International Journal for Housing Science and Its Applications
Publish August 6, 2025. Volume 46, Issue 3 Pages 8407-8416

https://doi.org/10.70517/ijhsa463719

Long-term time series data analysis of the coupled effects of climate change and human activities on vegetation cover in the source region of the Fen River

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Abstract Under the dual coercion of global climate change and human activities, the study of the driving mechanism of vegetation cover in the ecologically fragile area of the eastern Loess Plateau is crucial for regional ecological recovery. In this paper, the Fen River Basin is taken as the research object, and we integrate the multi-source data of MODIS-NDVI from 2010 to 2024, and construct a nonlinear regression model to quantitatively analyze the long-term impacts of climate change and human activities on vegetation cover. The standardized spatio-temporal dataset was formed through geographic alignment, projection transformation and mask cropping, and the vegetation cover was estimated by the image element binary model, and the trend was analyzed by the Theil-Sen median method. The results showed that the vegetation cover in the Fen River basin showed a significant improvement trend from 2010 to 2024, with 74.31% of the area improved, the proportion of high cover increased from 25.30% to 37.98%, and the area of low cover decreased by 85.3%, with the recovery of the middle and lower reaches being particularly significant. The bias correlation coefficients of vegetation NDVI with precipitation and temperature were 0.672 and 0.473, respectively, with the upstream relying on precipitation with a bias correlation coefficient of 0.702 and the downstream being more strongly driven by temperature, with R=0.633. The contribution rates of climate change and human activities were quantified by the residual decomposition, and the positive contribution rate of climate change averaged 53.10%, with a high of 59.92% in the downstream, and that of human activities was 9.40%, but urbanization downstream led to a negative contribution of 8.63%. Among the key human activity factors, the average correlation coefficient of 0.568 for agricultural expansion and R=0.524 for afforestation significantly contributed to vegetation recovery, while urbanization R=-0.455 and industrial development R=-0.352 inhibited vegetation growth. It can be seen that climate warming and humidification is the dominant factor for vegetation improvement, but human activities can locally strengthen the restoration effect through ecological engineering and agricultural management, and downstream we need to be alert to the potential risk of urbanization squeezing ecological space.

Index Terms nonlinear regression, climate change, human activities, Fen River source area, vegetation cover change

I. Introduction

In the context of global warming and intensified human activities, terrestrial ecosystems have undergone significant changes, and vegetation, as an important component of terrestrial ecosystems, is a link connecting the atmosphere, soil, and water bodies, and can fully reflect the environmental evolution [1]-[3]. Vegetation dynamics is the result of the joint action of climate and human activities, and to a certain extent, it characterizes the overall change of the ecological environment [4]. Therefore, in-depth understanding of the mechanism of the driving forces in the process of vegetation dynamic change and systematic evaluation of the relative roles of the driving factors in the process of vegetation dynamic change is the key to effective vegetation construction, which contributes to the healthy development of the ecosystem [5].

Changes in vegetation dynamics are considered as indicators of climate change to a certain extent, and the mutual feedback relationship between vegetation dynamics and climate change has become a research hotspot in related fields [6]. Long-term climate change will lead to a slow shift in vegetation distribution and dynamics, which is manifested in affecting the matching conditions of light, heat and water in the vegetation growth and development process, and then affecting the ecosystem productivity [7]-[9]. Climate extremes, on the other hand, can cause large differences in the short term [10]. Compared with changes in the mean state of climate, extreme climate events are characterized by suddenness, difficulty in prediction, damage and significant geographical differences, and when such rapid changes exceed the ability of vegetation to adapt to the new environmental conditions, terrestrial ecosystems will encounter great challenges [11]-[13]. For example, climate extremes such as droughts, floods, and high-temperature heat waves cause crop failures, ecological structure destruction, public health hazards, and environmental degradation [14]. In addition, the dynamic change of vegetation also reflects the process of human activities, which inevitably affect the balance and stability of the ecosystem, and under the influence of accelerated urbanization and population growth, the type of land use has also changed dramatically, with a large amount of natural land cover transformed into agricultural land and artificial construction land, which results in a series of ecological problems, including soil erosion, desertification and land degradation etc [15]-[19]. Therefore, a comprehensive and accurate understanding and assessment of climate change, especially extreme climate events, and the impacts of human activities on terrestrial ecosystems as well as the risk effects have become a major scientific issue in the current research in the field of global change, which is crucial for improving the ability of human society to cope with and adapt to climate change [20]-[23].

In this study, the Fen River Basin is taken as the research object, and a nonlinear regression framework is constructed by combining multi-source remote sensing data and statistical modeling to systematically analyze the long-term mechanisms of climate change and human activities on vegetation cover. The article firstly elucidates the geographic characteristics, climatic background and soil types of the Fen River Basin to provide a spatial basis for the subsequent analysis. Based on the MODIS-NDVI data, land use data and afforestation area data from 2010 to 2024, a standardized dataset is formed through geographic alignment, projection transformation and mask cropping to ensure spatial and temporal consistency. We also analyzed the calculation and trend of vegetation cover, estimated the vegetation cover using the image element binary model, and quantified the trend of cover change using the Theil-Sen median method to avoid the interference of outliers and reveal the long-term pattern of vegetation dynamics. Based on this, the nonlinear coupling effect of climate and human activities is addressed, and the gradient descent method and Newton's method are introduced to optimize the parameters and establish a nonlinear regression model, which breaks through the limitations of linear assumptions and improves the prediction accuracy. Finally, the contribution of climate change and human activities to the change of vegetation cover is analyzed. Through residual decomposition and scenario simulation, climate-driven and human-disturbed terms are separated, and six types of scenarios are designed to quantify the relative contributions of the two, and to clarify the direction and intensity of different driving factors.

II. Study on the dynamic analysis of vegetation cover in Fen River Basin based on nonlinear regression

II. A. Overview of the study area and data pre-processing

II. A. 1) Overview of the study area

Fen River is the second largest tributary of the Yellow River, originating from the southern foot of Guanmian Mountains in Ningwu County, Shanxi Province, with its main stream running from north to south between Luliang Mountains and Yunzhong Mountains, flowing eastward through Fen River Reservoir and passing through Lancun of Taiyuan City (upstream section); southward through Lancun through the Taiyuan Basin, and southwesterly out of Jiexiu to Lingshi and Huozhou, and meandering between Linghuoshan Gorge to Hongdong (middle reaches section); southwesterly through Linfen Basin through Hongdong, and then rapidly turning westward in Xinjiang County of Wanrong County, where it joins the Yellow River (downstream section) in Miaomian Village of Ronghe Town of Wanrong County. In Xinjiang County, the river turns sharply westward and joins the Yellow River (downstream section) in Miaoqian Village, Ronghe Town, Wanrong County. The Fen River Basin is located in the eastern part of the Loess Plateau, spanning 34 counties and cities in Shanxi Province, with a geographic location of $35^{\circ}20'-39^{\circ}00'N$, $110^{\circ}30'-113^{\circ}32'E$, and a length of about 415 km from north to south. , which is about 415 km long from north to south and 188 km wide from east to west, is distributed in a belt shape, with a basin area of about $40000km^2$. Fen River Basin belongs to the temperate continental monsoon climate, located in the transition zone of semi-arid and semi-humid climate, with rain and heat at the same time, and four distinct seasons, with cold and dry winter and spring seasons, less rain and snow, and higher temperatures and concentrated precipitation in the summer and fall seasons. Soil types in the watershed mainly include brown loam, red clay, tidal soil, chestnut calcium soil, yellow sheep soil, brown soil and black clay soil, etc., of which brown soil is the main zonal soil, mainly distributed in the basin and hilly areas.

II. A. 2) Data sources and pre-processing

The data used in this study mainly include (1) MODIS-NDVI remote sensing image data from 2010 to 2024; (2) land use/cover data from 2010 to 2024; and (3) afforestation area data from 2010 to 2024.

Source and processing of MODIS-NDVI data. The MODIS vegetation index product (MOD13A1) provided by the National Aeronautics and Space Administration (NASA) was selected, which has been corrected for the edge distortion generated during the imaging process of the remote sensors, and it is a three-level sinusoidal projection product with a spatial resolution of 513m and 18d synthesis. In order to study the spatial and temporal patterns of vegetation cover in the Fen River Basin, this paper downloads the data products of the peak plant growth season (July-August) from 2010 to 2024, with the map number H26V05 and H27V05. Firstly, multiple image data of the same time period were spliced in GIS software, and then the sinusoidal projection was transformed into transverse Mercator projection using MODIS reprojection tool, and the geographic coordinates were set to WGS84. Finally, the vector data of Fen River Basin with the same projection were used for the mask cropping, and the mean value was processed to get the 2010-2024 MODIS- NDVI data.

The land use/cover data from 2010 to 2024 were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (CAS), with a spatial resolution of 36 m. The data were classified using a two-tiered classification system: the primary land classes included six categories, which were divided into cropland, forest land, grassland, watersheds, construction land, and unutilized land according to the land resources and their attributes; and the secondary land classes were divided into 25 types, mainly based on the natural attributes of the land resources The secondary land categories are mainly based on the natural attributes of land resources, and are divided into 25 types, among which forest land includes forested land, shrubland, open forest land and other forest land, and grassland includes high-cover grassland, medium-cover grassland and low-cover grassland.

Data on the area of afforestation from 2010 to 2024 were obtained from the statistical yearbooks of Shanxi Province in previous years.

II. B.Vegetation cover calculation and trend analysis

After completing the geographic characterization of the study area and the standardization of multi-source data, the spatial and temporal dynamics of vegetation cover need to be further quantified. In this section, based on the preprocessed NDVI data, the long-term trend of vegetation cover in the Fen River basin is systematically analyzed by combining the image element dichotomous model with the Theil-Sen median method.

II. B. 1) Calculation of vegetation cover

In this paper, the image element binary model was used to calculate the vegetation cover of the Fen River Basin based on the normalized vegetation index (NDVI). The image element dichotomous model is a simple and practical remote sensing assessment model. The model assumes that the surface of a pixel contains two parts with and without vegetation cover, and the spectral information observed by the remote sensing sensor is fused by the linear weighting of these two parts, and the weights of each part depend on the proportion of the area they account for in the pixel.The correlation between the NDVI and the vegetation cover is very reliable, and the model for the estimation of vegetation cover is established:

$$FVC = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \tag{1}$$

where FVC denotes the vegetation cover, $NDVI$ denotes the NDVI value of the mixed image element, $NDVI_{\max}$ denotes the maximum NDVI value of the image element, which is close to 1, and $NDVI_{\min}$ denotes the minimum NDVI value of the image element, which is close to 0. Different raster imagery is affected by the meteorological conditions, the type and distribution of the vegetation cover and seasonal variations, and so on. Due to meteorological conditions, vegetation cover type and distribution characteristics, seasonal variations and other factors, the $NDVI_{\max}$ and $NDVI_{\min}$ of different raster images may have some differences. Using 5% and 95% confidence level (the cumulative percentage of the number of pixels corresponding to the NDVI value in a single period), the maximum and minimum values of NDVI data in each period were selected as the thresholds to complete the estimation of the multi-year long time series of vegetation cover in Fen River Basin.

II. B. 2) Calculation of trends in vegetation cover changes

The trend of vegetation cover change aims to analyze the relationship between the independent variable vegetation cover and the time variable, and the relationship can be approximated as a straight line after testing.The Theil-Sen median method is a reliable and robust nonparametric statistical technique that is usually used for trend analysis. The method is suitable for analyzing long time series data, has efficient computational power, and is not affected by measurement errors and outliers. Its calculation formula is:

$$\beta = Median\left(\frac{x_j - x_i}{j - i}\right), \forall j > i \tag{2}$$

where $1 < i < j < n$; β represents the slope, and the $\beta > 0$ time series exhibits an upward trend and vice versa.

II. C.Fundamentals of the nonlinear regression calibration algorithm

The trend of vegetation cover reveals its potential association with temporal variables, but the impacts of climate change and human activities may present nonlinear characteristics. To break through the limitations of linear models, this section introduces a nonlinear regression algorithm to capture the interaction mechanism of complex driving factors through parameter optimization.

The effects of climate change and human activities on vegetation cover may present nonlinear characteristics. This may limit the predictive power and reduce the accuracy of linear regression models. As a mathematical model that describes the nonlinear relationship between dependent and independent variables, nonlinear regression models can effectively capture the nonlinear characteristics of climate change, human activities, and vegetation cover, thus improving the prediction performance and meeting the needs of long-run impact studies. The nonlinear regression model is suitable for data with nonlinear relationship between the independent variable and the dependent variable. Compared to linear regression, nonlinear regression is able to fit more complex data patterns, providing higher predictive accuracy in some cases. The general form of a nonlinear regression model is shown in equation (3):

$$y = f(x,\theta) + \varepsilon \tag{3}$$

where, y represents the dependent variable, x represents the independent variable, θ represents the model parameter vector, $f(x,\theta)$ denotes the nonlinear function, and ε denotes the error term. Optimization algorithms such as gradient descent method and Newton's method are usually used in the nonlinear regression solution process. The model parameters are optimized by iterative methods to minimize the sum of squared errors.

II. D.Contribution of climate change and human activities to changes in vegetation cover

On the basis of constructing a nonlinear regression model, it is necessary to further separate the difference between the contributions of climate factors and human activities. In this section, we design a multidimensional assessment framework through residual decomposition and scenario simulation methods to quantitatively analyze the relative roles of the two types of driving factors on the changes of vegetation cover, so as to provide a basis for decision-making in ecological policy formulation.

By constructing a baseline model of vegetation-climate response, the spatial residual decomposition technique was used to decompose the vegetation NDVI time series into climate-driven terms and human disturbance terms, and the relative contribution of the two types of drivers to vegetation cover was quantified by means of scenario simulation assessment. Then, we used the image element-based climate-vegetation response analysis framework to construct a gridded multiple linear regression model to quantitatively decouple the driving factors, and obtained the predicted values of the climate-driven terms of vegetation NDVI $\left(N_p\right)$.

If only the effects of climate factors and human activities on vegetation cover are considered, the vegetation NDVI residual values can be regarded as the effects caused by human factors on vegetation cover. The specific expression for the residual analysis is given below:

$$N_p = a \times P + b \times T + c \tag{4}$$

$$\varepsilon = N_o - N_p \tag{5}$$

where P and T are the cumulative precipitation (mm) and the mean air temperature (℃) during the growing season, respectively; a, b, and c are the regression coefficients of the cumulative precipitation, the mean air temperature, and the constant term in the multiple linear regression model; N_p and N_o are the predicted and observed values of vegetation NDVI, respectively; ε is the vegetation NDVI residual value, when $\varepsilon > 0$, it means that human activities promote the change of vegetation cover, and vice versa.

Scenario simulation assessment method is a method to construct different scenarios based on the trends of N_o, N_p and ε, β_o, β_p and β_c, and to quantitatively assess the relative contribution of drivers in the process of vegetation cover improvement and degradation. In order to accurately quantify the relative impacts of climate change and human activities on vegetation cover changes, this paper designed six scenarios based on β_o, β_p and β_c. When $\beta_o > 0$, $\beta_p > 0$, and $\beta_c > 0$, it means that climate change and human activities jointly contribute to the restoration of vegetation cover; when $\beta_o > 0$, $\beta_p > 0$, $\beta_c < 0$, it means that climate change promotes vegetation recovery; when $\beta_o > 0$, $\beta_p < 0$, $\beta_c > 0$, it means that human activities promote vegetation recovery;

when $\beta_o < 0$, $\beta_p < 0$, $\beta_c < 0$, it means that climate change and human activities together contribute to vegetation degradation; when $\beta_o < 0$, $\beta_p < 0$, $\beta_c > 0$, it means that climate change contributes to vegetation degradation; when $\beta_o < 0$, $\beta_p > 0$, $\beta_c < 0$, it means that human activities contribute to vegetation degradation. The calculation method of the contribution of specific vegetation cover drivers is shown in Table 1.

Table 1: Calculation method of the contribution of vegetation coverage driving factors

Scenarios	β_o	β_p	β_c	Relative contribution of climate change/%	Relative contribution of human activities/%
1	Vegetation improvement area>0	>0	>0	$\frac{\lvert\beta_p\rvert}{\lvert\beta_p\rvert+\lvert\beta_c\rvert}\times 100$	$\frac{\lvert\beta_c\rvert}{\lvert\beta_p\rvert+\lvert\beta_c\rvert}\times 100$
2		>0	<0	100	0
3		<0	>0	0	100
4	Vegetation degradation areas<0	<0	<0	$\frac{\lvert\beta_p\rvert}{\lvert\beta_p\rvert+\lvert\beta_c\rvert}\times 100$	$\frac{\lvert\beta_c\rvert}{\lvert\beta_p\rvert+\lvert\beta_c\rvert}\times 100$
5		<0	>0	100	0
6		>0	<0	0	100

Note: β_o is the slope of NDVI observations, β_p is the slope of NDVI predictions, and β_c is the slope of NDVI residuals.

III. Characteristics of spatial and temporal evolution of vegetation cover in the Fen River Basin and the response mechanism of multiple driving factors

Based on the nonlinear regression model constructed in Chapter 2 and the standardized processing framework of multi-source data, this chapter focuses on the spatial and temporal dynamic characteristics of vegetation cover in the Fen River Basin from 2010 to 2024, and systematically analyzes the synergistic effect and spatial heterogeneity of climate change and ecological engineering by quantifying the correlations between NDVI and climatic factors and human activities, so as to provide empirical support for the revelation of the long-period ecological evolution law.

III. A. Characteristics of spatial and temporal changes of vegetation cover in the Fen River Basin

III. A. 1) Analysis of changes in vegetation cover

The degree of change of vegetation cover in the upper, middle and lower reaches of the Fen River Basin can be obtained through linear trend analysis and then with the help of area tabulation in ArcGIS 10.2 software.The results of the trend analysis of the upper, middle and lower reaches of the Fen River Basin for the period of 2010-2024 are shown in Fig. 1.

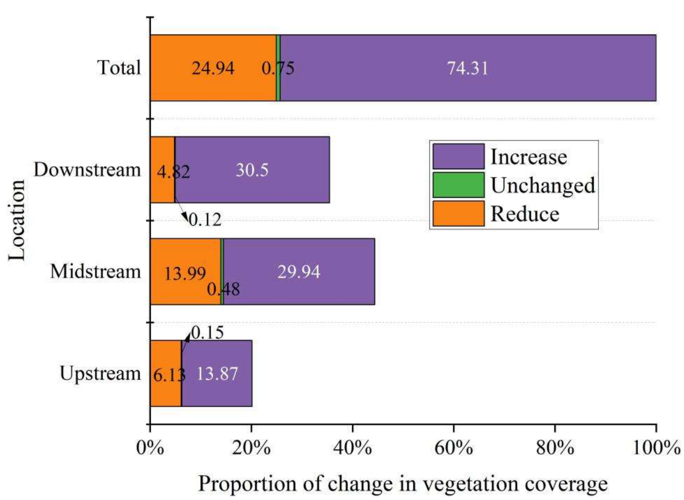

Figure 1: Trend analysis of the upper, middle and lower reaches of the Fen River Basin

As a whole, it can be seen that the degree of change of vegetation cover in the Fen River Basin from 2010 to 2024 is mainly an increasing trend, which occupies 74.31% of the total area covered by vegetation in the study area;

while the area with unchanged vegetation cover is only 0.75%. Among them, the increase in vegetation cover was mainly concentrated in the middle and lower reaches of the Fen River Basin, and the proportion of the area with increased vegetation cover in the middle and lower reaches was 29.94% and 30.50%, respectively. Meanwhile, the area of decreasing vegetation cover is dominated by the middle reaches, occupying 13.99% of the total area, and the proportion of the area with unchanged vegetation cover is very small, but still, it can be seen that the middle reaches of the Fen River area has the largest proportion of unchanged degree of vegetation change, but on the whole, the vegetation cover of the Fen River Basin as a whole shows a trend of improvement.

III. A. 2) Analysis of different vegetation covers

Using the image element dichotomous model, the five periods of remote sensing data integrated with the vegetation cover of the Fen River Basin from 2010 to 2024 were estimated and statistically analyzed, in order to obtain the area and proportion of the distribution types of different vegetation cover for each year as shown in Fig. 2.

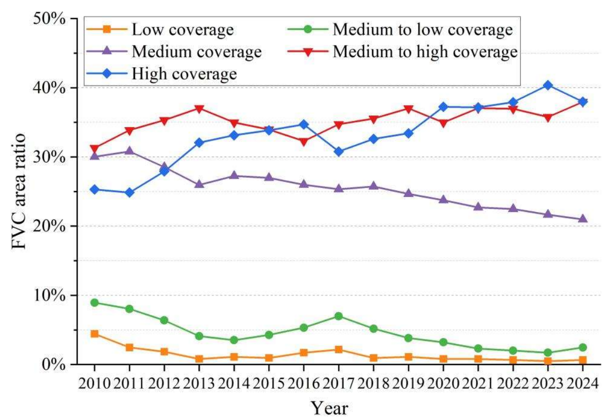

Figure 2: The proportion of areas with different vegetation coverage

According to the change data of area proportion of different vegetation cover classes in the Fen River Basin from 2010 to 2024, the vegetation cover showed a significant optimization trend. Specifically, the proportion of low-coverage area decreased continuously from 4.43% in 2010 to 0.65% in 2024, with a decrease of 85.3%; the proportion of medium-low-coverage area decreased from 8.94% to 2.46%, with a decrease of 72.5%. The proportion of medium-coverage area similarly decreases, from 30.03% to 20.97%, a decrease of 9.06 percentage points, indicating a gradual transformation of medium-coverage vegetation to higher classes.

In contrast, the proportion of medium-high cover area increased from 31.31% to 37.94%, an increase of 6.63 percentage points, and the proportion of high cover area increased from 25.30% to 37.98%, an increase of 12.68 percentage points, with the proportion of high cover reaching a peak of 40.38% in 2023. It is worth noting that the medium-high and high-coverage areas showed a stable growth trend after 2013, and only fluctuated slightly in 2017 due to a brief decline in the medium-high coverage ratio to 34.74%, but the overall trend remained upward.

In terms of inter-annual changes, the low-coverage area reached its lowest value of 0.81% in 2013, followed by small fluctuations, but always below the initial level. The high-coverage area increased significantly after 2020, with an average percentage of 37.95% during the period 2020-2024, indicating that the effect of vegetation restoration in the Fen River Basin in the last five years has been particularly significant. The above data indicate that the vegetation cover structure in the study area has migrated from low to medium level to high and medium level, and the overall ecological quality has significantly improved. This trend is closely related to the implementation of ecological protection policies and afforestation projects in the basin, and may also be influenced by the promotion of vegetation growth by climate change.

III. B. Vegetation NDVI response to climate change and human activities

On the basis of clarifying the characteristics of spatial and temporal changes in vegetation cover, in order to further reveal the driving mechanism, this section explores the response pattern of vegetation NDVI to precipitation, temperature and other climatic factors through partial correlation analysis and residual decomposition methods, and isolates the independent contribution of human activities to vegetation restoration.

III. B. 1) Correlation of NDVI with climate factors

Figure 3 illustrates the bias correlation coefficients of the normalized vegetation index NDVI with precipitation and temperature for the Fen River headwater area (upper, middle and lower reaches) from 2010 to 2024.

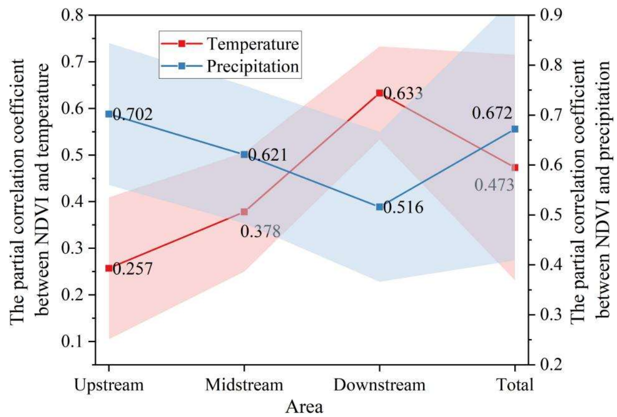

Figure 3: Partial correlation coefficient of NDVI with precipitation and temperature

As can be seen from Fig. 3, the partial correlation coefficient between precipitation and NDVI in the upstream was 0.702, which was significantly higher than that of 0.257 for temperature, indicating that vegetation growth in the upstream was more dependent on precipitation, probably because it was located in a semi-arid area where moisture was the main factor limiting vegetation recovery; the partial correlation coefficients between precipitation and temperature in the middle reaches were 0.621 and 0.378, respectively, both of which were significant, but with precipitation still being the dominant factor, Reflecting that the vegetation in the middle reaches is jointly influenced by precipitation and thermal conditions, but the precipitation-driven ecological effect is more prominent; the bias correlation coefficient between air temperature and NDVI in the lower reaches is as high as 0.633, significantly higher than that of precipitation (0.516), which suggests that thermal conditions (e.g., warmer air temperatures) in the downstream flat area promote vegetation growth more significantly, probably related to the local climatic regulation brought by irrigated agriculture and urbanization. Overall the partial correlation coefficients of NDVI with precipitation and air temperature in the Fen River headwaters area from 2010 to 2024 were 0.672 and 0.473, respectively, indicating that it was more influenced by precipitation.

III. B. 2) Correlation between NDVI and human activities

Residual analysis was used to exclude the influence of climate and obtain the effect of human activities on vegetation change.The average of NDVI residual trend in the Fenheyuan area from 2010 to 2024 was 0.0033, which indicated that the human activities had a predominantly facilitating effect on the vegetation growth in the Fenheyuan area. The dynamic transformation of land use macroscopically reflects the transformation of nature by human activities. The statistical NDVI and residual trend values of land use types in different regions are shown in Fig. 4.

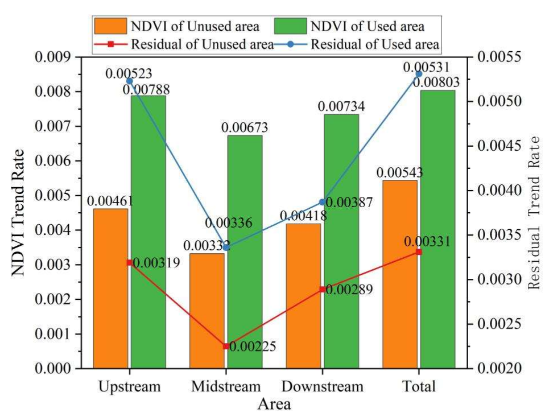

Figure 4: Trend rate statistics of the impact of human activities on NDVI and residuals

Figure 4 quantifies the driving effect of human activities on the NDVI of vegetation in different areas (upstream, midstream, and downstream) of the Fen River headwaters area, which is divided into two land types, unutilized and utilized, where the NDVI trend rate of the upstream of the unutilized land is 0.00461 with a residual trend rate of 0.00319, and that of the midstream of the unutilized land is 0.00332 with a residual trend rate of 0.00225; The downstream NDVI trend rate was 0.00418 with a residual trend rate of 0.00289. The upstream NDVI trend rate that has been utilized by human activities amounted to 0.00788 with a residual trend rate of 0.00523; the midstream NDVI trend rate was 0.00673 with a residual trend rate of 0.00336; and the downstream NDVI trend rate had the highest rate of 0.00734 with a residual The NDVI trend rate of the Fen River headwaters area as a whole was affected by human activities, and its NDVI trend rate increased to 0.00803, with a residual trend rate of 0.0051. The vegetation growth of the utilized land was enhanced by the direct influence of human activities (e.g., agricultural intensification, urban greening), and the residual contribution of the downstream accounted for 52.7%, which indicated that the regulation of high-productivity land by human activities played a significant role in the development of the Fen River. This indicates that human activities have a significant role in regulating high-productivity land. The NDVI and residuals of each land use showed an increasing trend, and the trend of residuals was consistent with the trend of NDVI changes, which also indicated the significant promotion of vegetation growth by human activities.

III. C. Study on the contribution of climate change and human activities to changes in vegetation cover and the factors affecting them

In order to accurately quantify the relative contribution of climate change and human activities to changes in vegetation cover, this section combines the scenario simulation method with multiple regression modeling to construct a framework for assessing contribution based on the correlation coefficients of the driving factors in different regions (upstream, midstream, and downstream), and to identify the directions and intensities of the roles of the key human activity factors.

III. C. 1) Contribution rate

Figure 5 shows the contribution of climate change and human activities to vegetation changes in each region of the Fen River source area.

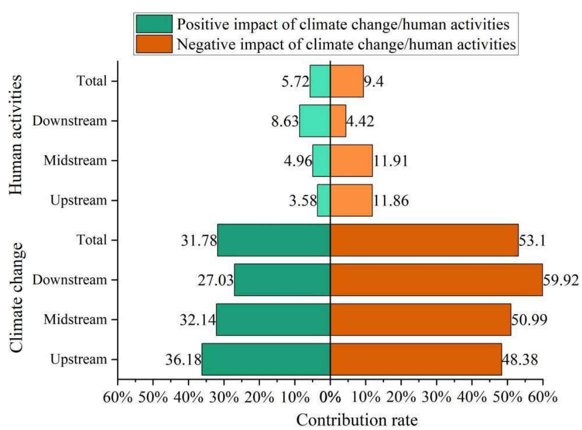

Figure 5: Contribution rate of climate change and human activity to vegetation change

Overall, the positive contribution of climate change was 53.10%, which was significantly higher than that of human activities (9.40%), suggesting that climate change was the main driver of the improvement in vegetation cover. At the sub-regional level, the positive contribution of climate change was highest in the downstream area with 59.92%, while it was lowest in the upstream area with 48.38%, which may be related to the better thermal conditions and sufficient precipitation in the downstream flat area. The positive contribution of human activities was the lowest in the downstream with 4.42%, while it was 11.86% and 11.91% in the upstream and midstream, respectively, which may be related to the continuous promotion of ecological protection policies in the middle and upper reaches. It is worth noting that the negative contribution of climate change varies significantly between upstream and downstream (36.18% in the upstream and 27.03% in the downstream), reflecting that the vegetation in the upstream is more sensitive to climate change, and that the risk of degradation may be exacerbated by extreme drought events. In addition, the negative contribution rate of human activities is highest in the downstream, at 8.63%, implying that the inhibitory effect of urbanization and land expansion for construction on vegetation is more prominent in the downstream.

III. C. 2) Main impact factors

Analyzing on the prediction model of climate factors on the vegetation in the main urban area of Nanjing, both temperature (R=0.473, $p<0.05$) and precipitation (R=0.672, $p<0.01$) have a significant positive correlation with NDVI, and the correlation between temperature and vegetation is even closer. The main influence factors of human activities on the vegetation changes in the Fen River source area include five aspects: agricultural expansion, urbanization and construction land expansion, afforestation and reforestation, improvement of irrigation facilities, and industrial and mining development. The correlation coefficients of the main influence factors of human activities on the NDVI of vegetation changes in the Fen River source area are shown in Table 2.

Table 2: Correlation coefficient between the human activity impact factor and NDVI

	Agricultural expansion	Urbanization and the expansion of construction land	Afforestation and returning farmland to forest	Perfect irrigation facilities	Industrial and mining development
Upstream	0.496	-0.422	0.505	0.465	-0.309
Midstream	0.543	-0.451	0.559	0.463	-0.354
Downstream	0.665	-0.492	0.507	0.538	-0.392
Average	0.568	-0.455	0.524	0.489	-0.352

Table 2 reveals the correlation coefficients between different anthropogenic factors and vegetation NDVI. Agricultural expansion contributed most significantly to vegetation cover, with a downstream correlation coefficient of 0.665, indicating that agricultural intensification (e.g., expansion of irrigated farmland) significantly enhanced vegetation productivity. Afforestation and returning farmland to forest also showed significant positive correlation, with an average R=0.524, with the highest correlation coefficient of 0.559 in the middle reaches, confirming the effectiveness of ecological projects in the region. In contrast, urbanization and construction land expansion had a significant inhibitory effect on vegetation cover, with a correlation coefficient of -0.492 in the downstream, probably due to the crowding out of ecological land by urban expansion. The negative impact of industrial and mining development was small in the upstream, R=-0.309, but intensified in the downstream, R=-0.392, reflecting the destructive effect of intensive industrial activities on vegetation in the downstream. Improved irrigation facilities were positively correlated with NDVI, with R=0.489 in the Fen River headwaters area as a whole, and R=0.538 especially in the downstream, suggesting that water resource management is crucial for vegetation restoration. Overall, agricultural expansion and ecological engineering were the main anthropogenic factors contributing to vegetation cover, while urbanization and industrialization were key inhibitors.

IV. Conclusion

In this study, the temporal and spatial evolution of vegetation cover and its driving mechanism in the Fen River Basin from 2010 to 2024 were systematically analyzed through nonlinear regression modeling and multi-source data fusion, and the main conclusions are as follows.

The vegetation cover of the Fen River Basin showed an overall upward trend from 2010 to 2024, with 74.31% of improved areas and 13.99% of degraded areas. The proportion of high-coverage area increased from 25.30% to 37.98%, and the low-coverage area decreased by 85.3%, among which the recovery of vegetation in the middle and lower reaches of the river was particularly significant, with an increase of 29.94% in the middle reaches and 30.50% in the lower reaches. This trend is closely related to climate warming and humidification and ecological engineering synergy.

Precipitation and air temperature are the key climate factors for vegetation change, and the bias correlation coefficients of NDVI with precipitation and air temperature in the whole basin are 0.672 and 0.473, respectively. Vegetation growth in the upper reaches was highly dependent on precipitation with a bias correlation coefficient of 0.702, while the lower reaches were more significantly driven by temperature (0.633), which may be related to the alleviation of water limitation by irrigated agriculture.

The positive contribution of climate change to vegetation improvement averaged 53.10%, with a maximum of 59.92% in the downstream, while the contribution of human activities was 9.40%. The average correlation coefficient of agricultural expansion (0.568) and afforestation (0.524) were the main contributing factors, but the correlation coefficient of downstream urbanization (-0.492) and industrial development (-0.392) led to a negative contribution of 8.63%, highlighting the squeezing effect of construction land expansion on ecological space.

Funding

This work was supported by the Innovation and Entrepreneurship Training Program for College Students in Shanxi Province (20240625).

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