{Y}_h$ represents the linear regression coefficient of forest-grass vegetation coverage in subregion h; Var_h represents the variance of forest-grass vegetation coverage in subregion h; and n_h represents the number of samples in subregion h.

3. Results and Analysis

3.1 Spatial Distribution Characteristics of Forest-Grass FVC in Hetao Irrigation District [Figure 2: see original paper] shows the spatial distribution maps of vegetation coverage levels in Hetao Irrigation District during the study period. The forest-grass vegetation coverage in Hetao Irrigation District generally showed an east-high-west-low distribution pattern during the peak growth month of July each year. Over the years, low vegetation coverage (15%–30%) forest-grass was mainly distributed in the western Ulan Buh irrigation area (43.2%–51.6%), while high and very high vegetation coverage forest-grass was mainly distributed in the eastern area around Wuliangsuhai Lake. This is because the forest-grass in the west mostly exists in the form of desert-meadow, with low and unstable groundwater levels, resulting in poor forest-grass growth. In contrast, the east has abundant water sources such as Wuliangsuhai Lake, and ecological protection efforts have been strengthened in recent years due to the "One Lake, Two Seas" policy. However, since 2015, the number of higher and high vegetation coverage areas in the southwest has increased, while those in the northeast have decreased.

To further explore and analyze the changes in forest-grass cover in Hetao Irrigation District, a grade transfer matrix was calculated for different levels of forest-grass vegetation coverage from 2000 to 2019. Table 3 shows the grade transfer matrix of forest-grass vegetation coverage in Hetao Irrigation District from 2000 to 2019. It can be seen that during the study period, 2,613.94 km^2 of other land use types were converted to forest-grass, with more conversions to lower vegetation coverage (652.75 km^2) and medium vegetation coverage (984.38 km^2). Meanwhile, 1,647.79 km^2 of forest-grassland was converted to other land use types, with more conversions from low vegetation coverage (413 km^2) and lower vegetation coverage (1,078.26 km^2), mainly distributed in the desert zone of Ulan Buh irrigation area. Overall, the quantity of forest-grassland showed a decreasing trend, but in terms of vegetation coverage level conversion, 520.62 km^2 of low-level vegetation coverage was converted to high-level vegetation coverage, while only 151.51 km^2 of high-level vegetation coverage was converted to low-level vegetation coverage, indicating that the growth status of forest-grassland in Hetao Irrigation District has been improved overall.

3.2 Temporal Variation Characteristics of FVC in Hetao Irrigation District As shown in [Figure 3: see original paper], forest-grass vegetation coverage in Hetao Irrigation District was dominated by lower vegetation coverage, accounting for 37.01%–43.53% of the total forest-grass area, followed by low vegetation coverage, medium vegetation coverage, and higher vegetation coverage, while high vegetation coverage forest-grassland was the least distributed, accounting for 3.8%–6.24% of the total forest-grass area. From 2000 to 2009, the proportion of low and lower vegetation coverage showed a decreasing trend, while medium, higher, and high vegetation coverage showed an increasing trend, indicating that the growth status of forest-grassland in Hetao Irrigation District improved during this period. From 2010 to 2014, the proportion of low and lower vegetation coverage showed an increasing trend, while medium, higher, and high vegetation coverage showed a decreasing trend, indicating that forest-grass growth status deteriorated during this period. From 2015 to 2019, the proportion of low and lower vegetation coverage showed a decreasing trend again, while medium, higher, and high vegetation coverage showed an increasing trend, indicating that forest-grass growth status improved again.

[Figure 4: see original paper] shows that the multi-year average FVC in Hetao Irrigation District fluctuated significantly, with peaks in 2003 and 2016 (31.2% and 30.8%, respectively) and troughs in 2001 and 2012 (25.6% and 25.9%, respectively). Throughout the study period, the average FVC showed obvious fluctuation, with frequent alternation between high and low values. The multi-year average FVC was 28.3%. The linear trend was not significant, with no obvious overall change. The relative change rate showed that forest-grass cover increased and improved at a relatively fast rate during 2000–2009 and 2015–2019, while it decreased at a relatively fast rate during 2010–2014.

3.3 Gravity Center Migration of Forest-Grass FVC at All Levels The gravity center migration model mainly reflects changes in direction and distance characteristics, which can indicate landscape spatiotemporal changes. As shown in [Figure 5: see original paper], the gravity center of low-coverage forest-grass was located in Yongji irrigation area throughout the study period, with the maximum migration distance of 12.154 km in 2005. The gravity center of lower-coverage forest-grass was located in the southwest of Yongji irrigation area, generally northeast of the low-coverage class, with the maximum migration distance of 11.857 km in 2015. The gravity center of medium-coverage forest-grass was distributed in the junction area between Yongji and Yichang irrigation areas, generally northeast of low and lower coverage classes, with the maximum migration distance of 8.137 km in 2010. The gravity center of higher-coverage forest-grass was distributed in the junction area between Yongji and Yichang irrigation areas, generally northeast of low, lower, and medium coverage classes, with the maximum migration distance of 15.455 km in 2015. The gravity center of high-coverage forest-grass was distributed in the southwest of Yichang irrigation area, with the maximum migration distance of 9.707 km in 2015. The gravity centers of forest-grass vegetation coverage at all levels showed an overall migration trend toward the southwest, and the gravity centers of vegetation coverage at all levels showed a decreasing trend from northeast to southwest.

3.4 Analysis of Driving Factors

3.4.1 Single Factor Analysis To explore the influence of different environmental factors and human activities on the spatial differentiation of forest-grass vegetation coverage in Hetao Irrigation District, 11 detection factors were selected for analysis. The explanatory power q values of single-factor impacts were obtained [Figure 6: see original paper]. The ranking of explanatory power for each factor was: groundwater depth (0.439) > distance to water bodies (0.427) > annual average precipitation (0.368) > annual average temperature (0.318) > distance to residential areas (0.217) > GDP (0.198) > elevation (0.181) > distance to cultivated land (0.154) > distance to roads (0.142) > population (0.121). The q values of distance to water bodies, groundwater depth, precipitation, and temperature were all greater than 0.3, indicating they are the dominant environmental factors affecting the spatial distribution of forest-grass vegetation coverage in the irrigation district. The q values of distance to cultivated land, distance to roads, distance to residential areas, GDP, and population were less than 0.3, indicating relatively small explanatory power for the spatial distribution of forest-grass vegetation coverage. This shows that natural factors are the main influences on forest-grass vegetation coverage distribution in Hetao Irrigation District.

3.4.2 Interaction Analysis Through interaction detection, the interactions among various influencing factors on forest-grass vegetation coverage in Hetao Irrigation District were analyzed. The results [Figure 7: see original paper] showed that under the interaction of dual factors, the explanatory power for forest-grass vegetation coverage was enhanced, mainly showing dual-factor enhancement. The interactions with greater influence on forest-grass vegetation coverage included: distance to cultivated land groundwater depth (0.624), distance to residential areas groundwater depth (0.617), distance to roads groundwater depth (0.612), and distance to residential areas distance to water bodies (0.605). The explanatory power of other factor interactions on forest-grass vegetation coverage was less than 0.6. The interactions of distance to water bodies, groundwater depth, and annual average precipitation with other factors were generally high, indicating that regional water content is the main factor affecting the growth status of forest-grassland in Hetao Irrigation District.

3.4.3 Risk Zone Detection Since the single-factor analysis and interaction analysis of elevation and GDP showed relatively small explanatory power, risk detection only listed the results for the other eight factors. As shown in Table 4, forest-grass vegetation in Hetao Irrigation District had the highest mean vegetation coverage in the precipitation range of 147–157 mm, and overall, forest-grass vegetation coverage gradually increased with precipitation, showing a positive correlation. This indicates that precipitation amount is a key factor for the growth status of forest-grass vegetation. Forest-grass vegetation had the highest mean coverage in the annual average temperature range of 8.9–9.2 °C, in the groundwater depth range of 1.8–2.8 m, in the distance to residential areas range of 7,537–11,250 m, in the distance to roads range of 10,014–13,121 m, in the distance to cultivated land range of 1,566–2,254 m, and in the distance to water bodies range of 0–670 m. Overall, the growth status of forest-grass vegetation was positively correlated with distance to residential areas and distance to roads, indicating that forest-grass vegetation growth status is negatively correlated with human activities. The farther from areas with active human activities, the better the forest-grass growth status.

4. Discussion

Through long-term investigation of forest-grassland in Hetao Irrigation District, it was found that low vegetation coverage forest-grass was mainly distributed in the Ulan Buh irrigation area, while higher and high vegetation coverage forest-grass was mainly distributed in the eastern area around Wuliangsuhai Lake. This is because the forest-grass in the west mostly exists as desert-meadow with low groundwater levels and weak stability, resulting in poor growth. In contrast, the east has abundant water sources such as Wuliangsuhai Lake, and ecological protection efforts have been strengthened due to the “One Lake, Two Seas” policy. The overall forest-grass vegetation coverage showed an east-high-west-low pattern, and the vegetation coverage level in Hetao Irrigation District showed an upward trend over the years, consistent with Zhang Zhiqiang’s research results on spatiotemporal changes in vegetation coverage in the Yellow River Basin from 2000 to 2019. Through the gravity center migration model, it was found that the gravity centers of vegetation coverage at all levels showed a migration trend toward the southwest, mainly because the change trends of groundwater depth and annual average temperature in the southwest were smaller than those in the northeast, while the change trend of precipitation in the southwest was greater than that in the northeast [Figure 8: see original paper]. The gravity center of low-coverage forest-grass was located in Yongji irrigation area throughout the study period, while the gravity center of high-coverage forest-grass was mainly distributed in the southwest of Yichang irrigation area. The gravity centers of vegetation coverage at all levels showed a decreasing trend from northeast to southwest.

Previous studies have found that forest-grass growth status in Hetao Irrigation District improved overall during 2000–2019, while this study further points out that the quantity of forest-grassland decreased during this period, which remains a major challenge for ecological restoration. This result is also consistent with Wang Juan et al.'s conclusion that there is not much correlation between total vegetation amount and unit vegetation coverage in a region. This situation is closely related to both regional natural environment and regional social development and engineering construction. To make full use of the unique conditions of the irrigation district, large-scale water conservancy projects have been constructed since the founding of the People's Republic of China, from the initial "Second Yellow River" and "Sanshenggong Water Control Project" to the current 13 main canals and tens of thousands of sublateral canals supplying water to the irrigation district, enabling more uniform allocation of water resources and benefiting vegetation growth. This is an important reason for the gradual improvement in forest-grass vegetation growth status. However, the construction of water conservancy projects also occupied large areas of forest-grassland, and with the improvement of water conservancy facilities, large areas of forest-grassland were reclaimed as cultivated land, with 718 km^2 of newly added cultivated land occupying forest-grassland during 2000–2019, which is also the main reason for the 逐年减少 of forest-grassland quantity in the irrigation district.

This study used the geographical detector and selected not only some natural factors but also elevation and some human activity data to conduct a more comprehensive and targeted analysis of the driving factors affecting the spatial distribution and changes of forest-grass FVC. The study found that distance to water bodies, groundwater depth, temperature, and precipitation had relatively strong explanatory power for the spatial differentiation of forest-grass vegetation coverage, indicating that natural conditions are the main driving factors affecting vegetation coverage in Hetao Irrigation District, and that hydrothermal conditions are the main reasons affecting forest-grass vegetation growth status. This is similar to Li Maolin et al.'s research conclusions on the arid and semi-arid regions of Xilingol League. Since 2015, the number of higher and high vegetation coverage areas in the southwest has increased, while those in the northeast have decreased. Figure 8 shows that the change trends of annual average temperature and groundwater depth in the southwest are generally smaller than those in the northeast, while the change trend of annual precipitation in the southwest is greater than that in the northeast, indicating that soil moisture is positively correlated with regional vegetation coverage, while temperature is negatively correlated. This is also similar to Chen Xiaoqiu et al.'s research conclusions on spatiotemporal changes in vegetation coverage in Inner Mongolia. Human activities mainly affect forest-grass vegetation coverage through distance to residential areas, distance to cultivated land, and distance to roads, reflecting that human activities mainly affect forest-grass vegetation through reclamation for cultivation and occupation for construction.

Since Hetao Irrigation District mainly relies on Yellow River water for flood irrigation, there are significant differences in Yellow River water diversion, soil salinization degree, and ecological management measures among different irrigation areas, which have important impacts on forest-grass vegetation coverage. However, due to data collection limitations and regional scale constraints, this study could not include the above influencing factors, which remain important considerations for future research.

5. Conclusion

Through analysis of the spatiotemporal distribution characteristics of forest-grass area and vegetation coverage in Hetao Irrigation District, the following conclusions were drawn:

1. From 2000 to 2019, the area of forest-grassland in Hetao Irrigation District showed an overall decreasing trend, with a reduction of 966.15 km^2. The vegetation coverage level of forest-grassland showed an overall upward trend, with a multi-year average forest-grass vegetation coverage of 28.3%. Spatially, forest-grass vegetation coverage in Hetao Irrigation District showed a spatial characteristic of decreasing from northeast to southwest, with the greatest changes occurring in the Ulan Buh irrigation area, where the proportion of improvement was relatively large in recent years.

2. Over the 20 years, the gravity centers of vegetation coverage at all levels were mainly located in the northeast of Yongji irrigation area and the southwest of Yichang irrigation area. The gravity centers of forest-grass vegetation coverage at all levels showed a decreasing trend from northeast to southwest, and all showed a migration trend toward the southwest, with migration distances ranging from 0.71 to 15.46 km in each period.

3. Distance to water bodies, groundwater depth, temperature, and precipitation were the dominant environmental factors affecting forest-grass vegetation coverage in the region, with explanatory powers of 0.427, 0.439, 0.318, and 0.368, respectively. The interactions between distance to water bodies, groundwater depth, annual average precipitation, and other factors were generally high, with explanatory powers exceeding 0.5, in-

dicating that regional water content is the main driving factor affecting the growth status of forest-grassland in Hetao Irrigation District. Each driving factor has its suitable range for forest-grass vegetation growth in Hetao Irrigation District.

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