RESPONSES OF SATELLITE OBSERVED VEGETATION GREENNESS TO CLIMATE CHANGE AND HUMAN ACTIVITY IN A SEMI-ARID BASIN OF NORTH CHINA

CHANG, T. Y.[1] – WANG, J. Q.[1] – SUN, W. C.[1*] – WANG, Z. C.[2]

[1]*Beijing Key Laboratory of Urban Hydrological Cycle and Sponge City Technology, College of Water Sciences, Beijing Normal University, Xinjiekouwai Street 19, Beijing 100875, China*

[2]*Chinese Research Academy of Environmental Sciences, Environmental Technology & Engineering Co. Ltd., Beijing 100012, China*
(phone/fax: + 86-10-8491-5158)

**Corresponding author*
e-mail: sunny@bnu.edu.cn; phone/fax: +86-10-5880-2736

(Received 23rd Jan 2024; accepted 28th Jun 2024)

Abstract. Changes in vegetation growth are important indicators of health of terrestrial ecosystems. Located in China's semi-arid and semi-humid transitional zone, the Fenhe River Basin is the second largest tributary of the Yellow River, which is vital for soil and water conservation in the Loess Plateau. In this study, based on the Normalized Difference Vegetation Index (NDVI) and meteorological data during 1982-2015, we evaluated the spatial-temporal distribution and changes in the vegetation greenness and meteorological variables in the Fenhe River Basin before and after the Grain for Green Program (GGP), in order to reveal the driving factors of changes in vegetation growth, and then quantify their relative contributions. The results show that since the GGP being implemented in 1999, the vegetation coverage in the Fenhe River Basin has significantly improved. Climate change and human activities are two important factors affecting the vegetation greenness detected from NDVI and the combined effects of the two factors play a leading role in NDVI change. After the implementation of GGP, the influence of climate on NDVI change has weakened, and the area proportion of human activities improving vegetation growth has raised significantly. This study is valuable for providing knowledge about the dynamic changes of vegetation in the Fenhe River Basin under the influence of climate change and human activities, and provides decision support information for vegetation restoration and sustainable development in the Fenhe River Basin.
Keywords: *Fenhe River Basin, changes in vegetation greenness, climate change, human activity, normalized difference vegetation index*

Introduction

As a crucial component of the terrestrial ecosystem, vegetation plays an important role in the terrestrial energy exchange (Shi et al., 2021), soil and water conservation (Guo et al., 2020), and carbon cycles (Xu et al., 2020). As a sensitive indicator, vegetation change is typically used to assess environmental conditions (Deng et al., 2019). In the past few decades, global climate has undergone significant changes, thus along with its impact on vegetation change it gained the broad attention (Chen et al., 2015; Guo et al., 2021). In addition to climate change, human activities have also greatly altered vegetation cover (Shi et al., 2021). Consequently, in the context of climate change and human activities, revealing the mechanisms of vegetation change and its driving factors is of great significance for the development of ecological protection strategies.

Precipitation and temperature are two key factors in studying the mechanisms of vegetation change (He et al., 2015). Potter et al. (1998) explored the driving factors of

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

global vegetation change and the results show that precipitation and soil moisture content accounted for 70% to 80% of the impact on vegetation. Satellite observation data in the past forty years indicate that with the increase of global temperature, there are significant differences in vegetation structure and coverage in different temperature zones in the Northern Hemisphere (Myneni et al., 1997; Nemani et al., 2003). In addition, with the increasing population and the continuous development of urbanization, the human impact is significant. On the one hand, overgrazing and overcultivation have caused vegetation degradation, and human overexploitation of natural resources have reduced vegetation coverage and disrupted the balance of the ecosystem (Feng et al., 2021). On the other hand, in order to solve ecosystem degradation problems, a series of ecological restoration projects have been carried out. Among them, the Grain for Green Program (GGP) of China was implemented on the Loess Plateau in 1999 with the aim of reducing soil erosion and improving the ecological environment in western China, which significantly improved vegetation coverage by afforestation and grass planting in farmland areas prone to soil erosion and desertification (Feng et al., 2016).

Exploring the impact of climate and human activities on vegetation requires long-term monitoring, but traditional vegetation monitoring methods are time-consuming and labor-intensive (Tong et al., 2019). The development of remote sensing technology has enabled efficient and accurate dynamic monitoring of large-scale vegetation cover. Currently, vegetation monitoring research mainly relies on vegetation indices (Hess et al., 1996). The recognized effective index in vegetation dynamic monitoring research is the NDVI (Normalized Difference Vegetation Index), which is widely used in various studies related to vegetation (Sun et al., 2015). The NDVI was obtained by calculating the ratio of the difference between the near-infrared and red-light bands and the sum of the two, with values ranging from -1 to 1 (Rouse et al., 1974). When NDVI is negative, it indicates no vegetation cover or other surface cover, while the opposite indicates vegetation cover, and the higher value means greater vegetation density (Myneni et al., 1995). With the rapid development of remote sensing technology, many reliable NDVI dataset can be obtained based on different satellite sensors. And many researches have been made in the use of NDVI data for dynamic monitoring of vegetation at different scales (Myneni et al., 1997; Sun et al., 2019; Wang et al., 2012; Wu et al., 2014). The Basin defines all areas that discharge water to the specific basin outlet and is one of the most important research scales for freshwater resource management (Vicuna et al., 2010). The imbalance between water supply and demand in arid and semi-arid regions is noticing, and exploring the driving factors of vegetation change can lead to better understand hydrological processes. Studying vegetation changes and their driving factors in arid and semi-arid basins is of great significance for both water resources management and ecosystem restoration (Sun et al., 2019).

The Fenhe River Basin is the second largest tributary of the Yellow River and is located in the semi-arid and semi-humid transition zone of China. As an independent watershed unit in the eastern part of the Loess Plateau, it is a key implementation area of the GGP, but there are relatively fewer studies investigating how vegetation cover changes in this area. The objective of this study is to explore how the vegetation greenness of the Fenhe River Basin changes before and after the implementation of the GGP, and how meteorological factors and human activities contributed to the changes in vegetation cover. In this study, the implementation of GGP was considered

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

as a temporal changing point, the spatiotemporal distribution and change characteristics of vegetation and meteorological elements were analyzed based on long-term NDVI and meteorological data from 1982 to 2015, then the impacts of climate change and human activities on NDVI changes were quantified. The findings from this study could provide important knowledge for decision-making on terrestrial ecosystem protection in the Fenhe River Basin and other similar basins in arid and semi-arid regions.

Material and methods

Study area

The Fenhe River Basin is the largest river in Shanxi Province, China and the second largest tributary of the Yellow River Basin. It is located in the eastern part of the Loess Plateau (110.5-113.5° E, 35.3-39.0° N), with an area of 39,471 km², accounting for 25.3% of the total area of Shanxi Province. The Fenhe River Basin is located between the Lvliang Mountains and the Taihang Mountains, with significant terrain fluctuations within the region. The overall terrain shows high in the north and low in the south, with an elevation range of 365-2687 m (*Fig. 1*). The Fenhe River flows from north to south through 8 prefecture level cities in Shanxi Province, including Xinzhou, Taiyuan, Jinzhong, lvliang, Changzhi, Linfen, Yuncheng, and Jincheng City (*Fig. 2*). *Figure 3* shows the land use of the Fenhe River Basin in 1982, 1999, and 2015, using GLASS-GLC data (available at: https://doi.pangaea.de/10.1594/PANGAEA.913496) with a resolution of 5 km. It is found that cropland, forest and grassland are three major land use types in the basin.

Data sources and processing

NDVI data

In this study, the NDVI was used as the indicator for the spatiotemporal distribution and change characteristics of vegetation cover in the Fenhe River Basin. The GIMMS NDVI3g data were observed by the Global Monitoring and Simulation Research Group at NASA’s Goddard Space Center, and is more effective than previous data in monitoring vegetation (Wang et al., 2014). This dataset provides relatively standard long series NDVI data on a global scale since 1981 with a spatial resolution of 8 km and a temporal resolution of 15 days. In this study, the monthly NDVI data of the Fenhe River Basin from 1982 to 2015 were obtained based on the maximum value synthesis method (Li et al., 2016) and then annual average values were computed after the data were converted into GeoTIFF format and WGS1984 coordinate system.

Meteorological data

To ensure the uniformity and consistency of the spatial distribution of meteorological data in the research area, the research has selected the monthly rainfall (mm) and average temperature (℃) data for the 12 meteorological stations located in the Fenhe River Basin and adjacent regions from 1982 to 2015 (*Fig. 1*). The data are available on the China Meteorological Data Sharing Service (http://data.cma.cn/). The inverse distance weighting method was used for spatial interpolation to obtain grid scale meteorological data of the Fenhe River Basin, with a spatial resolution of 8 km.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

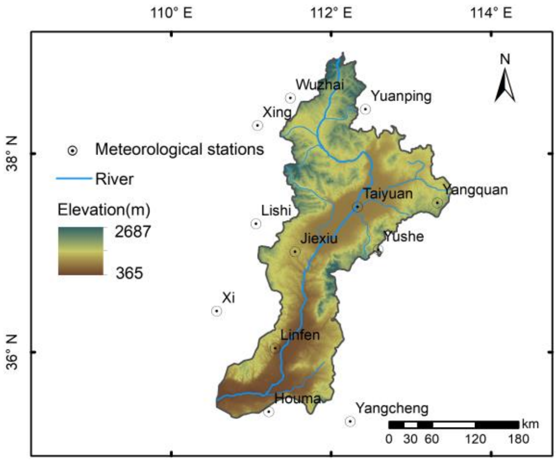

Figure 1. *Topography and meteorological stations of the Fenhe River Basin in China*

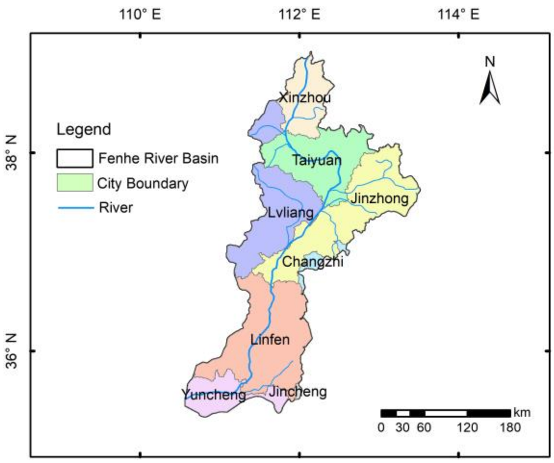

Figure 2. *Boundary of prefecture level cities in the Fenhe River Basin*

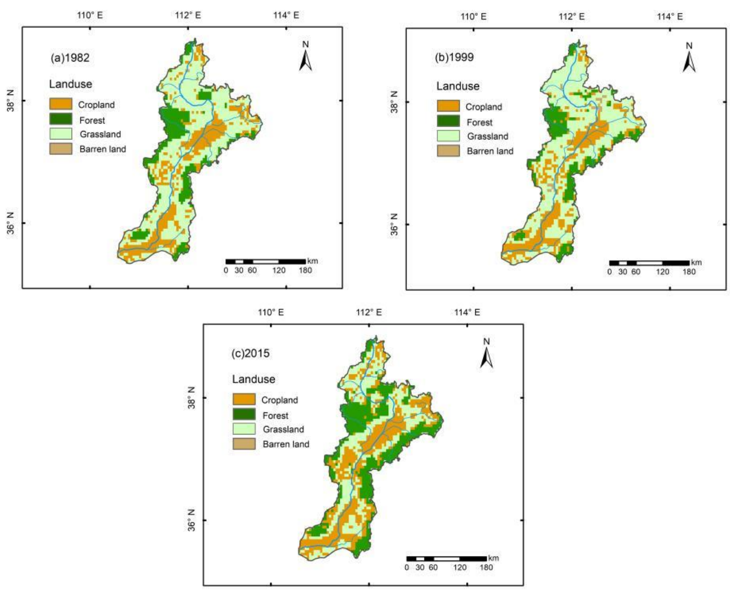

Figure 3. *Land use map of the Fenhe River Basin for (a) 1982, (b) 1999, and (c) 2015*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

Methods

Trend analysis method

To explore the spatiotemporal variation trends of vegetation cover and meteorological elements in the Fenhe River Basin, this study used the univariate linear regression method for analysis. This method is widely used in research on vegetation cover and meteorological element changes as follows:

$$y_i = a + slope \times x_i + \xi_i \tag{Eq.1}$$

$$slope = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{Eq.2}$$

where y_i represents NDVI or meteorological variables at the *i*th year; *a* is the intercept; *slope* is the annual trend slope of change; x_i is the time; ξ_i indicates error; *n* represents the total number of years during the research period; $\bar{x}$ and $\bar{y}$ are the average values of *x* and *y*.

Multiple regression residual analysis

This study used multiple regression residual analysis method to explore the response of NDVI to climate change and human activities. It is assumed that meteorological factors affecting changes in vegetation NDVI are precipitation and temperature, and that non-meteorological factors influence the vegetation NDVI mainly through human activities such as afforestation and urbanization. Multiple regression residual analysis method is widely used in the study of driving forces of vegetation cover change, and its calculation process includes the following three steps: (a) Establish a linear regression equation with NDVI as the dependent variable and precipitation and temperature as the independent variables, and calculate the values of each parameter in the model; (b) Substitute measured meteorological data into the model for calculation to obtain NDVI predicted values, which are used to represent the impact of climate change on vegetation NDVI; (c) The difference between the measured and predicted NDVI values is used to represent the impact of human activities on vegetation NDVI. The calculation formulas are as follows:

$$NDVI_{CC} = a \times P + b \times T + c \tag{Eq.3}$$

$$NDVI_{HA} = NDVI_{obs} - NDVI_{CC} \tag{Eq.4}$$

where $NDVI_{CC}$ represents the computed *NDVI* due to climate change; *a*, *b* and *c* are parameters; *P* and *T* represent precipitation and temperature, respectively, with units of mm and °C; $NDVI_{HA}$ is the computed *NDVI* due to human activity; $NDVI_{obs}$ is the real *NDVI* derived from satellite observations.

Analysis of contributions of climate change and human activity on vegetation growth

Applying the univariate linear regression method, the slope of $NDVI_{CC}$ ($Slope(NDVI_{CC})$), $NDVI_{HA}$ ($Slope(NDVI_{HA})$) and $NDVI_{obs}$ ($Slope(NDVI_{obs})$) were computed. Based on different combinations of $Slope(NDVI_{obs})$, $Slope(NDVI_{CC})$ and $Slope(NDVI_{HA})$,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

the contributions of climate change and human activities on vegetation growth are quantified under 6 different situations, as shown in *Table 1*. In the cases that values of $Slope(NDVI_{obs})$, $Slope(NDVI_{CC})$ and $Slope(NDVI_{HA})$ are all positive or negative, it is considered that the changes in vegetation growth are caused by the combined effects of climate change and human activities. Their relative contributions are computed as follows:

$$Con_{CC} = \frac{Slope\ (NDVI_{CC})}{Slope\ (NDVI_{obs})} \tag{Eq.5}$$

$$Con_{HA} = \frac{Slope\ (NDVI_{HA})}{Slope\ (NDVI_{obs})} \tag{Eq.6}$$

where Con_{CC} and Con_{HA} represent the relative contributions of climate change and human activities to NDVI change, respectively. For the other 4 cases in *Table 1*, the changes of NDVI are considered by either climate change or human activities, alone, for which the contribution is regarded as 100%.

Table 1. *Methods for assessing the relative contributions of climate change (CC) and human activities (HA)*

Situations of detected slope of $NDVI_{obs}$	**Situations of detected slope of $NDVI_{CC}$ and $NDVI_{HA}$**		**Identified driving factors**	**Relative contribution (%)**	
	$Slope(NDVI_{CC})$	**$Slope(NDVI_{HA})$**		***CC***	***HA***
> 0	> 0	> 0	*CC and HA*	$\frac{Slope(NDVIcc)}{Slope(NDVIobs)}$	$\frac{Slope(NDVI_{HA})}{Slope(NDVIobs)}$
	> 0	< 0	*CC*	100	0
	< 0	> 0	*HA*	0	100
< 0	< 0	< 0	*CC and HA*	$\frac{Slope(NDVIcc)}{Slope(NDVIobs)}$	$\frac{Slope(NDVI_{HA})}{Slope(NDVIobs)}$
	< 0	> 0	*CC*	100	0
	> 0	< 0	*HA*	0	100

Results

Spatiotemporal distributions and trends of the normalized difference vegetation index

In *Figure 4*, it can be seen that the NDVI in the western and southeastern areas of the Fenhe River Basin generally decreased in 1999 compared to 1982. In 2015, vegetation NDVI increased significantly in the whole Fenhe River Basin, especially the proportion of vegetation NDVI value above 0.70 in the eastern and western parts of the basin expanded, and the vegetation NDVI value in the central part of the basin also basically reached above 0.30.

The average NDVI of the Fenhe River Basin from 1982 to 2015 was 0.384, of which the average NDVI from 1982 to 1999 was 0.370. After the implementation of The Grain for Green Project in the Loess Plateau region in 1999, the average NDVI increased to 0.40 from 2000 to 2015. The NDVI of the Fenhe River Basin ranged from 0.07 to 0.70. *Figure 5* shows that the distribution of average NDVI from 1982 to 1999 and 2000 to 2015 was generally high in the eastern and western regions and low in the middle of the basin. After the implementation of the GGP, the area with low NDVI in the upper and

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

middle reaches of the Fenhe River Basin was significantly reduced. The higher NDVI values in *Figure 5b* compared with those in *Figure 5a* indicate that the vegetation cover of the Fenhe River Basin has been significantly improved after the GGP Project.

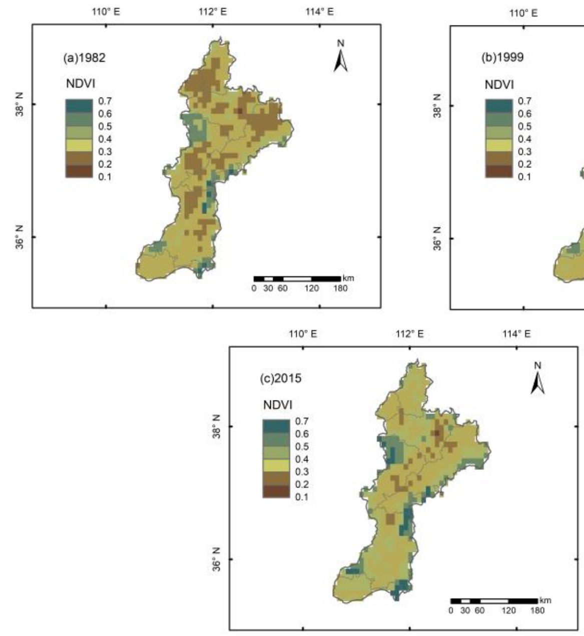

Figure 4. *Spatial distribution of annual NDVI of the Fenhe River Basin for (a) 1982, (b) 1999, and (c) 2015*

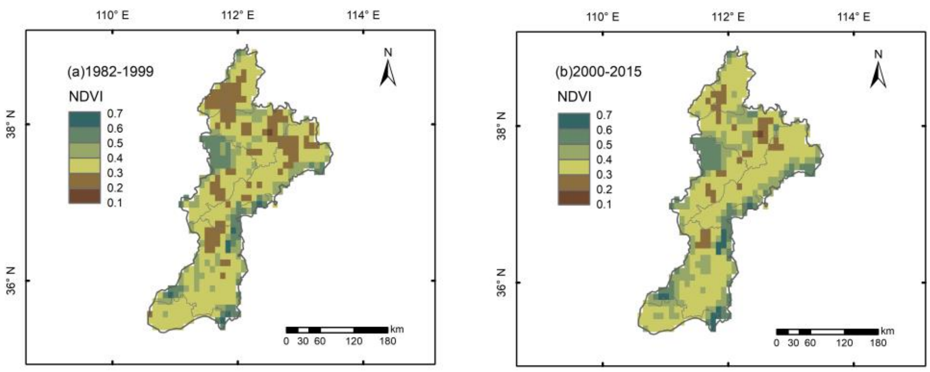

Figure 5. *Spatial distribution of average annual NDVI values (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

The inter-annual trend of NDVI for the whole Fenhe River Basin from 1982 to 2015 is shown in *Figure 6*, from which it can be seen that the regional average NDVI values ranged from 0.35 to 0.44. The overall NDVI showed a significant increasing trend in the last 34 years, and the inter-annual trend slope was 0.017/10a. Taking the implementation of GGP as the demarcation point and dividing the whole period into two phases, it can be seen that in the first phase (1982-1999), the NDVI value was relatively small, and the overall trend showed only a statistically insignificant increase, and the inter-annual trend slope of change was only 0.003/10a. In the second stage (1999-2015), the NDVI showed a significant increasing trend which reached 0.049/10a,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

and the increase slope was about 16 times of the previous period, among which the NDVI value increased most obviously in 2007-2008, and the average value of NDVI in the Fenhe River Basin reached more than 0.40 in a few years after the implementation of the GGP in 1999. In 2014 the NDVI reached a peak of 0.43. Overall, vegetation cover in the Fenhe River Basin has improved significantly since 1999.

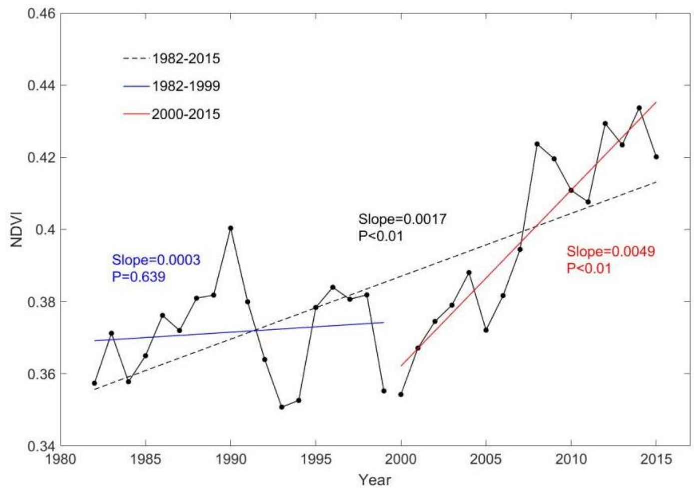

Figure 6. *Basin averaged inter-annual variations of the annual average normalized difference vegetation index (NDVI) for the period of 1982-2015 in the Fenhe River Basin*

Trends of NDVI at pixel scale were also analyzed (*Fig. 7*). The change of NDVI in the Fenhe River Basin from 1982 to 2015 showed obvious spatial heterogeneity. Before the implementation of the GGP, the trend slope of NDVI change ranged from -0.004/a to 0.003/a, among which 60.4% of pixels showed an increasing trend of vegetation cover, mainly concentrated in the upper and lower reaches of the Fenhe River Basin. The areas showing a decreasing trend accounted for 39.6%, mainly concentrated in the middle reaches of the Fenhe River Basin, especially in Lvliang and Changzhi City. After the implementation of the GGP in the Fenhe River Basin, the trend of NDVI increased to -0.002-0.010/a, and the vegetation cover of the Fenhe River Basin increased significantly, and the proportion of the area with the increasing trend expanded to 97.1%.

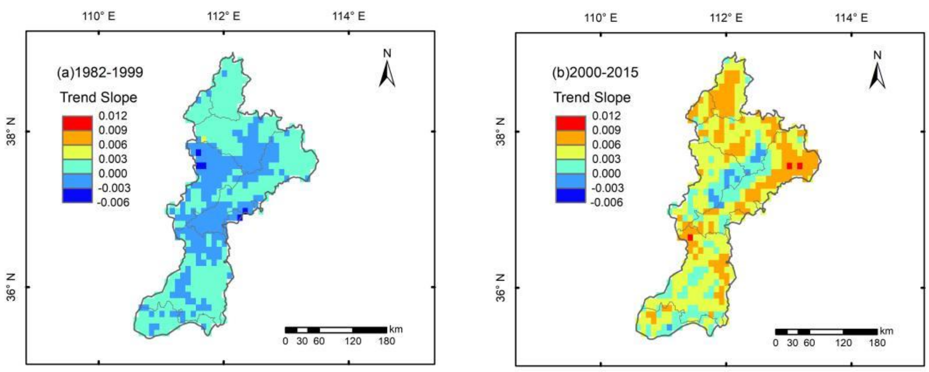

Figure 7. *Trends of NDVI at pixel scale (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

Spatiotemporal distributions and trends of meteorological elements

Figure 8 shows the spatial distribution of precipitation in the Fenhe River Basin in the year of 1982, 1999 and 2015. At the basin scale, it is shown that the precipitation gradually decreases from southeast to northwest. The average annual precipitation in the Fenhe River Basin from 1982 to 2015, 1982 to 1999, and 1999 to 2015 was 525.9 mm, 526.2 mm and 525.6 mm, respectively, indicating little change in precipitation. *Figure 9* shows the precipitation for the periods of 1982 to 1999, and 1999 to 2015, and it is found that the minimum value of annual precipitation appears in the middle reaches of the basin. By comparing the two figures, it was found that there was little difference in the spatial distribution of annual precipitation in the study area before and after 1999.

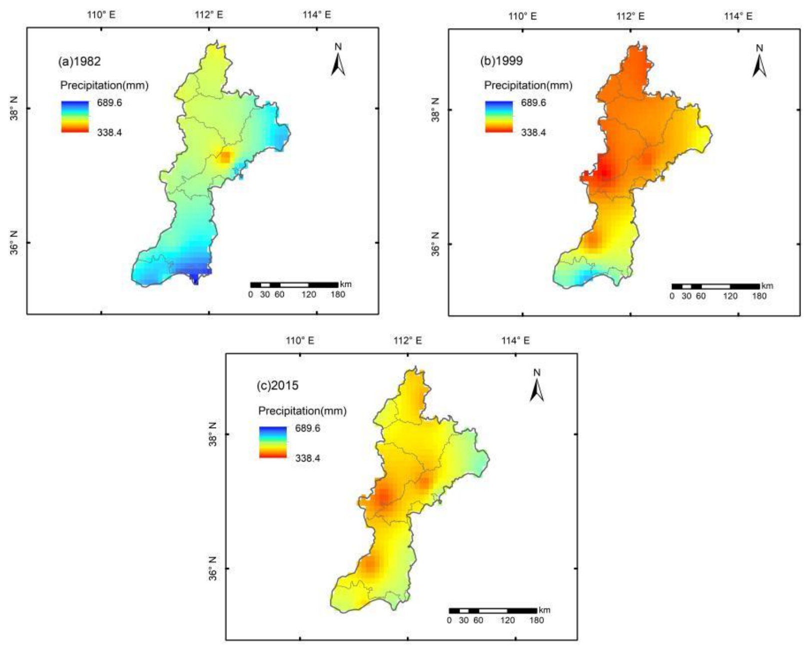

Figure 8. *Spatial distribution of annual precipitation of the Fenhe River Basin for (a) 1982, (b) 1999, and (c) 2015*

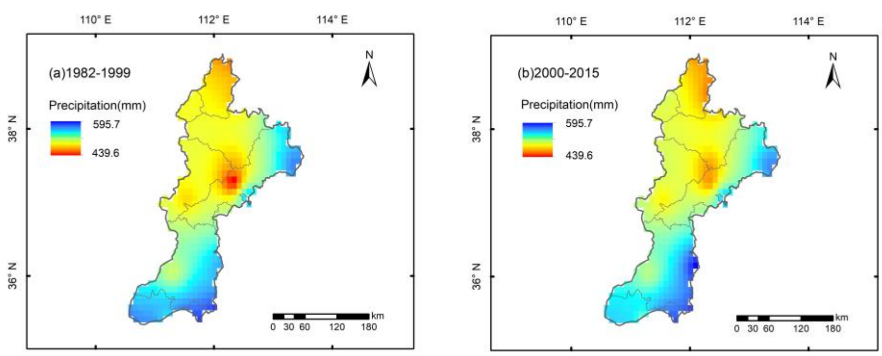

Figure 9. *Spatial distribution of average annual precipitation (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

The precipitation values of the Fenhe River Basin from 1982 to 2015 were within the range of 340-700 mm, and the annual precipitation showed only a statistically

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

insignificant decreasing trend in the last 34 years (*Fig. 10*), with an average decrease slope of -0.575 mm/a. Taking the nodes before and after the implementation of GGP as two stages, it can be seen that that in the first stage, i.e., from 1982 to 1999, the inter-annual change of precipitation in the study area was uneven, with great fluctuations. It showed a statistically insignificant decreasing trend, with an inter-annual decreasing trend slope of -5.738 mm/a. Additionally, the annual precipitation in 1997 reached the lowest value of the period (342.2 mm). In the second stage, after the implementation of GGP, the annual precipitation in the Fenhe River Basin showed a statistically insignificant increasing trend, with a slope of 2.861 mm/a.

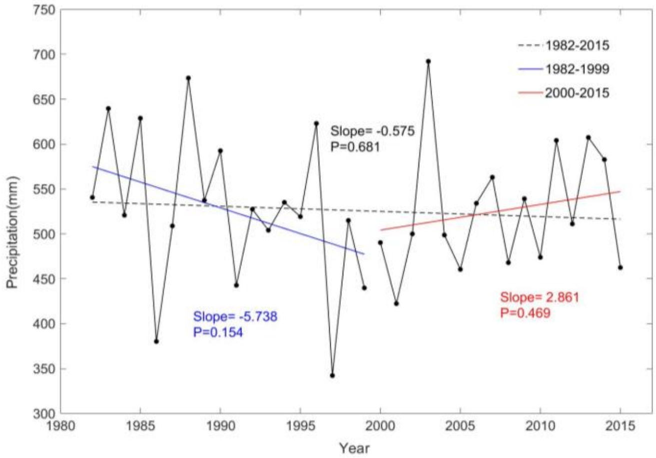

Figure 10. *Basin averaged inter-annual variations of annual total precipitation for the period of 1982-2015 in the Fenhe River Basin*

The trend of annual precipitation in each pixel in the study area was also analyzed. *Figure 11* shows the trends of annual precipitation before and after the implementation of GGP. From 1982 to 1999, the trend slope of annual precipitation in the Fenhe River Basin ranged from -12.4 mm/a to 0.6 mm/a, and almost the whole Fenhe River Basin showed a decreasing trend in precipitation. From 2000 to 2015, the precipitation in the study area generally increased in most areas. The annual precipitation range of the region increased to -2.1-6.1 mm/a, and the proportion of pixels with an increasing trend of precipitation in the region was as high as 96.7%. Among them, the increases of annual precipitation in Xinzhou, Taiyuan, lvliang and Jinzhong City were relatively high.

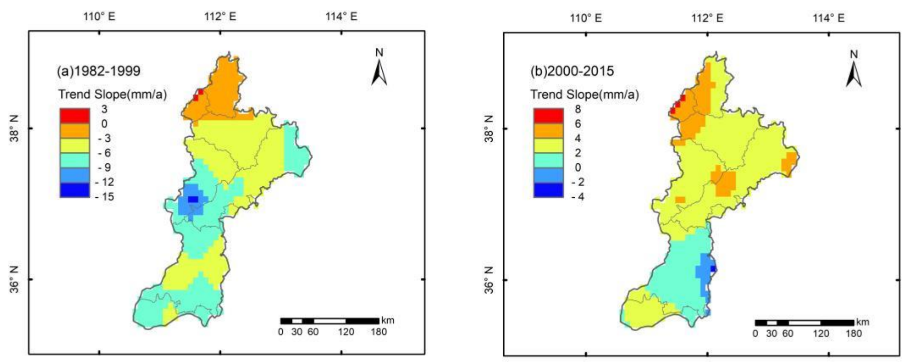

Figure 11. *Trends of annual precipitation at pixel scale (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

Figure 12 shows that the temperature in the Fenhe River Basin exhibits a gradually increasing trend from upstream to downstream. The temperature in 1999 was significantly higher than that in 1982, with the pixels with the highest temperature located in the southwest of Linfen City, downstream of the river basin. The temperature distribution characteristics of the basin in 2015 were basically consistent with those of 1999.

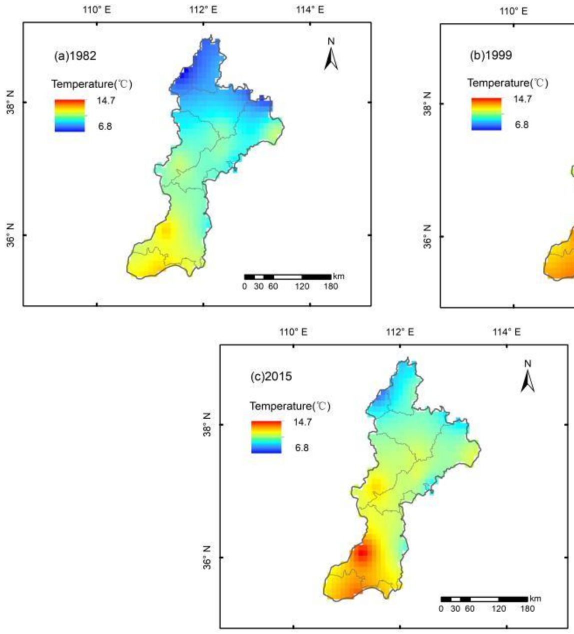

Figure 12. *Spatial distribution of average temperature of the Fenhe River Basin for (a) 1982, (b) 1999, and (c) 2015*

The annual average temperature in the Fenhe River Basin was 10.5°C for the period of 1982 to 2015, of which the average temperature was 10.1℃ for the period of 1982 to 1999, and increased to 10.8°C for the period of 2000 to 2015 (*Fig. 13*). Before the implementation of the GGP, the lowest annual average temperature of the Fenhe River Basin appeared in the north of Lvliang City, with a value of 6.8°C. After the implementation of the GGP, the average annual temperature in the study area becomes higher, especially in the north of Lvliang and Jinzhong City in the upper reaches of the basin and Linfen City in the lower reaches of the basin.

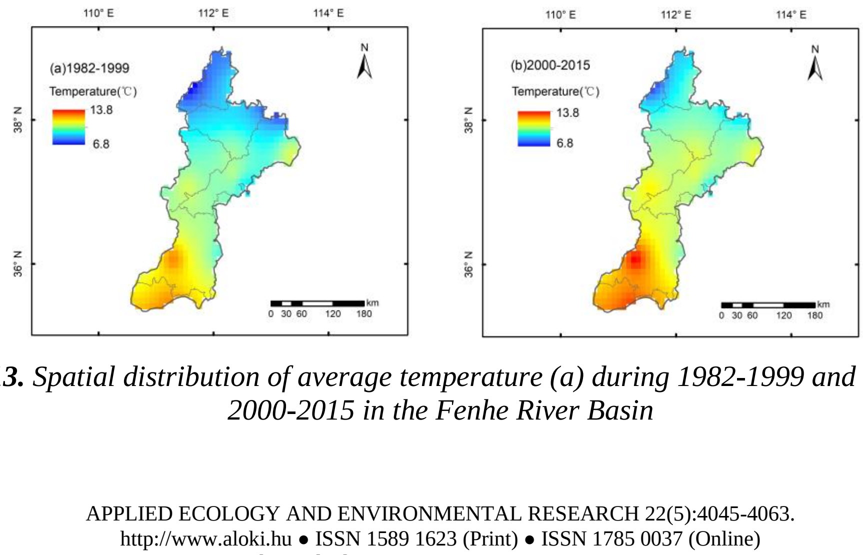

Figure 13. *Spatial distribution of average temperature (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

From *Figure 14*, it is shown that for the whole period of 1982 to 2015, the annual average temperature at the basin scale took on a statistically significant increasing trend, with a slope of 0.045°C/a. It can be seen that for the period of 1982 to 1999, the average temperature showed a significant upward trend with obvious inter-annual fluctuation, with a slope of 0.085°C/a, while for the period of 2000 to 2015, an insignificant increasing trend was observed with a slope of 0.009°C/a, and the average temperature basically fluctuated around 10.8°C.

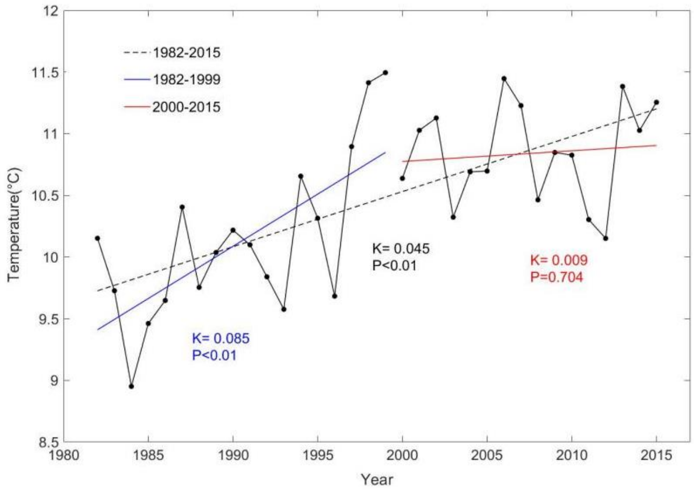

Figure 14. *Basin averaged inter-annual variations of annual average temperature for the period of 1982-2015 in the Fenhe River Basin*

The spatial distribution of trends in temperature were also explored at pixel scale (*Fig. 15*). For the period of 1982 to 1999, the annual average temperature of the entire region all showed an upward trend with different degree. The annual average temperature increased at the fastest rate in Xinzhou, Taiyuan, and the northern region of Jinzhong City in the upper reaches. For the period of 2000 to 2015, 94.8% of the study area showed an increase in temperature, especially in the central and western parts of Jinzhong City and southern part of Lvliang City, and southwestern Linfen City, while the trend slope decreased compared with the period of 1982 to 1999.

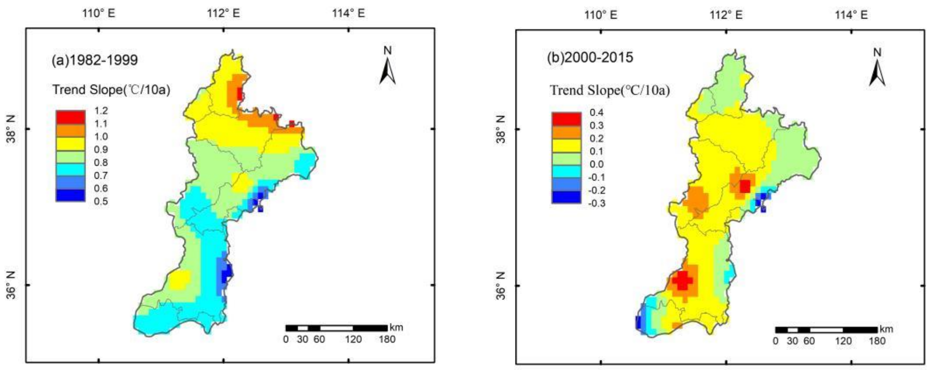

Figure 15. *Trends of temperature at pixel scale (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

Driving factors of the normalized difference vegetation index change

Figure 16a and *Table 2* show that before the implementation of GGP, the increase of vegetation NDVI in the Fenhe River Basin was mainly caused by the joint effects of climate change and human activities, which accounted for 39.2% of the basin area. The regions that increases of NDVI caused by climate change and human activities alone occupy 9.7% and 11.6% of the basin area, respectively. The area of NDVI reduction caused by climate change and human activities accounted for 24.7% of the study area, mainly distributed in the middle reaches of the Fenhe River Basin, while the area of NDVI reduction caused by climate change accounted for 10.0%, scattered in Changzhi, Lvliang and Taiyuan City. *Figure 16b* and *Table 2* show that after the implementation of the GGP, the area of NDVI change caused by synergistic influences of climate change and human activities accounted for 83.3% of the total basin area, indicating a leading role in the change of NDVI. Their effects caused an increase in NDVI in 80.7% of the basin area. The areas where human activities alone contributed to the NDVI increase were mainly located in the middle reaches of the Fenhe River Basin, accounting for 16.4% of the basin area.

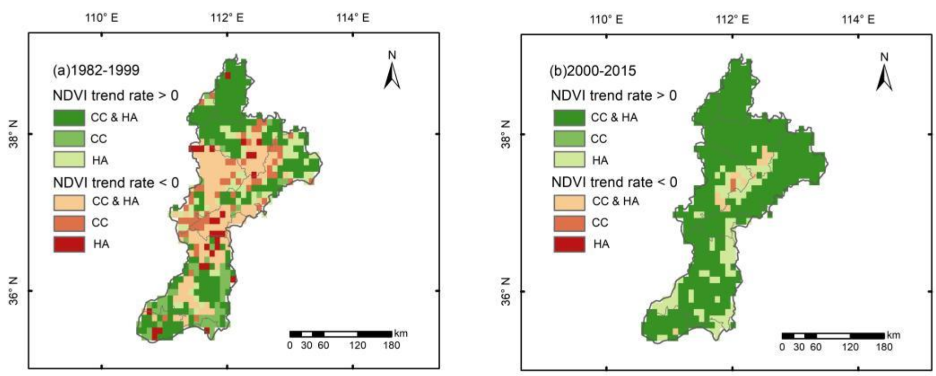

Figure 16. *Spatial distribution of vegetation cover changes driven by climate change (CC) and human activities (HA) (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

Table 2. *The ratios of area that changes in NDVI driven by climate change (CC) and human activities (HA) to the total basin area*

Detected slope of $NDVI_{obs}$	**Driving factors**	**Area proportion (%)**	
		1982-1999	**2000-2015**
> 0	*CC&HA*	39.2	80.7
	CC	9.7	0
	HA	11.6	16.4
< 0	*CC&HA*	24.7	2.6
	CC	10.0	0.4
	HA	4.8	0

The contributions of climate change on vegetation greenness were further quantified in *Figure 17* and *Table 3*. Before the implementation of GGP, climate

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

change promoted the growth of vegetation NDVI in 48.9% of the area, and the relative contribution was evenly distributed in areas with different contribution degrees, mainly in the upper and lower reaches of the Fenhe River Basin. The area of the decreasing of NDVI caused by climate change accounted for 51.1% of the total basin area, mainly distributed in the middle reaches of the Fenhe River Basin. *Figure 17b* and *Table 3* show that after the implementation of GGP, 80.7% of vegetation greenness increase in the region was related to climate change, while its contribution was mainly in the range of 0-20%, accounting for 78.8% of the total area. The percentage of the region where climate change had a negative influence on vegetation growth was 19.3%, mainly located in Taiyuan and Lvliang City, and the relative contribution was mainly within -20-0%.

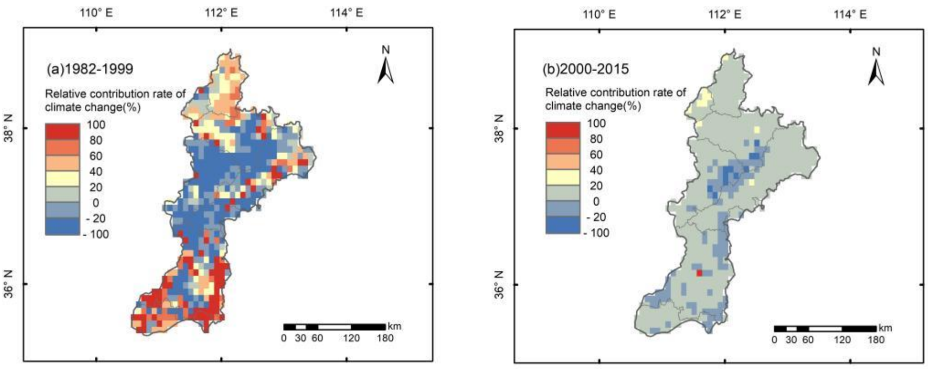

Figure 17. *Spatial distribution of contributions of climate change to vegetation growth (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

Table 3. *The proportions of basin area with different levels of contribution of climate change to vegetation greenness*

Relative contribution of human activities	**Range of relative contributions（Percentage）**						
	< -20	**-20-0**	**0-20**	**20-40**	**40-60**	**60-80**	**⩾ 80**
Percentage of basin area for 1982-1999	32.0	19.2	7.1	10.2	11.6	6.9	13.1
Percentage of basin area for 2000-2015	1.9	17.4	78.8	1.7	0.00	0.00	0.2

The contributions of human activities on changes in NDVI were also evaluated. *Figure 18* and *Table 4* show that before the implementation of GGP, the area where human activities contributed to the increase of vegetation NDVI accounted for 50.8% of the total study area, and in most of these areas, the relative contribution was larger than 40%. The areas with contribution greater than 80% were concentrated in Xinzhou, Taiyuan and Jinzhong City. The pixels that human activities having negative influences on NDVI accounted for 49.2% of the total basin area, and mainly located in the northern and central parts of the basin. After the implementation of GGP, the percentage of the area where human activities contributed to the increase of NDVI basically covered the whole basin area (97.1%), for which the relative contribution was mostly larger than 80%.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

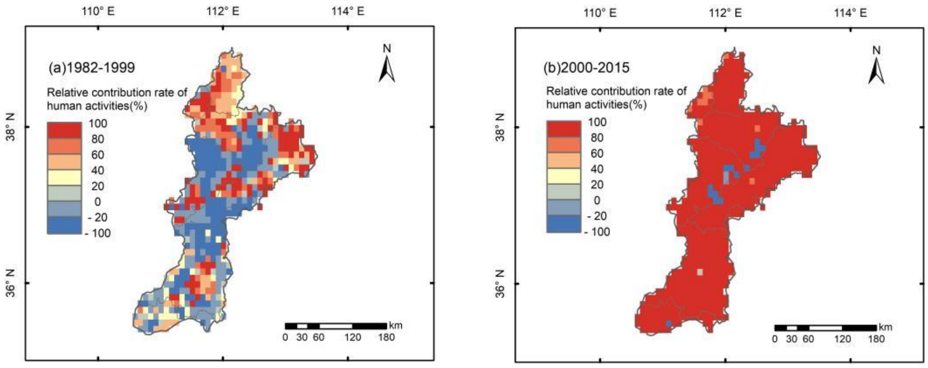

Figure 18. *Spatial distribution of the relative contributions of human activities to vegetation growth (a) during 1982-1999 and (b) during 2000-2015 in the Fenhe River Basin*

Table 4. *The proportions of basin area with different levels of contribution of human activities to vegetation greenness*

Relative contribution of human activities (%)	**Range of relative contributions（Percentage）**						
	< -20	**-20-0**	**0-20**	**20-40**	**40-60**	**60-80**	**⩾ 80**
Percentage of basin area for 1982-1999	26.4	22.8	3.5	6.9	11.6	10.2	18.7
Percentage of basin area for 2000-2015	2.6	0.4	0.2	0.00	0.00	1.7	95.2

Discussion

Precipitation and temperature are two important meteorological factors that determining the vegetation dynamic and phenological characteristics. The results indicated that at the basin scale, the precipitation took on an insignificant decreasing trend for the period of 1982 to 2015, which is consistent with the finding of Xie et al. (2016) for the whole Loess Plateau. For the temperature, a significant increase trend was found at the basin scale. The increasing slope was 0.447°C/10a, while the average value of China is 0.27°C/10a for the period of 1960-2014 (Cao et al., 2016), indicating that the magnitude of climate warming is more significant in the Fenhe River Basin. It is also found that after the implementation of the GGP, the slope of temperature upward trend decreased from 0.846°C/10a to 0.087°C/10a, which may imply the effects of vegetation cooling (Zeng et al., 2017). For the Fenhe River Basin, Zhang et al. (2022) found an increasing trend of NDVI derived from MODIS satellite products for the period of 2005 to 2020. With the use of GIMMS NDVI in this study, even the spatial resolution is lower than MODIS NDVI, it is possible to analyze the vegetation greenness as early as 1980s. An overall increasing trend of NDVI was found for the period of 1982 to 2015, and the slope of increase became higher after the implementation of the GGP, which is consistent with the general situation of the Loess Plateau (Sun et al., 2015; Zheng et al., 2019). The area ratios of major land use types are listed in *Table 5*. It is shown that the area covered by forest was about 18.1% of the whole basin area in 1982, and decreased to 15.9% in 1999, and then increased to 29.6% in 2015. The increases of forest area for the period of 2000 to 2015 may partially explain the accelerated rising trend of NDVI in this period.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

Table 5. *Area ratios of major land use types in 1982, 1999 and 2015*

Land use types	**Area ratios (%)**		
	1982	**1999**	**2015**
Cropland	27.1	28.0	36.3
Forest	18.1	15.9	29.6
Grassland	54.6	54.9	34.1

The impacts of climate change and human activities on vegetation cover changes are quantified for the period of 1982 to 1999 and 2000 to 2015, respectively. For the period of 1982 to 1999, the results showed that the areas where the relative contribution of climate change to the increase of vegetation NDVI higher than 80% were mainly concentrated in the southern part of the Fenhe River Basin, where precipitation was relatively abundant and temperature was relatively high. The areas where the relative contribution of climate change to the increases of NDVI was in the range of 40-80% were mainly distributed in the northwest of the study area, where precipitation showing an increasing trend. During 1982-1999, the inhibition effect of human activities on vegetation greenness was mainly detected in the middle and lower reaches of the Fenhe River Basin, which may be caused by the effect of urbanization. After the implementation of the GGP in 1999, the relative contribution of climate change to NDVI change for the pixels in the basin was mainly concentrated in 0-20%, indicating that the influence of climate on vegetation growth was weakened. In 95.2% of the basin area, relative contribution of human activities to the increase of NDVI is larger than 80%. It is demonstrated that the influences of human activities on vegetation growth became stronger than those of climate change in the period of 2000 to 2015. Many studies have found that ecological restoration projects like GGP in China improve regional ecological system security by improving vegetation quality (Xin et al., 2008; Zheng et al., 2019), increasing soil carbon storage (Chang et al., 2011), and reducing soil erosion (Deng et al., 2012). Therefore, for the Fenhe River Basin, GGP has a high possibility to be one of the dominant human activities to improve vegetation greenness detected from the GIMMS NDVI dataset.

Conclusion

Vegetation is an important component of terrestrial ecosystems, and its growth condition is an important indicator of regional ecological environment conditions. This study explored the vegetation growth of the Fenhe River Basin from 1982 to 2015 using NDVI data at both basin and pixel scales. The spatiotemporal distribution and change of vegetation cover and meteorological elements in the study area were analyzed, the main driving factors of NDVI changes in the study area were revealed, and their relative contributions were quantified. The results show that the vegetation growth in the study area has improved significantly after the implementation of GGP in 1999. From 1982 to 2015, NDVI showed an overall upward trend, and the annual trend slope of NDVI after the GGP reached 0.049/10a, approximately 16 times for the period of 1982 to 1999. While the annual average precipitation distribution in the Fenhe River Basin did not change significantly, and the temperature had an overall increasing trend. The analysis of the driving factors of vegetation change shows that climate change and human

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

activities played a leading role in the change of NDVI in the Fenhe River Basin from 1982 to 2015. For the period of 2000 to 2015, the impacts of climate on the change of NDVI weakened, and the area with increased NDVI caused by human activities accounted for 97.1% of the total basin area. It is indicated that, after the implementation of GGP, the vegetation coverage in the Fenhe River Basin has improved.

Acknowledgements. This study was supported by the National Key Research and Development Program of China (Grant no. 2022YFC3204403), National Natural Science Foundation of China (Grant nos. 52179002, 52394232).

REFERENCES

[1] Cao, L., Zhu, Y., Tang, G., Yuan, F., Yan, Z. (2016): Climatic warming in China according to a homogenized data set from 2419 stations. – International Journal of Climatology 36(13): 4384-4392.
[2] Chang, R., Fu, B., Liu, G., Liu, S. (2011): Soil carbon sequestration potential for “Grain for Green” project in Loess Plateau, China. – Environmental Management 48(6): 1158-1172.
[3] Chen, A., He, B., Wang, H., Huang, L., Zhu, Y., Lv, A. (2015): Notable shifting in the responses of vegetation activity to climate change in China. – Physics and Chemistry of The Earth 87-88: 60-66.
[4] Deng, C., Zhang, B., Cheng, L., Hu, L., Chen, F. (2019): Vegetation dynamics and their effects on surface water-energy balance over the Three-North Region of China. – Agricultural and Forest Meteorology 275: 79-90.
[5] Deng, L., Shangguan, Z., Li, R. (2012): Effects of the grain-for-green program on soil erosion in China. – International Journal of Sediment Research 27(1): 120-127.
[6] Feng, K., Wang, T., Liu, S., Yan, C., Kang, W., Chen, X., Guo, Z. (2021): Path analysis model to identify and analyse the causes of aeolian desertification in Mu Us Sandy Land, China. – Ecological Indicators 124.
[7] Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., Wu, B. (2016): Revegetation in China’s Loess Plateau is approaching sustainable water resource limits. – Nature Climate Change 6(11): 1019-+.
[8] Guo, E., Wang, Y., Wang, C., Sun, Z., Bao, Y., Mandula, N., Jirigala, B., Bao, Y., Li, H. (2021): NDVI indicates long-term dynamics of vegetation and its driving forces from climatic and anthropogenic factors in Mongolian Plateau. – Remote Sensing 13(4).
[9] Guo, M., Wang, W., Wang, T., Wang, W., Kang, H. (2020): Impacts of different vegetation restoration options on gully head soil resistance and soil erosion in loess tablelands. – Earth Surface Processes and Landforms 45(4): 1038-1050.
[10] He, B., Chen, A., Wang, H., Wang, Q. (2015): Dynamic response of satellite-derived vegetation growth to climate change in the three north shelter forest region in China. – Remote Sensing 7(8): 9998-10016.
[11] Hess, T., Stephens, W., Thomas, G. (1996): Modelling NDVI from decadal rainfall data in the North East Arid Zone of Nigeria. – Journal of Environmental Management 48(3): 249-261.
[12] Li, H., Li, Y., Gao, Y., Zou, C., Yan, S., Gao, J. (2016): Human impact on vegetation dynamics around Lhasa, Southern Tibetan Plateau, China. – Sustainability: 8(11).
[13] Myneni, R., Keeling, C., Tucker, C., Asrar, G., Nemani, R. (1997): Increased plant growth in the northern high latitudes from 1981 to 1991. – Nature 386(6626): 698-702.
[14] Myneni, R. B., Hall, F. G., Sellers, P. J., Marshak, A. L. (1995): The interpretation of spectral vegetation indexes. – IEEE Transactions on Geoscience and Remote Sensing 33(2): 481-486.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

[15] Nemani, R., Keeling, C., Hashimoto, H., Jolly, W., Piper, S., Tucker, C., Myneni, R., Running, S. (2003): Climate-driven increases in global terrestrial net primary production from 1982 to 1999. – Science 300(5625): 1560-1563.
[16] Potter, C., Brooks, V. (1998): Global analysis of empirical relations between annual climate and seasonality of NDVI. – International Journal of Remote Sensing 19(15): 2921-2948.
[17] Rouse, J. W., Haas, R. H., Schell, J. A., Deering, D. W. (1974): Monitoring vegetation systems in the Great Plains with ERTS. – In: Third Earth Resources Technology Satellite-l Symposium. Volume I: Technical Presentations Section A. Paper A-20. Goddard Space Flight Center: Washington, D.C, December 10-14, 1973. National Aeronautics and Space Administration: Washington, DC, pp. 309-317.
[18] Shi, S., Yu, J., Wang, F., Wang, P., Zhang, Y., Jin, K. (2021): Quantitative contributions of climate change and human activities to vegetation changes over multiple time scales on the Loess Plateau. – Science of the Total Environment 755.
[19] Sun, W., Song, H., Yao, X., Ishidaira, H., Xu, Z. (2015a): Changes in remotely sensed vegetation growth trend in the Heihe Basin of arid northwestern China. – Plos One 10(8).
[20] Sun, W., Song, X., Mu, X., Gao, P., Wang, F., Zhao, G. (2015b): Spatiotemporal vegetation cover variations associated with climate change and ecological restoration in the Loess Plateau. – Agricultural and Forest Meteorology 209: 87-99.
[21] Sun, W., Wang, Y., Fu, Y., Xue, B., Wang, G., Yu, J., Zuo, D., Xu, Z. (2019): Spatial heterogeneity of changes in vegetation growth and their driving forces based on satellite observations of the Yarlung Zangbo River Basin in the Tibetan Plateau. – Journal of Hydrology 574: 324-332.
[22] Tong, R., Song, H., Sun, W., Xu, Z., Yao, X., Yu, J. (2019): Analyzing the impact of climate change on natural vegetation greenness using improved statistical vegetation index simulation model. – Applied Ecology and Environmental Research 17(2): 4677-4691.
[23] Vicuna, S., Dracup, J., Lund, J., Dale, L., Maurer, E. (2010): Basin-scale water system operations with uncertain future climate conditions: methodology and case studies. – Water Resources Research 46.
[24] Wang, J., Dong, J., Liu, J., Huang, M., Li, G., Running, S., Smith, W., Harris, W., Saigusa, N., Kondo, H., Liu, Y., Hirano, T., Xiao, X. (2014): Comparison of gross primary productivity derived from GIMMS NDVI3g, GIMMS, and MODIS in Southeast Asia. – Remote Sensing 6(3): 2108-2133.
[25] Wang, Q., Fan, X., Qin, Z., Wang, M. (2012): Change trends of temperature and precipitation in the Loess Plateau Region of China, 1961-2010. – Global and Planetary Change 92-93: 138-147.
[26] Wu, D., Wu, H., Zhao, X., Zhou, T., Tang, B., Zhao, W., Jia, K. (2014): Evaluation of spatiotemporal variations of global fractional vegetation cover based on GIMMS NDVI data from 1982 to 2011. – Remote Sensing 6(5): 4217-4239.
[27] Xie, B., Jia, X., Qin, Z., Shen, J., Chang, Q. (2016): Vegetation dynamics and climate change on the Loess Plateau, China: 1982-2011. – Regional Environmental Change 16(6): 1583-1594.
[28] Xin, Z., Xu, J., Zheng, W. (2008): Spatiotemporal variations of vegetation cover on the Chinese Loess Plateau (1981-2006): Impacts of climate changes and human activities. – Science in China Series D-Earth Sciences 51(1): 67-78.
[29] Xu, H., Wang, X., Qu, Q., Zhai, J., Song, Y., Qiao, L., Liu, G., Xue, S. (2020): Cropland abandonment altered grassland ecosystem carbon storage and allocation and soil carbon stability in the Loess Hilly Region, China. – Land Degradation & Development 31(8): 1001-1013.
[30] Zeng, Z., Piao, S., Li, L. Z., Zhou, L., Ciais, P., Wang, T., Li, Y., Lian, X., Wood, E., Friedlingstein, P., Mao, J., Estes, L., Myneni, R., Peng, S., Shi, X., Seneviratne, S.,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_40454063

Wang, Y. (2017): Climate mitigation from vegetation biophysical feedbacks during the past three decades. – Nature Climate Change 7(6): 432-436.

[31] Zhang, H., Li, Y., Zhang, N. (2022): Relationship between temporal and spatial characteristics of vegetation coverage and topographic factors in Fenhe River Basin. – Bulletin of Soil and Water Conservation 42(01): 353-359 + 368.

[32] Zheng, K., Wei, J., Pei, J., Cheng, H., Zhang, X., Huang, F., Li, F., Ye, J. (2019): Impacts of climate change and human activities on grassland vegetation variation in the Chinese Loess Plateau. – Science of the Total Environment 660: 236-244.