RESPONSE OF VEGETATION DYNAMICS TO CLIMATE CHANGE AND HUMAN ACTIVITIES IN THE URBAN AGGLOMERATION OF THE YANGTZE RIVER MIDDLES REACHES, CHINA

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Abstract. To quantitatively assess the response of vegetation dynamics to climate change and human activities in the UAYRMR (urban agglomeration of the Yangtze River middles reaches, UAYRMR), China, this paper analyzed the spatio-temporal change characteristics of vegetation and their relationship with climate change and human activities using trend analysis, partial correlation analysis and residual analysis based on SPOT/VEGETATION NDVI (Normalized Difference Vegetation Index, NDVI) datasets. The results showed that: (1) the annual average NDVI significantly increased at the rate of 0.002/a during 1998-2018. (2) The spatial distribution heterogeneity of vegetation NDVI was significant. The improved regions mainly distributed in Xiangyang, Western Yichang and Eastern Huanggang. The degraded regions mainly distributed in the Wuhan metropolitan area, Changsha and Nanchang. (3) The area ratio of vegetation NDVI positively and negatively correlated with temperature and precipitation was 41.09% and 58.91%, 20.18% and 79.82%, respectively. (4) The area of vegetation NDVI continuously increasing and decreasing due to human activities accounted for 50.87% and 6.75%, and the area of that remained unchanged accounted for 42.38%. The impact of human activities on vegetation NDVI was greater than that of temperature and precipitation, and the positive impact of human activities on vegetation growth was greater than the negative impact.

Keywords: *NDVI, temperature, precipitation, human activities, residual analysis*

Introduction

As an important component of terrestrial ecosystems, vegetation is an intermediate link connecting ecological elements such as atmosphere, hydrosphere, and soil, and plays an important role in soil and water conservation, climate regulation, and maintaining ecosystem stability (Zhu et al., 2016; Bryan et al., 2018). Vegetation change can well reflect the impact of climate change and human activities on the pattern, function, and process of terrestrial ecosystems, and is an important topic in current global change research (Song et al., 2018). Although many studies have explored the correlation between climate change, human activities and vegetation change on a global or regional scale, this process is very complex. Therefore, it is still difficult to quantify the impact of climate change and human activities on vegetation change, and the priority of human factors and climate factors remains a controversial issue in academia (Piao et al., 2020).

Climate change and human activities are the two driving factors of vegetation change (Seddon et al., 2016; Zhang et al., 2022). Previous studies have shown that the rise of temperature caused the advance and extension of the growth season of vegetation in the middle and high latitudes of the northern Hemisphere, which significantly promotes the increase of vegetation greenness (Myneni et al., 1997; Ichii et al., 2002; Nemani et al., 2003). The decline of precipitation leads to the decrease of vegetation greenness in global arid and semi-arid regions (Li et al., 2015). Due to the differences in vegetation types and growth environments, the response of vegetation to climate change is extremely complex. Temperature rise has promoted the enhancement of vegetation activity in most regions of the world, but weakened vegetation activity in tropical, arid, and semi-arid regions (Cao et al., 2021). Liu et al. (2015) studied the characteristics of global vegetation cover change from 1982 to 2004, and found that the increase in vegetation NDVI was significantly positively correlated with the increase in temperature, but the impact of temperature on vegetation NDVI gradually weakened, especially in arid regions, where there was even a negative correlation. With the rapid increase of population and the rapid development of social economy, the impact of human activities on the ecological environment is becoming increasingly strong, which has directly or indirectly caused changes in the trend of vegetation change (Jiang et al., 2021). Morawitz et al. (2006) found that there was a strong correlation between population density and vegetation NDVI in the central Puget Bay region of the United States, confirming the driving role of human activities on vegetation change. Boschetti et al. (2013) found that agricultural irrigation and population migration had a significant impact on vegetation change in the Sahel region of Africa. Chi et al. (2018) conducted a study on the driving factors of vegetation change in Xilingol grassland and found that the decrease in grazing pressure is the main influencing factor for the increase in grassland vegetation productivity. Since 1998, China has successively launched and implemented six major forestry projects. These ecological projects have an important role in the greening of vegetation throughout the country (Mao et al., 2016; Zhang et al., 2021; Zheng et al., 2021).

With the increasing impact of human activities on the ecological environment, how to correctly distinguish and evaluate the impacts of climate change and human activities on vegetation change becomes a prerequisite for formulating ecosystem sustainability management strategies (Zhang et al., 2016). Currently, the attribution analysis methods of vegetation change mainly include linear regression model, residual trend analysis method, and ecological process model (Liu et al., 2015; Chen et al., 2019). Many scholars have made a lot of attempts to quantitatively distinguish and evaluate the impact of climate factors and human factors on vegetation change. Mueller et al. (2014) used a linear regression model to analyze the relationship between global vegetation cover changes and human activities, indicating that 20% of global vegetation cover changes are affected by human activities. Piao et al. (2015) used five ecosystem models to conduct attribution analysis of vegetation greening in China, indicating that climate change was the main influencing factor for vegetation greening during 1982~2009. The regression analysis method assumes that there is a linear relationship between vegetation change and driving factors. In fact, there is no strict statistical standard linear relationship under the superimposed impact of climate change and human activities. Due to complex model structures and a large number of model parameters, the uncertainty of ecological process models will increase (Ma et al., 2019). The introduction of residual analysis in recent years has made it possible to quantitatively distinguish and assess the impact of climate change and human activities on vegetation change (Jiang et al., 2017; Ge et al., 2021).

The UAYRMR is a highly dynamic region in the central region of China, occupying an important position in the national ecological pattern. In recent decades, with the intensification of climate change and human activities, significant changes have taken place in the vegetation cover of UAYRMR, bringing significant ecological and environmental changes. Therefore, the UAYRMR is an excellent area for studying the internal relationship between climate change, human activities and vegetation change. Under the dual impact of climate change and human activities, monitoring the spatio-temporal characteristics of vegetation change in the UAYRMR and exploring the impact of climate change and human activities on vegetation change have important guiding significance for protecting the ecological environment of urban Agglomeration, promoting green development of urban Agglomeration, and building ecological civilization of urban Agglomeration.

Materials and methods

Study area

The UAYRMR is located in the central region of China (26° 07’ 05”-30° 23’ N, 110° 15’-118° 28’ 58” E), covering 31 prefecture-level cities in Hubei, Hunan, and Jiangxi provinces (*Fig. 1*), with a total area of about 0.317 million km^2 (Dai et al., 2020). Economically, this area is not only an important part of the Yangtze River economic belt but also a key region for implementing the strategy of promoting the development of the central region (Dai et al., 2022). The UAYRMR is characterized by a subtropical monsoon humid climate, with sufficient sunlight and simultaneous rain and heat (Xiong et al., 2018). The overall landform of the urban agglomeration is dominated by plains, with dense regional river networks and fertile soil. It is an important grain producing area in China.

Data source and pre-processing

The vegetation index product data selected in this article is based on SPOT/VEGETATION NDVI satellite remote sensing data (https://www.resdc.cn/), and the time period is 1998-2018. The annual vegetation index dataset is generated using the maximum synthesis method based on ENVI (The Environment for Visualizing Images, ENVI) software.

The meteorological data comes from the Resource Environment and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), and the time period is 1980-2015. In this paper, the sorted meteorological data were processed using spatial masks method, and the same spatiotemporal series dataset data with the vegetation index NDVI were obtained using the Anusplin interpolation method (He et al., 2021) based on GIS (Geographic Information System, GIS) software.

Methods

Theil–Sen Median trend analysis and Mann–Kendall (MK) method

Theil–Sen Median is a robust nonparametric statistical trend analysis method that has been widely used in research fields such as meteorology, geography and hydrology. This method does not require samples to follow a certain distribution, and is not affected by outliers. It has high computational efficiency and is suitable for trend analysis of long time series data (Jiang et al., 2022). The calculation formula is as follows:

$$\beta = Median\left(\frac{x_i - x_j}{i - j}\right),\ 1 < \ j < i < n \tag{Eq.1}$$

where Median represents the median of the sequence; x_i and x_j are the sequential data in the series; i and j are the year; Positive β represents an upward trend, negative β represents a downward trend.

The MK method was used to perform a significance test on the trend analysis results of Theil–Sen Median based on Matlab software. At a given level of significance α, if $-Z_{1-\alpha/2} \leq Z \leq Z_{1-\alpha/2}$, it indicates that the sequence does not pass the significance test at this significance level; if $Z > Z_{1-\alpha/2}$ or $Z < -Z_{1-\alpha/2}$, it indicates that the sequence passes the significance test at this significance level.

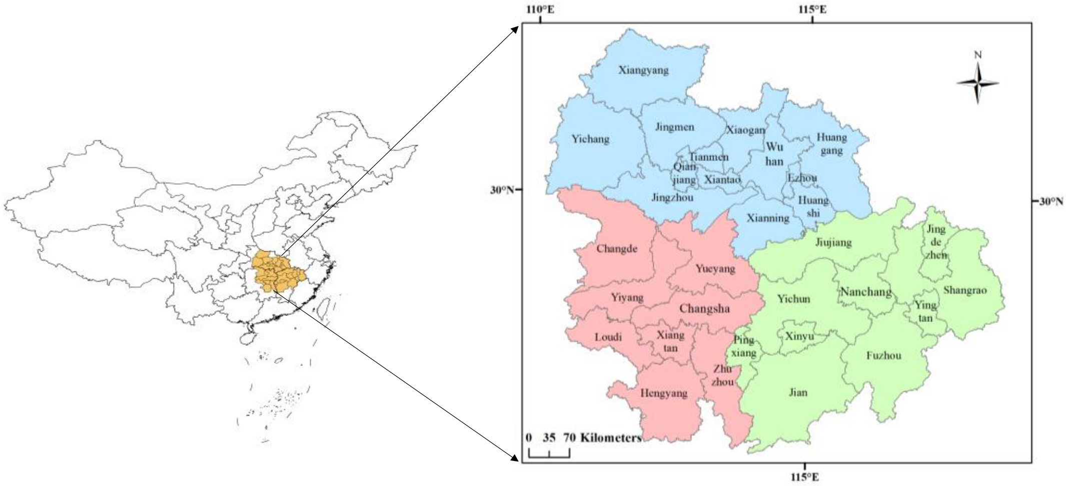

Figure 1. *Geographical location of the study area*

Correlation analysis

The correlations of vegetation NDVI with temperature, precipitation are calculated by Pearson correlation analysis based on Matlab software. The calculation formula is as follows:

$$R = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \tag{Eq.2}$$

where Y_i represents the annual average temperature and precipitation in the i year; $\overline{Y}$ represents multi-year average of temperature and precipitation; X_i represents the annual average NDVI in the i year; $\overline{X}$represents multi-year average of NDVI. The correlation coefficient R ranges from -1.0 to 1.0.

Residual analysis method

Based on the residual analysis model, it is assumed that vegetation NDVI is mainly determined by regional climate change and human activities. If other conditions do not change, simulate the change of vegetation NDVI only under climate change by establishing a regression model between the NDVI and climate elements. Then obtain the impact of human activities on NDVI using the actual NDVI values observed by remote sensing to subtract the predicted values based on climate change (Jiang et al., 2017). The calculation formula is as follows:

$$NDVI_{\text{residual value}} = NDVI_{\text{actual value}} - NDVI_{\text{simulation value}} \qquad \text{(Eq.3)}$$

where $NDVI_{residual\ value}$ is the difference between the actual value and the simulated value of vegetation NDVI; if $NDVI_{residual\ value} > 0$, it indicates that human activities improve the ecological environment and promote an increase in NDVI; if $NDVI_{residual\ value} < 0$, it indicates that human activities cause vegetation degradation and led to a decline in NDVI; if $NDVI_{residual\ value} = 0$, it indicates human activities have no impacts on vegetation NDVI.

Results

Spatio-temporal variation characteristics of temperature and precipitation

Figure 2 showed the temporal variation characteristics of the annual average temperature and annual precipitation of the UAYRMR from 1980 to 2015. The annual average temperature was 13.6°C, with the lowest (12.51°C) and highest (14.39°C) values occurring in 1984 and 2006, respectively. After 1996, the annual average temperature was higher than the annual average temperature except for 2011 and 2012 (*Fig. 2a*). The annual average temperature of the UAYRMR showed a significant increase trend from 1980 to 2015 with an increase rate of 0.36°C/10a at the 1% significance level, indicating that the overall climate in the study area was warming. The multi-year precipitation of the UAYRMR from 1980 to 2015 was 820.80 mm, with the lowest value (611.52 mm) and the highest value (1009.10 mm) appearing in 2011 and 2002, respectively (*Fig. 2b*). From 1980 to 2015, the annual precipitation of the UAYRMR fluctuated greatly, showing a general downward trend with a decline rate of 8.97 mm/10 a, but did not reach a significant level.

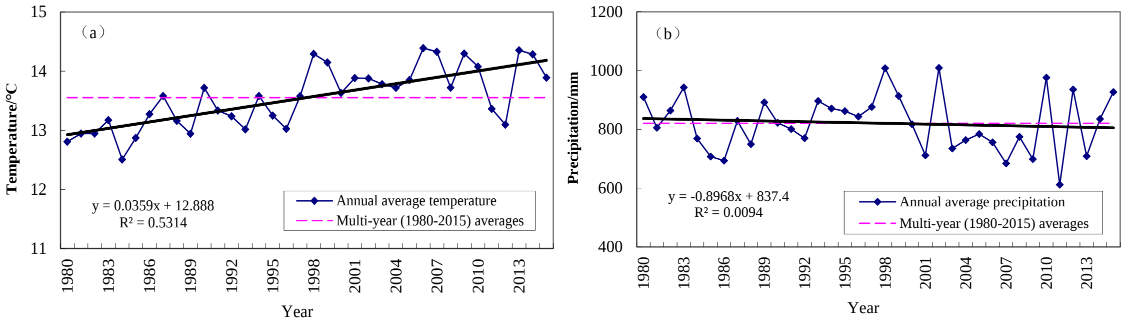

***Figure 2.** Annual change of temperature (a) and precipitation (b) in the study area*

There are significant spatial differences in the annual average temperature and precipitation of UAYRMR. The lowest annual average temperature is mainly distributed in Xiangyang and western Yichang, while the highest annual average temperature is mainly distributed in the southern part of the study area, namely Hengyang, Fuzhou, Ji'an, and Yingtan (*Fig. 3a*). The overall precipitation decreases from southeast to northwest, with the maximum precipitation mainly distributed in Shangrao, Jingdezhen, Yingtan and Fuzhou, and the minimum precipitation mainly distributed in the northern part of Xiangyang (*Fig. 3b*).

The temperature in most areas of the UAYRMR showed an increasing trend during 1980-2015, mainly distributed in the Wuhan metropolitan area, Ji'an, and western Yichang, with the highest growth rate reaching 0.56℃/10a (*Fig. 3c*). The area where the temperature remained unchanged was mainly located in the northern part of Xiangyang. The spatial differences in the annual precipitation variation trend of UAYRMR were significant. The annual precipitation in the northern part of the study area showed a decreasing trend, while the annual precipitation in a small number of areas in the eastern, central, and western parts of the study area showed an increasing trend (*Fig. 3d*). However, the variation trend of precipitation in most of study area did not reach a significant level.

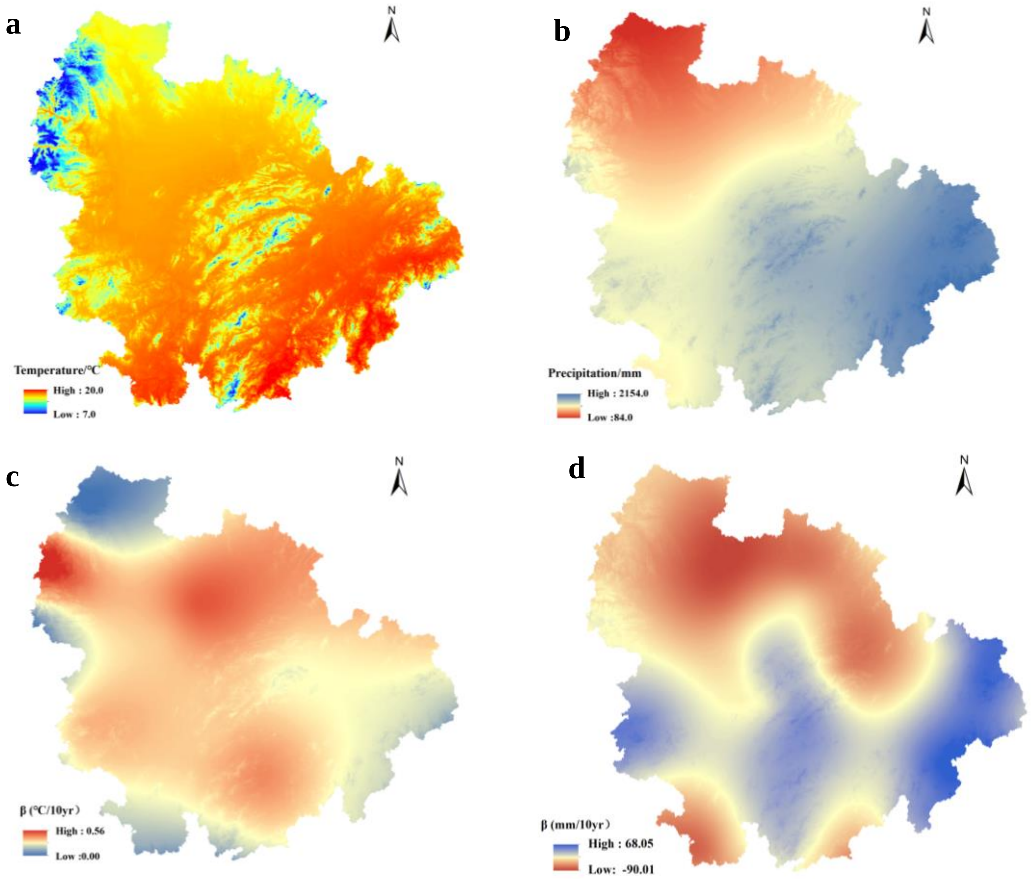

Figure 3. *Spatial distribution of annual average temperature (a) and precipitation (b) and their variation trend in the study area (c, d)*

Spatio-temporal variation characteristics of NDVI

Figure 4 showed the temporal variation characteristics of NDVI in the study area. The NDVI values were 0.36-0.40 during 1998-2018, with the lowest and highest values occurring in 2001 and 2017, respectively. The multi-year average NDVI was 0.38. After 2005, the NDVI value was higher than the multi-year average. The annual average

NDVI of the UAYRMR showed a significant upward trend from 1998 to 2018, with an increase rate of 0.002/a at the 1% significance level, indicating that the vegetation growth status of the UAYRMR was getting better and better.

Based on the annual average NDVI data of the study area from 1998 to 2018, the spatial distribution map of the multi-year average NDVI was obtained (*Fig. 5a*). The vegetation NDVI of the UAYRMR was generally high, and there were significant differences in spatial distribution of vegetation coverage. The regions with lower NDVI values were mainly distributed in Wuhan, Changsha and Nanchang, while the regions with higher NDVI values were mainly distributed in the central and surrounding areas of the UAYRMR.

The area of NDVI in the UAYRMR showed an increasing trend, accounting for 53.6%, while the area showing a decreasing trend accounted for 46.4% (*Fig. 5b*). The areas with decreased vegetation NDVI were mainly distributed in the Wuhan urban area, the eastern part of Yichang, the western part of Jingmen, Changsha, and the surrounding areas of Nanchang, with the maximum decrease rate of 0.37/10a. The areas with increased vegetation NDVI were mainly located in Xiangyang, western Yichang, eastern Huanggang, Hengyang, Zhuzhou, Ji'an, Fuzhou, Yichun, and other places, with a maximum increase rate of 0.47/10a.

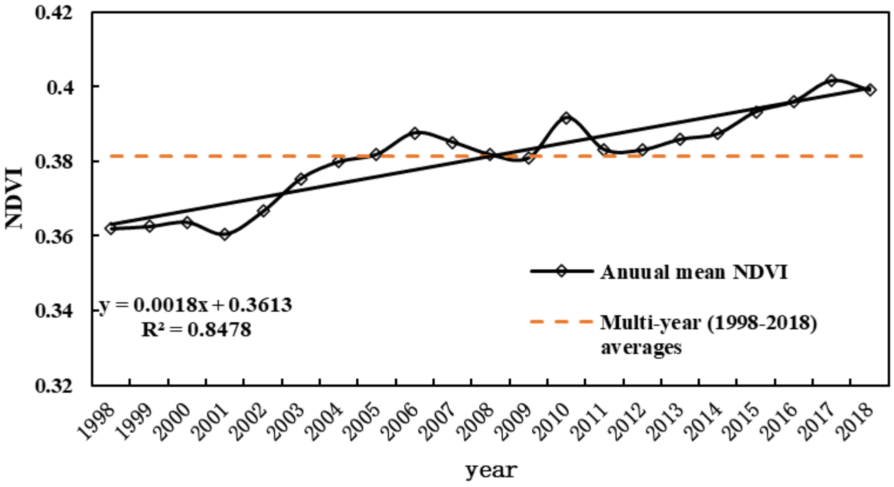

Figure 4. *Annual changes of NDVI in the study area*

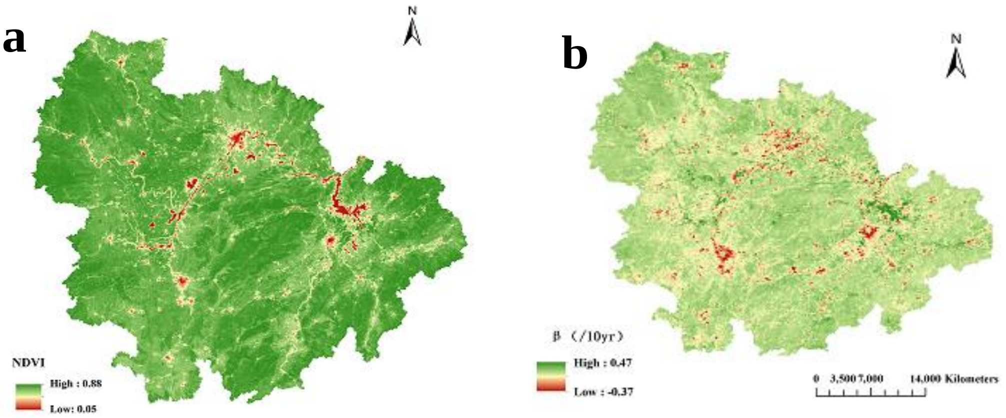

Figure 5. *Spatial distribution of NDVI (a) and its variation trend (b) in the study area*

The impact of temperature and precipitation on NDVI

To explore the impact of temperature and precipitation on vegetation NDVI in the study area, the correlation coefficient between vegetation NDVI and temperature, precipitation was calculated using Pearson correlation analysis (*Fig. 6*). The area with a positive correlation between vegetation NDVI and temperature accounted for 41.09%, mainly located in most areas such as Fuzhou, Yingtan, Jingdezhen, Shangrao, Loudi, Yiyang, Changde, and Yueyang, with a maximum correlation coefficient of 0.60 (*Fig. 6a*). The area with a negative correlation between vegetation NDVI and temperature accounted for 58.91%, mainly located in most areas such as Xiangyang, Yichang, northern Changde, Huanggang, Changsha, and Nanchang, with a maximum correlation coefficient of -0.40 (*Fig. 6a*).

The area where vegetation NDVI was positively correlated with precipitation accounted for 20.18%, mainly located in some areas such as Huanggang, Xiaogan, Zhuzhou, Pingxiang, etc., with a maximum correlation coefficient of 0.80 (*Fig. 6b*). The area with a negative correlation between vegetation NDVI and precipitation accounted for 79.82%, mainly located in some areas such as Yiyang, Changsha, Yueyang, and Nanchang, with a maximum correlation coefficient of -0.90 (*Fig. 6b*).

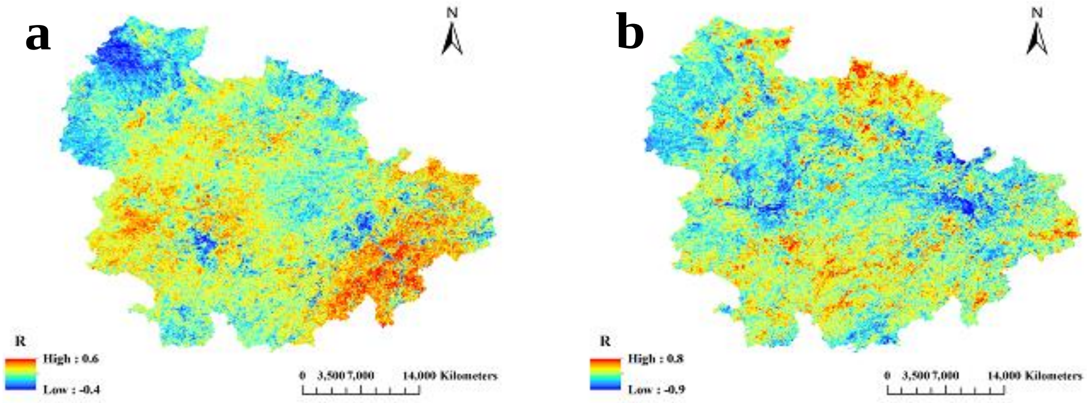

Figure 6. *Spatial distribution of correlation coefficients between NDVI and temperature (a), precipitation (b) in the study area*

The impact of human activities on NDVI

Figure 7 showed the spatial distribution of residual values in 1998, 2005 and 2015 based on residual theory, the change trend and fit goodness R^2 of residual values during 1998-2015. The NDVI of vegetation in the study area showed significant differences in spatial distribution due to human activities in 1998, 2005, and 2015. *Figure 7a-c* showed that there were significant differences in the spatial distribution of vegetation NDVI affected by human activities in the study area in 1998, 2005, and 2015. The NDVI residual in the UAYRMR is -0.38-0.36 in 1998 (*Fig. 7a*). The area of NDVI reduction caused by human activities (50.63%) was greater than the area of NDVI increase (6.89%), and the area with unchanged impact accounted for 42.38% in 1998. The areas where human activities promoted the increase of NDVI were mainly distributed in parts of Wuhan, Changsha, and Nanchang. The areas where human activities caused the decrease of NDVI were mainly distributed in Hengyang, Zhuzhou, Ji’an, Pingxiang, Xinyu, and the northern part of Xiangyang (*Fig. 7a*). Compared to

1998, the residual NDVI was -0.44-0.38 in 2005. The area of NDVI increase promoted by human activities (29.77%) significantly increased, mainly distributed in the southern part of the study area, Wuhan and surrounding cities. Conversely, the area of NDVI decrease caused by human activities (19.96%) significantly decreased, mainly distributed in most areas of Yichang and Xiangyang, with an unchanged impact accounting for 50.27% (*Fig. 7b*). In 2015, the residual NDVI was -0.47-0.62. The area of NDVI increase promoted by human activities (43.93%) further increased, while the area of NDVI decrease caused by human activities (11.55%) was relatively reduced, mainly distributed in some areas along the Yangtze River (*Fig. 7c*). *Figure 7d* showed that the variation trend in the impact of human activities on vegetation NDVI in the study area from 1998 to 2015. The proportion of areas affected by human activities that continued to increase was 50.87%, the proportion of areas affected by human activities that continued to decrease was 6.75%, and the proportion of areas affected by human activities that remained unchanged was 42.38%.

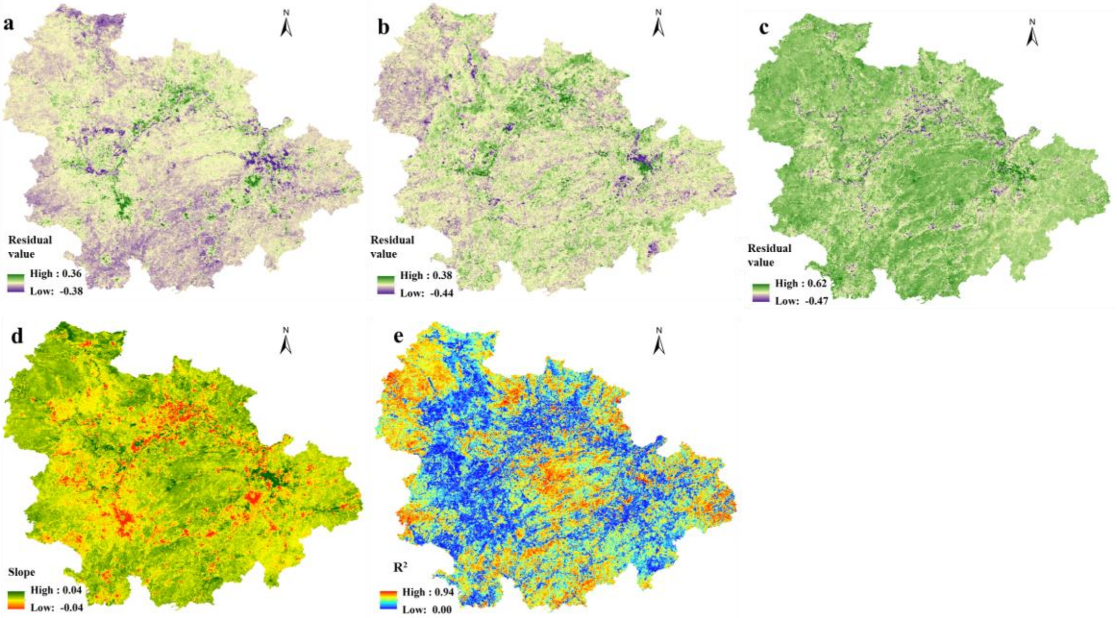

Figure 7. *The residual of NDVI in the study area in 1998, 2005 and 2015 (a, b, c), variation trend of residual (d) and the goodness of fit (e)*

Discussion

With the implementation of the strategy of the rise of the central region, the UAYRMR holds a pivotal position in China’s regional development pattern and is in a leading position in ecological environment protection. After the 18th National Congress of the Communist Party of China, the “Development Plan for UAYRMR” approved by the State Council clearly proposed to establish and improve the linkage mechanism for regional ecological civilization construction from three aspects: building ecological barriers, promoting green urban development, and jointly building cross regional environmental protection mechanisms, forming a harmonious development pattern between humans and nature. This study analyzed and explored the spatiotemporal changes of vegetation NDVI and its influencing factors in UAYRMR. From 1998 to 2018, the NDVI of the study area showed an overall upward trend, which is consistent with the relevant research by Yi et al. (2021). Yi et al. (2021) showed that the vegetation status of the UAYRMR has been good in the past 16 years, with the average NDVI of vegetation increasing from 0.72 to 0.80. Jin (2020) found that 70% of the regions in China showed an increasing trend in vegetation cover from 1982 to 2015, and vegetation cover in the middle and lower reaches of the Yellow River, the middle reaches of the Yangtze River, and the Huai River basin increasing rapidly. In terms of space, the areas with increasing NDVI were mainly located in Xiangyang, western Yichang, eastern Huanggang, Hengyang, and other places, while the areas with reduced NDVI mainly distributed in urban areas with high human activity intensity, such as the Wuhan metropolitan area, Changsha, and the surrounding areas of Nanchang.

The vegetation growth is closely related to climate. Heat quantity is one of the most important conditions for vegetation growth, while water is also an important factor in promoting plant growth. Therefore, temperature and precipitation are two important climate factors that affect vegetation cover change (Seddon, et al., 2016). Temperature rise is the main climate factor contributing to the increase in vegetation cover in China, but vegetation cover is more sensitive to precipitation changes in arid and semi-arid regions (Jin et al., 2020; Jiang et al., 2022). This study found that the area with a positive and negative correlation between vegetation NDVI and temperature in the urban agglomeration of the middle reaches of the Yangtze River accounted for 41.09% and 58.91%, respectively. The area with a positive and negative correlation between vegetation NDVI and precipitation were 20.18% and79.82%, respectively. Yi et al. (2023) found that the area with a positive correlation between vegetation NDVI and temperature during the growth season accounted for 80.80% in the Yangtze River basin. These regions are rich in water resources, and vegetation has relatively little dependence on precipitation. In addition, temperature increase is beneficial for vegetation growth due to higher altitude. Therefore, temperature becomes the main limiting factor for vegetation growth in these regions.

In addition to climate factors such as temperature and precipitation, human activities are also the main factors affecting surface vegetation changes (Jiang et al., 2017). The impact of human activities on vegetation change has both positive and negative effects (Qu et al., 2020). On the one hand, it promotes the increase of NDVI, such as afforestation and returning farmland to forest, and on the other hand, it causes the reduction of NDVI, such as urban expansion and deforestation. Based on residual analysis, it was found that in 1998, the area of NDVI decrease caused by human activities was greater than the area of increase, mainly distributed in Zhuzhou, Pingxiang, and Xinyu. These cities had a relatively high level of urbanization, with an average urbanization index exceeding 0.4 (Jiang et al., 2020). The rapid development of urbanization has further reduced the area of forest land, arable land, and wetlands. The area of NDVI increase due to human activities significantly increased in 2015. This was related to the steady promotion of soil erosion control projects and natural forest protection projects in the region, as well as the active implementation of policies such as the construction of the Yangtze River protective forest system and the return of farmland to forests and grasslands (Qu et al., 2020). The conversion of farmland to forests project is a major ecological engineering in China. In 2002, China launched the conversion of farmland to forests project in an all-round way. According to the topographic and geomorphic characteristics, hydrothermal conditions, and soil erosion, the project area is divided into 10 types of areas, including low mountains and hills in the middle and lower reaches of the Yangtze River.

Conclusions and future work

(1) The annual average temperature of the UAYRMR significantly increased at the rate of 0.36°C/10 a, while the precipitation showed a downward trend of 8.97 mm/10 a, indicating that the overall climate in the study area was developing towards a warm and dry trend from 1980 to 2015. The regions with higher rates of temperature rise were mainly distributed in Wuhan urban agglomeration, Ji'an, and western Yichang, while the regions with higher rates of precipitation decrease were mainly distributed in the northern part of the UAYRMR.

(2) The annual average NDVI of the UAYRMR significantly increased at the rate of 0.002/a, indicating that the vegetation growth status was getting better and better during 1998-2018. The areas with increased vegetation NDVI were mainly located in Xiangyang, western Yichang, eastern Huanggang, etc., with a maximum increase rate of 0.47/10 a.

(3) The area with a positive correlation between vegetation NDVI and temperature accounted for 41.09%, with a maximum correlation coefficient of 0.60, mainly located in the southeast of the UAYRMR. The area with a negative correlation between vegetation NDVI and temperature accounted for 58.91%, with a maximum correlation coefficient of -0.40, mainly located in some areas of Xiangyang, Changsha, and Nanchang. The area where vegetation NDVI was positively correlated with precipitation accounted for 20.18%, with a maximum correlation coefficient of 0.80; The area with a negative correlation between vegetation NDVI and precipitation accounted for 79.82%, with a maximum correlation coefficient of -0.90.

(4) The area where human activities promoted NDVI increase significantly increased, while the area where human activities cause NDVI declined relatively decreased during 1998-2015. From the perspective of variation trends in the impact of human activities on NDVI, the proportion of areas affected by human activities that continued to increase was 50.87%, the proportion of areas affected by human activities that continued to decrease was 6.75%, and the proportion of areas affected by human activities that remained unchanged was 42.38%.

(5) Although it is helpful to analyze the impact of climate change and human activities on vegetation change for protecting the ecological environment, large uncertainties in vegetation dynamics still exist due to complicated impact factors. Climate change and human activities are the two driving factors of vegetation change. Moreover, human activity is one of the reasons for the climate change. Therefore, we should consider the impact of human activity on climate change, and develop a process-based methodology for analyzing the impact of climate change and human activities on vegetation change in future work.

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