Research Article

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Analysis on vegetation cover changes and the driving factors in the mid-lower reaches of Hanjiang River Basin between 2001 and 2015

Abstract: The mid-lower reaches of the Hanjiang River Basin, located in the core of economic development in Hubei Province, is an integral part of the Yangtze River Economic Belt. In recent years, the watershed ecosystem has become more sensitive to climate changes and human activities, thus affecting the regional vegetation cover. To maintain a stable watershed ecosystem, it is critical to analyze and evaluate the vegetation change and its response to temperature, precipitation, and human activities in this region. This study, based on the trend analysis, partial correlation analysis, and residual analysis, evaluated the change characteristics of vegetation cover as well as the corresponding driving factors in the basin from 2001 to 2015. The results showed that (1) the overall spatial pattern of vegetation cover in the study area was "high in the west and north, lower on both sides of Hanjiang River, and lowest in the center and southeast," and the pattern changed parabolically with the increasing elevation. (2) Over the 15 years, vegetation cover in the basin showed an increasing trend, and the increased and decreased areas were 90.72 and 9.23%, respectively. (3) The response of vegetation cover to climatic factors varies greatly depending on the increasing elevation. That is, the lag effect under the impact of temperature disappeared gradually, while it became more evident under the impact of precipitation. (4) On the whole, human activities had a positive effect on the regional vegetation cover. The negative effect in the areas around the Nanyang Basin and the positive effect in most parts of the Jianghan Plain were gradually decreased.

Keywords: $NDVI_g$, watershed ecology, spatial-temporal characteristic, climate change, human activities, mid-lower reaches of Hanjiang River Basin

1 Introduction

Hanjiang River, the primary tributary of Yangtze River, is the water source for the middle route of the South-to-North Water Transfer Project. The Hanjiang River Basin is one of China's major commodity grain bases. Its eco-environmental changes significantly affect the Yangtze River Economic Belt and the ecological and grain safety of regions along with the South-to-North Water Transfer Project. Vegetation cover change, one of the important indexes for monitoring regional eco-environmental quality [1–3], can effectively reflect the changes in climate, hydrology, and human activities in basins. Against the backdrop of hydraulic engineering construction and modern agricultural development, studying vegetation cover change in the Hanjiang River Basin and the corresponding driving factors is of great practical importance.

Climatic factors and human activities are the two most common indicators in vegetation cover studies. Especially as the global climate is radically changing, vegetation response to such a situation has become a central concern for many scholars [4–6]. A lot researches have showed that higher annual average temperatures are the leading cause of vegetation change [7–9]. In addition, the vegetation growth condition was susceptible to

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precipitation variation [10–12], especially in arid and semi-arid areas [13,14]. Besides climate changes, human activities such as urban construction, environmental governance, and ecological engineering are also crucial to vegetation cover [15–17], which has gained much attention [18–20]. Other researchers concentrated more on the correlation between vegetation cover and topographic factors, including altitude, slop, and aspect [21–23].

Currently, studies on the vegetation cover in the Hanjiang River Basin mostly center on Southern Shaanxi, where the water comes from, and the upper reaches [24–27]. Also, the upper and mid-lower reaches of the Hanjiang River differ in landform and hydrologic patterns. They are facing different ecological problems, especially under the influence of hydraulic engineering construction. So far, many researchers have analyzed from different perspectives such as river water quality, industrial development, and climate (temperature, humidity, and relative humidity) [28–30]. However, there is still lack of analysis of vegetation cover changes. Therefore, taking the mid-lower reaches of the Hanjiang River Basin as the study object, this study analyzed the change characteristics of the regional vegetation cover as well as its driving factors over the 15 years, with the elevation elements taken into consideration.

The specific approaches of this study were as follows: (1) Based on the Normalized Difference Vegetation Index (NDVI) and meteorological data from 2001 to 2015, this study disclosed the change characteristics of vegetation cover in different elevations over the 15 years using the pixel-based linear fitting approach. (2) With partial correlation, this study further analyzed the effect of temperature and precipitation in different periods on vegetation in various elevations. (3) This study established a "climate-NDVI" model to probe into impact of human activities on vegetation under the pretext of hydraulic engineering construction and modern agricultural development using the residual analysis method. The study's significance is to provide a relevant theoretical basis and realistic reference for the formulation of policy on vegetation restoration and ecological protection in the water basin.

2 Methods and data

2.1 Study area

Hanjiang River, the Yangtze River's primary tributary, has a trunk stream of 1,577 km in length. The segment from Danjiangkou to Hankou is the mid-lower reach, which is as long as 652 km. The Hanjiang River Basin, with a control area of 64,000 km^2, locates in the subtropical monsoon region, where the climate is mild and humid, and the annual precipitation is 800–1,300 mm. The water is abundant, but is unevenly distributed throughout the year. The runoff from May to October approximately accounts for 75% of the whole year. With a great interannual variation, the Hanjiang River is the most changeable one among all tributaries of the Yangtze River. Thereinto, the middle reach is about 270 km, extending from Danjiangkou to Zhongxiang. It is mainly covered by mountain lands (distributed in the west and the north) and hills (distributed in the Nanyang Basin) and primarily used for croplands and forest lands. The segment below Zhongxiang is the lower reach, which is about 382 km. Here, the topographic relief is not significant, and the river branches crisscross this reach. There are many flat alluvial plains and small lakes (distributed in the Jianghan Plain), and the reach is mainly used for croplands.

2.2 Study data

The NDVI data from 2001 to 2015 were derived from the MOD13Q1 product on the NASA MODIS Terrestrial Science Team (http://landval.gsfc.nasa.gov). The spatial and temporal resolutions of this product are 250 m and 16 days. Now, it has been widely used for the dynamic monitoring of regional vegetation change. Considering the honological phase and climate characteristics in the study area, the NDVI data from April to October during these 15 years were accumulated to get NDVI$_g$ (the cumulative growing-season NDVI).

The meteorological data were obtained from the China Meteorological Data Service Center (http://data.cma.cn/), and observations from a total of 22 meteorological stations in and around the study area were selected. Since there are many methods to interpolate meteorological data, it is important to choose a suitable one according to the natural geographical characteristics of the study area. Thin plate spline (TPS) interpolation is a surface extension of the spline function, which uses smooth parameters to achieve an optimal balance between data fidelity and the smoothness of the fitted surface, ensuring a smooth and continuous interpolation surface with reliable accuracy [31]. Meanwhile, TPS can also introduce linear covariate submodels, such as temperature and elevation, which are suitable for areas with large topographic relief. Considering the topographic characteristics of the study area, this article used TPS for spatial interpolation of the temperature data. Ordinary Kriging (OK) interpolation can not only estimate the spatial distribution of the measured parameters but also estimate the variance distribution of the estimated parameters, which is one of the most common methods for interpolation of the precipitation

data [31]. Liu and Chen have pointed out that the highest accuracy could be obtained by OK interpolation for precipitation data in the Yangtze River Basin [32]. Therefore, this article chose to use OK interpolation for spatial interpolation of precipitation data.

The DEM data and vegetation type data were obtained from the Resource Environment Data Cloud Platform of CAS (http://www.resdc.cn/) and both were resampled to 250 m.

2.3 Study methods

2.3.1 Unary linear regression trend analysis based on the pixel

The growing-season $NDVI_g$ from 2001 to 2015 was calculated, and the least square method was employed to fit the change rate of $NDVI_g$ pixel by pixel. The variation trend of a single pixel was used to comprehensively reflect the spatial-temporal variation characteristics of vegetation cover in the study area. The computational formula can be expressed as follows:

$$B_{slope} = \frac{n \sum_{i=1}^{n} NDVI_g t_i - \sum_{i=1}^{n} NDVI_g \sum_{i=1}^{n} t_i}{n \sum_{i=1}^{n} t_i^2 - \left(\sum_{i=1}^{n} t_i\right)^2} \quad (1)$$

where $NDVI_g$ refers to the cumulative growing-season NDVI that can reflect the vegetation growth condition throughout the year. Besides, t_i represents the ith year of the research ($n = 15$), and B_{slope} is the slope of $NDVI_g$'s variation trend line. The situation that $B_{slope} > 0$ means the $NDVI_g$ keeps increasing over the 15 years. The higher the value, the more obvious the increase of vegetation coverage. Conversely, the coverage will decrease.

The F test was used to test the significance of the change trend, and is calculated as follows:

$$F = U \times \frac{n - 2}{Q}, \quad (2)$$

where $U = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2$ is the regression square sum, $Q = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$ is the residual sum of square, y_i is the ith year of $NDVI_g$, $\hat{y}_i$ is the regressive value, $\bar{y}$ is the average value of 15 years, and $n = 15$.

2.3.2 Calculation method about the influence of climate changes on the vegetation cover based on partial correlation analysis

The influence of climatic factors on the vegetation is mainly manifested as temperature and precipitation. By controlling the linear effect of the temperature (precipitation) in this article, the partial correlation method was employed to analyze each factor's impact on the vegetation separately. The computational formula is

$$r_{xy,z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}}, \quad (3)$$

where $r_{xy,z}$ refers to the partial correlation coefficient between variables x and y after the variable z is fixed. r_{xy}, r_{xz}, and r_{yz} represent the correlation coefficients between x and y, x and z, as well as y and z, respectively. Thereinto, x, y, and z represent the $NDVI_g$, temperature, and precipitation, respectively, and vice versa.

2.3.3 Calculation method about the influence of human activities on the vegetation cover based on residual analysis

In the context of climate changes, this study revealed the influence of human activities on the vegetation growth through the residual analysis. The specific methods are as follows:

(a) The Danjiangkou Reservoir Area of the Middle Route of the South-to-North Water Transfer Project had started a 5-year immigration plan at the end of 2008, which caused a huge disturbance to the regional vegetation cover. Thus, this article took 2001–2008 as the baseline period and 2009–2015 as the influence period. Besides, it was assumed that there was a balanced state among the vegetation system, climate changes, and human activities from 2001 to 2008.

(b) The "climate-NDVI" model based on climatic factors was obtained by means of the multiple regression analysis, and its simulation effect was evaluated with an adjusted determination coefficient. The computational formula can be expressed as follows:

$$R_a^2 = 1 - \frac{SSE/(n - k - 1)}{SST/(n - 1)}, \quad (4)$$

where R_a^2 is the adjusted determination coefficient, SSE is the residual sum of squares, and SST is the sum of squares of total deviations. Besides, $n - k - 1$ and $n - 1$ represent the degrees of freedom for squares' error sum and the total sum of squares, respectively.

(c) The "climate-NDVI" model was used to predict the $NDVI_g$ from 2009 to 2015 in the mid-lower reaches of the Hanjiang River Basin.

(d) The residual between real and simulated $NDVI_g$ values was calculated, and its variation trend with the year

was analyzed. The computational formula of this residual is expressed as follows:

$$\sigma = \text{NDVI}_g - \text{NDVI}_{g\text{-sim}}, \tag{5}$$

where $\text{NDVI}_{g\text{-sim}}$ represents the simulated NDVI_g, and σ represents the residual. If σ is positive, human activities will promote the vegetation cover. Conversely, they will impede the vegetation cover.

3 Results

3.1 Spatial-temporal variation characteristics of the vegetation cover

An overlay analysis was carried out based on the distribution of vegetation types (Figure 1(b)) and DEM data in the Basin to obtain their distribution at different elevations through statistics (Table 1). The concrete results were as follows: First, crops and most coniferous forests that were more frequently affected by human activities were primarily found below 300 m. Second, broad-leaved forests, shrub forests, and few crops were mixed between 300 and 1,900 m. These areas were mainly planted with economic trees, such as walnut, chestnut, and oil plants. Third, the shrub, coniferous, and broad-leaved forests were sparsely distributed above 1,900 m.

3.1.1 Temporal variation characteristics

From the whole basin (Figure 2(a)), the annual average NDVI_g was 4.01 over the 15 years, and the vegetation cover fluctuated and increased. From different elevations, the annual vegetation NDVI_g was averagely 3.70 at altitudes below 300 m and increased year by year in a similar way as that in the whole basin. The vegetation cover also showed an increased trend between 300 and 1,900 m. However, there was no significant change above 1,900 m. It is worth noting that the vegetation cover plummeted at altitudes above 1,900 m in 2010 for the Hanjiang River witnessed a once-in-a-century torrential rain that led to flash floods and landslides. Consequently, the mountainous vegetation was destructed extensively [35].

According to the month-by-month analysis, how the monthly average values of the growing-season NDVI changed with the elevation is shown in Figure 2(b), indicating that the vegetation NDVI's intraannual variation at different elevations had obvious seasonal characteristics in the Basin. The details were as follows: The vegetation was in a regreening stage from April to June when the NDVI value increased gradually. In July and August, the vegetation grew vigorously, and its NDVI surged. September and October were the final stage of the growing season, in which the value decreased gradually. On the whole, the vegetation NDVI at altitudes below 300 m peaked in July, and that above 300 m all peaked in June. According to the research conducted by Shen and
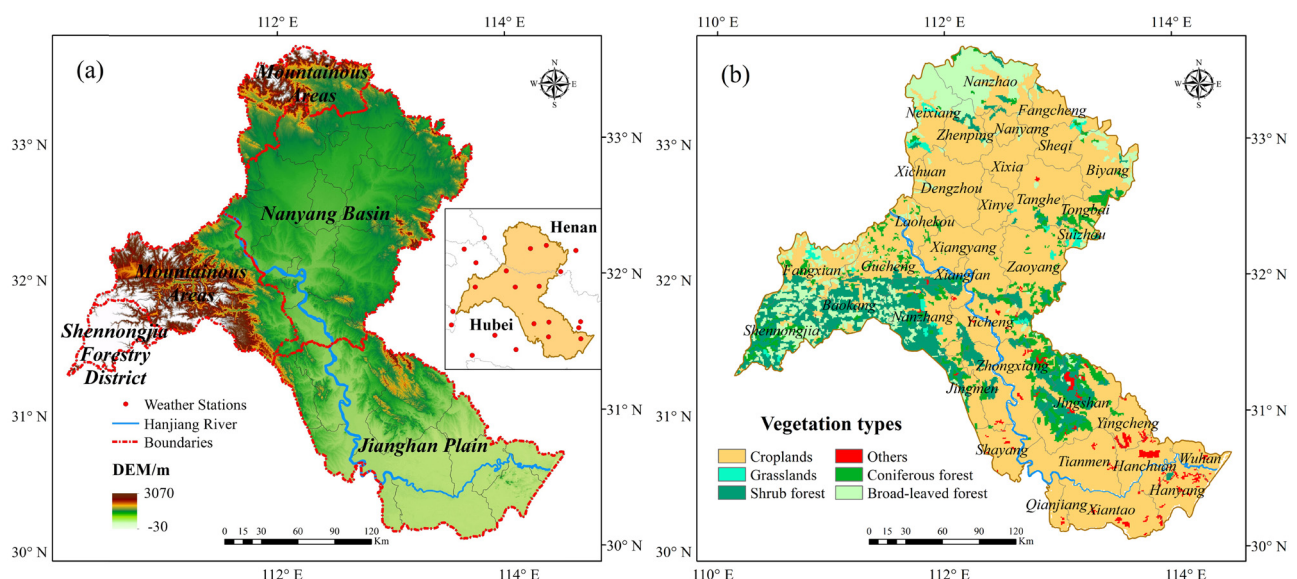
Figure 1: Location and vegetation types of the study area: (a) distribution of DEM and weather stations and (b) distribution of vegetation types.

Table 1: Vegetation distribution at different elevations

DEM	Vegetation distribution	Regions	Description
≤300 m	Crops: 93.363%; coniferous forests: 71.876%[a]	Nanyang Basin	Most areas in the middle reaches of the Hanjiang River
		Jianghan Plain	Most areas in the lower reaches of the Hanjiang River
300–1,900 m	Broad-leaved forests: 77.901%; shrub forests: 57.575%; crops: 6.363%	Western and northern mountainous areas (areas around Nanyang Basin)	Fangxian, Gucheng, Baokang, Nanzhang, Neixiang, Nanzhao
>1,900 m	Shrub forests: 4.226%; coniferous forests: 5.208%; broad-leaved forests: 3.237%	Shennongjia Forestry District	Shennongjia

[a] The coniferous forests distributed in the mid-lower reaches of the Hanjiang River Basin are mostly the secondary forests or the semi-natural forests formed through artificial cultivation [33,34].

Li and the spatial distribution of vegetation types (Figure 1(b)), this is mainly because the areas below 300 m are primarily covered by crops whose growing season begins later than that of other vegetation types [36]. Therefore, the crops' NDVI reaches its peak relatively late.

3.1.2 Spatial variation characteristics

In the mid-lower reaches of the Hanjiang River Basin, the vegetation coverage was "high in the west and the north, lower on both sides of Hanjiang River, and lowest in the center and the southeast," showing significant intraregional differences (Figure 3(a)). Thereinto, the average growing-season $NDVI_g$ value exceeded 4.5 in the Shennongjia Forestry District, as well as western and northern mountainous

areas. However, the value was 4–4.5 on both sides of the Hanjiang River and less than 4 in the Nanyang Basin and the Jianghan Plain. The $NDVI_g$ value was relatively low in the center of the basin because the vegetation may be destructed due to hydraulic engineering construction. However, the vegetation in the southeast was more likely affected by the rapid urbanization.

By calculating the average $NDVI_g$ values at different elevations in combination with the DEM data, it was found that the growing-season $NDVI_g$ changed with the increasing elevation "in a parabolic shape" (Figure 3(b)). The concrete manifestations are as follows: the $NDVI_g$ value (3.71 on average) was lowest below 300 m and ascended rapidly with the increasing elevation. The value (5.08 on average) was highest between 300 and 1,900 m and increased slowly with the increasing elevation. The
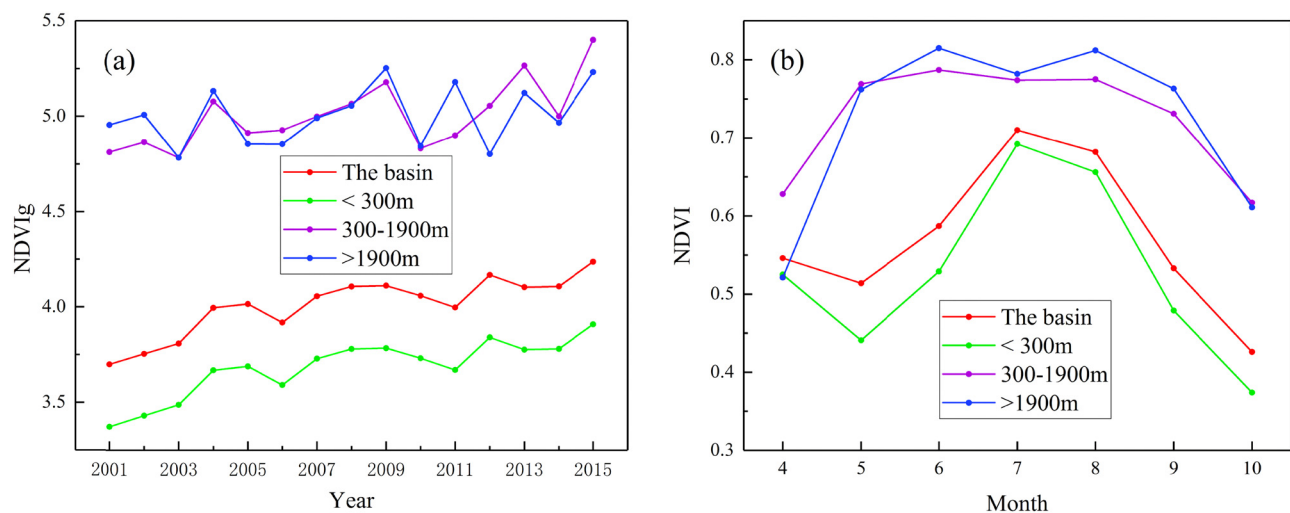
Figure 2: Temporal variation characteristics of the vegetation cover in the mid-lower reaches of the Hanjiang River Basin from 2001 to 2015: (a) annual variation of the $NDVI_g$ at different elevations and (b) monthly variation of the $NDVI_g$ at different elevations.
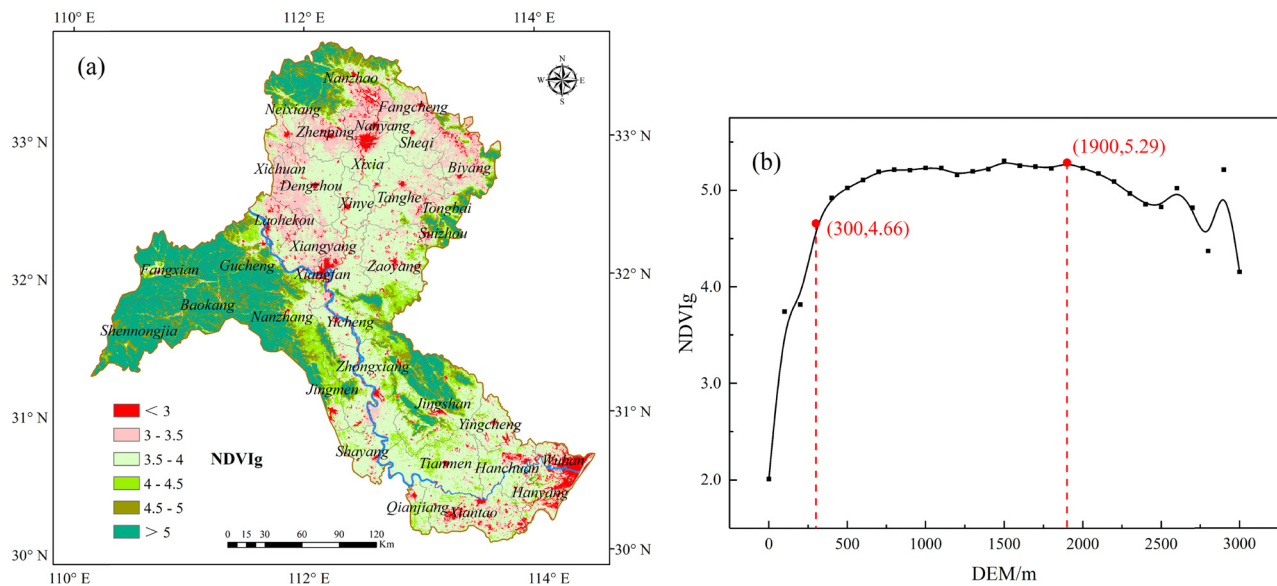
Figure 3: (a) Spatial distribution of the average NDVI$_g$ in the basin from 2001 to 2015 and (b) NDVI$_g$ variation with increasing elevation.

value was relatively low (5.07 on average) above 1,900 m and decreased steadily with the increasing elevation.

The variation trend for the vegetation cover in the basin from 2001 to 2015 was calculated based on the unitary linear regression model (Figure 4(a) and Table 2). In the study area, the vegetation cover, accounting for 83.02% of the total area, showed an increasing trend. The extremely significantly increased area was 41.8%, mainly distributed in the eastern part of the Nanyang Basin (Sheqi, Biyang, Tongbai, Suizhou, etc.) and its surrounding mountainous areas (Gucheng, Nanzhao,

etc.). The significantly increased and weakly significantly increased areas were 17.12 and 31.80%, respectively, and they covered almost the whole study area. The unchanged area was 0.05%. The decreased area was 9.23%, which was sporadicly distributed in the south of the Nanyang Basin (Xiangyang, Yicheng, etc.) and the southeastern of the Jianghan Plain (Hanchuan, Wuhan, Hanyang, etc.). The extremely significantly decreased area was 1.26%.

The vegetation change at different elevations was analyzed based on the DEM data, namely, the relation between B_{slope} and DEM (Figure 4(b)). During the 15 years,
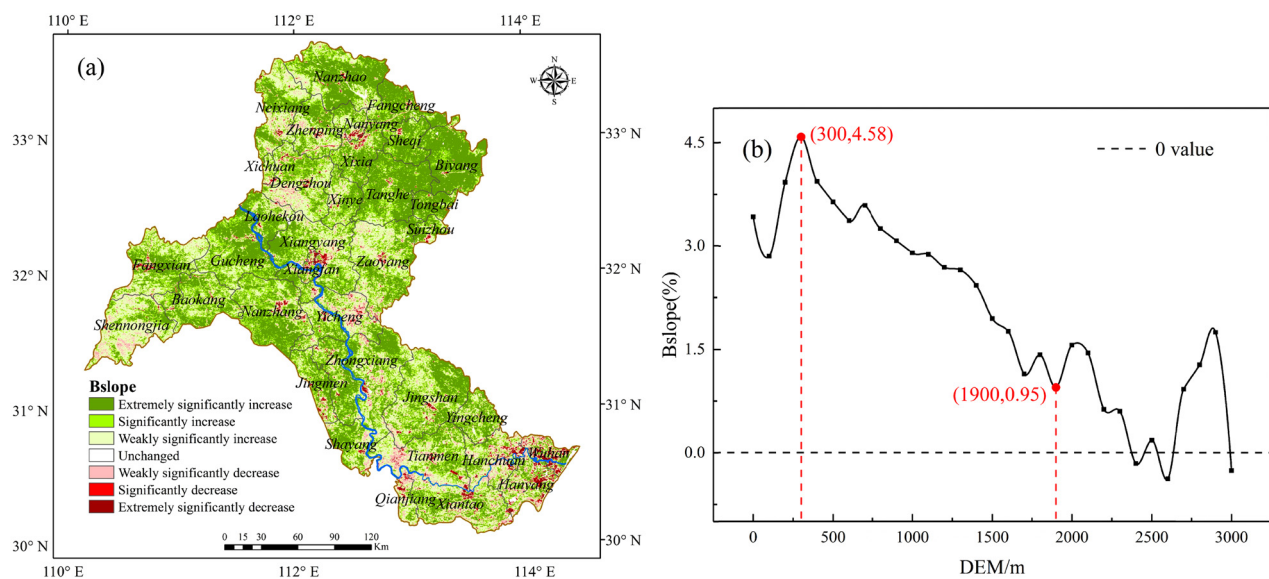
Figure 4: (a) Spatial distribution of B_{slope} in the basin from 2001 to 2015 and (b) B_{slope} variation with increasing elevation.

Table 2: Area and proportion of different vegetation change types in the mid-lower reaches of Hanjiang River

Type	Significant test	Area (km^2)	Percentage
Extremely significantly increase	$B_{slope} > 0$, $p < 0.01$	26381.13	41.80
Significantly increase	$B_{slope} > 0$, $0.01 < p < 0.05$	10805.92	17.12
Weakly significantly increase	$B_{slope} > 0$, $p > 0.05$	20073.81	31.80
Unchanged	$B_{slope} = 0$	33.86	0.05
Weakly significantly decrease	$B_{slope} < 0$, $p > 0.05$	4461.15	7.07
Significantly decrease	$B_{slope} < 0$, $0.01 < p < 0.05$	568.58	0.90
Extremely significantly decrease	$B_{slope} < 0$, $p < 0.01$	791.55	1.26

the B_{slope} value was higher than 0 below 300 m and increased gradually with the increasing elevation. The value was also above 0 between 300 and 1,900 m, but it decreased gradually with increasing elevation. The reason may be that with the increased elevation, the accessibility and frequency of human activities gradually decreased, which weakened the effect on vegetation. Finally, the NDVI$_g$'s B_{slope} value fluctuated around 0 above 1,900 m. Topographically, the vegetation cover showed an increasing trend below 1,900 m, while it changed little above 1,900 m.

3.2 Analysis of the driving factors of vegetation cover changes

To explore the vegetation's driving factors in different regions, the NDVI$_g$ time-series data from 2001 to 2015 were used to analyze the correlation between vegetation cover and climatic factors at different elevations in the basin. In addition, the residual analysis method was employed to analyze the effect of human activities on the vegetation change.

3.2.1 Climatic factors

In combination with the DEM data, the partial correlation analysis was used to calculate the partial correlation coefficient between NDVI$_g$ and temperature (precipitation) at different elevations from interannual and intraannual two-time scales. Figure 5 shows the spatial distribution of the correlation between the multi-year mean NDVI$_g$ and the multi-year mean temperature and precipitation in the growing season on the annual scale.

From the perspective of the whole basin, the significantly negatively correlated area between NDVI and temperature was 8.58%, mainly distributed in the western mountainous areas of the Nanyang Basin. The significantly positively correlated area was 18.52%, mainly distributed in the east of the Nanyang Basin (Figure 5(a) and Table 3). The significantly negatively correlated area between NDVI and precipitation accounted for 3.96%, mainly distributed in the northern mountainous area of the Nanyang Basin. The significantly positively correlated area was 27.65%, mainly distributed in the Nanyang Basin and the Jianghan Plain (Figure 5(b) and Table 3). As the elevation increased, correlation of NDVI$_g$ with temperature increased gradually, while that with the precipitation decreased gradually (Table 2).

For the change of hydrothermal conditions that have a certain lag effect on the vegetation growth, this article analyzed the correlation between the vegetation NDVI and temperature, precipitation on the monthly scale. This article calculated the partial correlation coefficients between the monthly NDVI and the temperature and precipitation in the current month, 1 month ago, and 2 months ago, and it was found that the vegetative response to temperature and precipitation showed significantly different lag effects in different regions.

From the perspective of different elevations, the vegetative response to temperature lagged by 2 months below 300 m, and the significant positive and negative correlated areas were 25.97 and 10.37%, respectively. By comparison, the response to precipitation had no obvious lag effect, and the significant positive and negative correlated areas were 16.57 and 15.41%, respectively (Table 4 and Figure 6(a and f)). Between 300 and 1,900 m, the response to temperature lagged by 2 months, and the response to precipitation lagged by 1 month. The significant positive and negative correlated areas were 23.81 and 29.91%, respectively (Table 4 and Figure 6(a and e)). There was no obvious lag effect in the response to th temperature above 1,900 m, and the response to precipitation lagged by 1 month. The significant negative and positive correlated areas were 31.58 and 24.73%, respectively (Table 4 and Figure 6(c and e)).
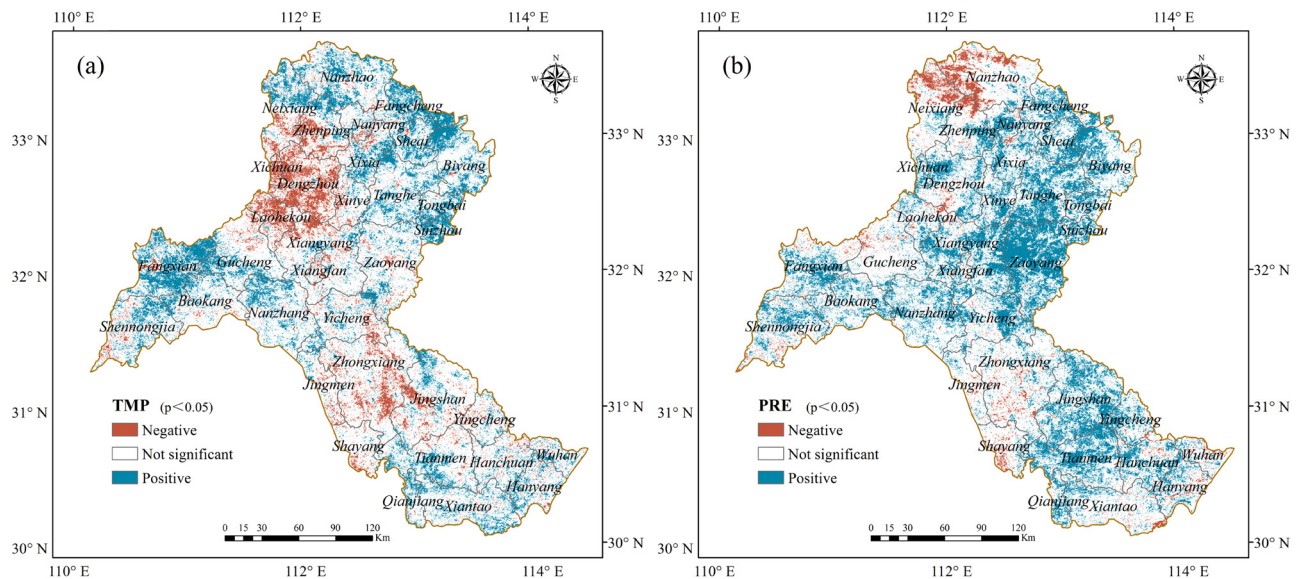
Figure 5: Correlation between NDVI$_g$ and temperature and precipitation on the annual scale: (a) NDVI$_g$ and temperature and (b) NDVI$_g$ and precipitation.

To sum up, as the elevation increased, the lag effect disappeared gradually under the impact of temperature, while it became more significant under the impact of precipitation. This is because the vegetation in croplands at low altitudes is mainly affected by human activities, and its growth is not completely synchronous with the temperature due to agricultural management measures such as mulching films and plastic houses. With the increasing elevation, the vegetation is affected by both temperature and precipitation. However, for the areas at high altitudes that are closer to the Danjiangkou Reservoir, where the water is abundant, the vegetation becomes more sensitive to temperature than to precipitation. The smaller the influence of precipitation is, the longer the lag time will be ref. [37].

By further analyzing the Nanyang Basin and the Jianghan Plain at low altitudes, it was found that the two regions were significantly different even if their altitudes were similar (Figure 6(a, c, e, and f) and Table 5). In the Nanyang Basin, the vegetation NDVI's response to temperature and precipitation lagged by 2 and 1 months, respectively, and the significant positive correlated areas were 28.09 and 32.37%, respectively. However, in the Jianghan Plain, the vegetative response to these two factors showed no obvious lag effect, and the significant positive correlated areas were 39.09 and 23.18%, respectively.

This may relate to the different crops in these two regions. The Nanyang Basin locates in the transition zone from subtropical one to temperate one. It is mainly planted with wheat, corn, and peanut. By comparison, Jianghan Plain, located in the subtropical zone, is mainly planted with rice and cotton. The crops' phenological characteristics directly affect the vegetation response to

Table 3: Area proportion of correlation between NDVI$_g$ and climatic factors at different elevations in the mid-lower reaches of Hanjiang River Basin from 2001 to 2015

DEM	Climatic factors	Negative (%)	Positive (%)	Not significant (%)
<300 m	Temperature	10.39	14.37	75.24
	Precipitation	2.35	30.42	67.23
300–1,900 m	Temperature	1.86	34.00	64.14
	Precipitation	9.67	18.31	72.02
>1,900 m	Temperature	12.31	79.11	8.57
	Precipitation	5.39	16.27	78.34
The basin	Temperature	8.58	18.52	72.90
	Precipitation	3.96	27.65	68.39

Table 4: Area proportion of correlation between the average monthly NDVI and climatic factors at different elevations in the mid-lower reaches of Hanjiang River Basin from 2001 to 2015

Climatic factors	Time scale	DEM	Negative (%)	Positive (%)	Not significant (%)
Temperature	2 months ago	<300 m	10.37	25.97	63.66
		300–1,900 m	7.82	23.81	68.37
		>1,900 m	27.49	3.09	69.42
	1 month ago	<300 m	11.63	10.91	77.46
		300–1,900 m	13.48	7.27	79.25
		>1,900 m	18.14	2.25	79.62
	In the month	<300 m	12.57	11.36	76.07
		300–1,900 m	12.87	13.00	74.13
		>1,900 m	31.58	0.96	67.46
Precipitation	2 months ago	<300 m	4.03	22.28	73.69
		300–1,900 m	9.34	9.83	80.83
		>1,900 m	2.83	23.40	73.78
	1 month ago	<300 m	15.98	12.8	71.22
		300–1,900 m	5.79	29.91	64.30
		>1,900 m	10.92	24.73	64.35
	In the month	<300 m	15.41	16.57	68.02
		300–1,900 m	30.23	5.22	64.56
		>1,900 m	33.65	1.41	64.94

climatic factors in the two regions. Moreover, the lag effect is not synchronous because of the agricultural management measures for different crops. This has been verified in the research conducted by Zhao et al. on the response of crop phenology to climate changes in North China [38].
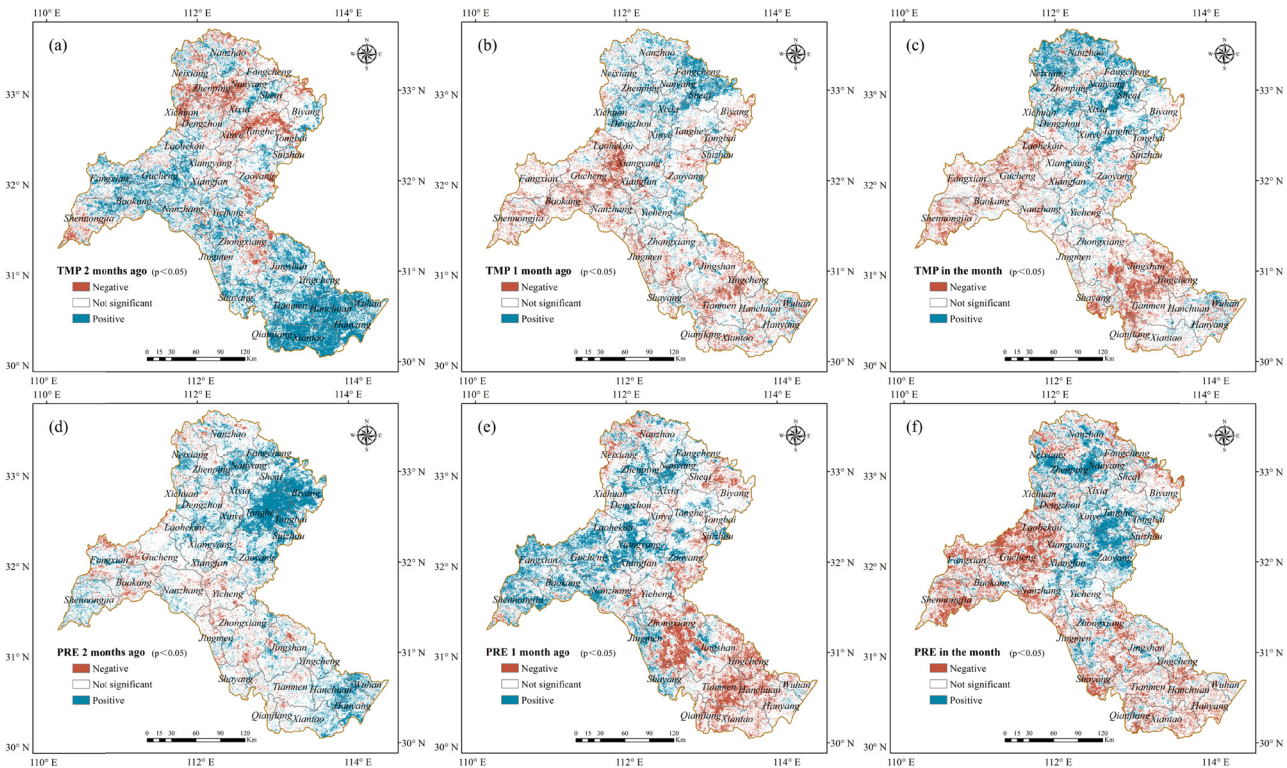
Figure 6: Partial correlation coefficient between the monthly NDVI and temperature and precipitation on the monthly scale: (a) NDVI and the temperature 2 months ago, (b) NDVI and the temperature 1 month ago, (c) NDVI and the temperature in the month, (d) NDVI and the precipitation 2 months ago, (e) NDVI and the precipitation 1 month ago, and (f) NDVI and the precipitation in the month.

Table 5: Area proportion of correlation between monthly NDVI and climatic factors below 300 m

Climatic factors	Time scale	Regions	Negative (%)	Positive (%)	Not significant (%)
Temperature	2 months ago	Nanyang Basin	4.70	28.09	67.21
		Jianghan Plain	17.48	13.69	68.84
	1 month ago	Nanyang Basin	17.55	2.44	80.00
		Jianghan Plain	4.98	16.53	78.49
	In the month	Nanyang Basin	15.82	2.98	81.20
		Jianghan Plain	4.64	39.09	56.27
Precipitation	2 months ago	Nanyang Basin	9.40	6.50	84.10
		Jianghan Plain	6.56	15.34	78.11
	1 month ago	Nanyang Basin	4.73	32.37	62.90
		Jianghan Plain	12.58	13.84	73.58
	In the month	Nanyang Basin	31.63	4.76	63.62
		Jianghan Plain	13.57	23.18	63.24

3.2.2 Human activities

With the acceleration of urbanization, human activities have profoundly affected the vegetation cover change. In this article, the "climate-NDVI" model was built based on the data between 2001 and 2008 to predict the $NDVI_g$ value from 2009 to 2015. Then, this predicted value was compared to the measured value between 2009 and 2015 for the analysis. Then, the residual analysis method was adopted to calculate the impact of human activities on the vegetation cover, thus analyzing the variation trend of the influence of human activities.

First, after the correlation between $NDVI_g$ and climatic factors was analyzed, a "climate-NDVI" model was built based on the temperature 2 months ago (L_1), the precipitation 1 month ago (L_2), the average growing-season temperature (L_3), and the average growing-season precipitation (L_4), which were highly correlated with $NDVI_g$. The regression equation for the $NDVI_g$ at different elevations in the mid-lower reaches of the Hanjiang River Basin is expressed as follows:

$$NDVI_g = \begin{cases} 3.992L_1 - 0.307L_2 - 3.925L_3 - 0.537L_4 \\ \quad (DEM \leq 300 \text{ m}) \\ 1.188L_1 - 0.396L_2 - 1.398L_3 - 1.083L_4 \\ \quad (300 < DEM \leq 1,900 \text{ m}) \\ -0.194L_1 - 0.859L_2 - 1.024L_3 + 1.282L_4 \\ \quad (DEM > 1,900 \text{ m}), \end{cases} \quad (6)$$

In the above three equations, the adjusted determination coefficients were all above 0.5. The F statistical value was over 150, and its corresponding p value was less than 0.01. The multiple regression model passed the significance test.

The "climate-NDVI" model was used to simulate the NDVI in the mid-lower reaches of the Hanjiang River

Basin from 2009 to 2015. Then, the simulated multi-year mean $NDVI_g$ was calculated (Figure 7(a)). According to the simulation results, the basin's vegetation cover decreased from northwest to southeast, which was similar to the measured $NDVI_g$ value. Thereinto, the vegetation growth condition was optimal in the Shennongjia Forestry District, as well as western and northern mountainous areas, showing a simulated mean $NDVI_g$ of over 4.5. The second was the Nanyang Basin, showing a simulated mean $NDVI_g$ of 3.5–4.5. The vegetation condition was worst in Jianghan Plain, with a simulated mean $NDVI_g$ of less than 3.5.

A residual analysis was carried out based on the measured and simulated $NDVI_g$ values, thus analyzing the effect of human activities on the vegetation cover in the basin (Figure 7(b)). The $NDVI_g$ residual was 0.26 on average, indicating that human activities promoted the regional vegetation growth. The concrete manifestations were as follows: the $NDVI_g$ residual was generally less than 0 in areas around the Nanyang Basin, which meant that such activities inhibited the vegetation growth slightly. However, in the central areas of the Nanyang Basin, the residual fluctuated around 0, indicating that the vegetation growth was not affected by these activities. The $NDVI_g$ of the Jianghan Plain generally exceeded 0, especially in Jingmen, Zhongxiang, Jingshan, Tianmen, etc. Here, human activities showed a more significant promoting effect.

Further calculation of the residual variation trend is shwn in Figure 7(c), which showed that the slope for the change of the influence of human activities is $0.07/15a$ on average. In this figure, the positive value indicated that the influence of human activities continued to increase, while the negative value meant the influence weakened. It can be known by combining with the residual spatial distribution in Figure 7(b) that human activities had an inhibited effect on the vegetation growth in areas around
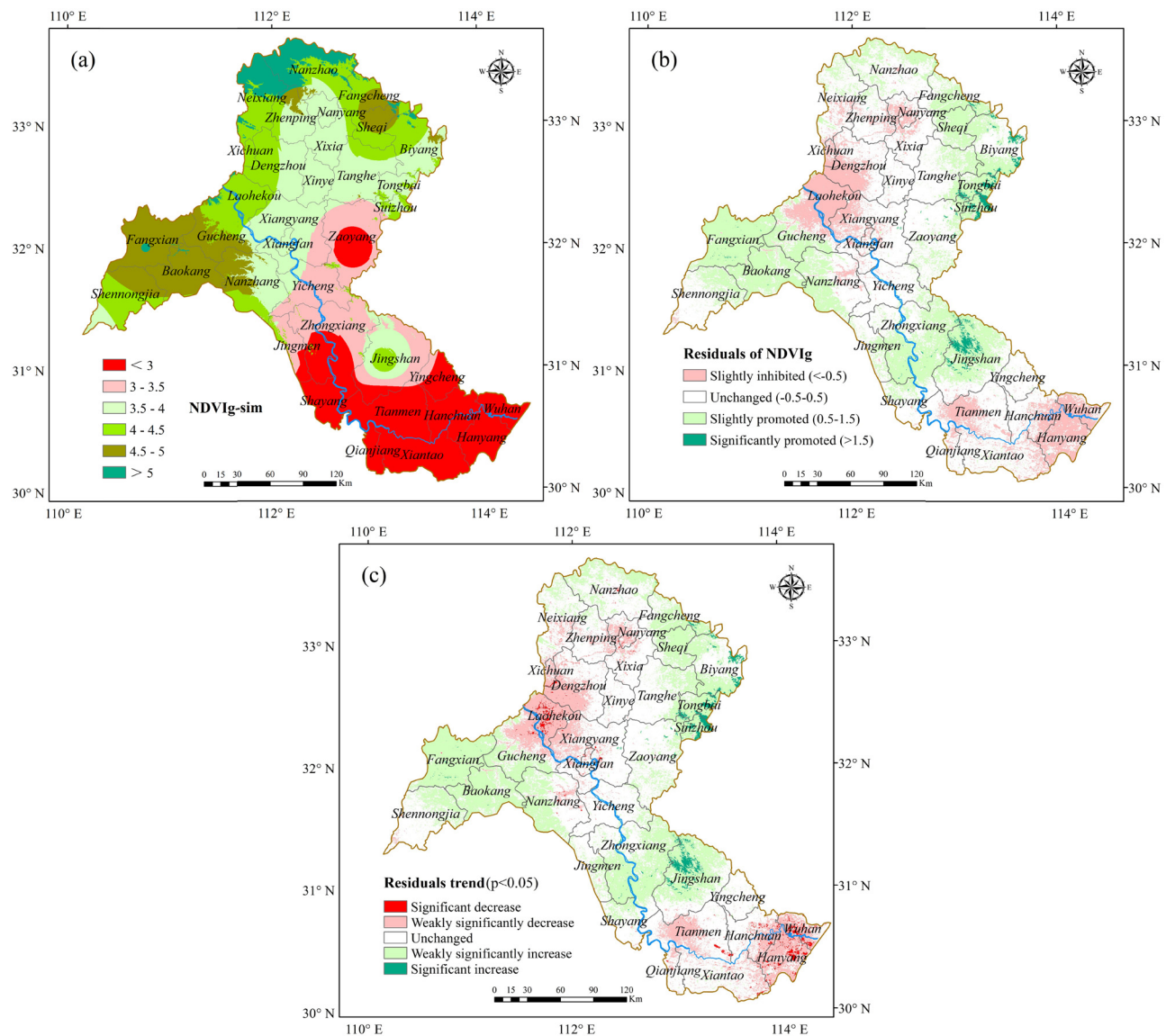
Figure 7: (a) Spatial distribution of the average NDVI$_{g\text{-sim}}$, (b) residuals spatial distribution, and (c) residuals variation trend.

the Nanyang Basin, but this effect decreased gradually. However, in most areas of the Jianghan Plain, such activities promoted the vegetation growth, and this promoting effect also decreased gradually.

4 Discussion

4.1 Vegetation cover change trend

During the study period, the vegetation cover had a fluctuated increasing trend in the basin, which was consistent with the variation trend in the whole Hanjiang River Basin [37]. The vegetation was improved most significantly in the Nanyang Basin and its surrounding areas. Relevant research indicated that this was associated with the strategy for the harmonious development of "new industrialization, new urbanization and agricultural modernization" as well as the project of returning farmland to forest and grassland in Henan [39,40]. In addition, vegetation cover in the southeastern of the Jianghan Plain showed a decreased trend, which may be related to the urban economic development, for it has been proved that the rapid GDP growth would reduce the vegetation cover [41].

4.2 Response of vegetation cover to climatic factors

On the interannual scale, the vegetation $NDVI_g$ was significantly negatively correlated with the average growing-season temperature in the western mountainous area of the Nanyang Basin, while it was positively correlated with the temperature in the east of the Nanyang Basin (Figure 5a). According to the previous study [42], the reason may be that higher temperatures accelerated the transpiration and evaporation of mountainous vegetation. Thus, the vegetation growth was restricted due to water shortage. However, in eastern agricultural regions, the increase of the temperature may prolong the frost-free season [43], thus extending the growing season and increasing the vegetation cover. In the Jianghan Plain, the $NDVI_g$ showed a weak correlation with the average growing-season temperature but showed a strong one with the mean precipitation (Figure 5(a and b)). However, Kong CF proposed that the vegetation growth was more strongly correlated with the annual average temperature than with the temperature [44]. Different temporal scales of studies may cause a discrepancy between the two conclusions. This article only calculated the annual growing-season data, while the previous results were obtained based on the full-year data.

On the intraannual scale, the vegetative response to temperature and precipitation lagged by 2 and 1 months, respectively, in the Nanyang Basin. There was no noticeable lag effect in the vegetative response to the two factors in the Jianghan Plain. However, the research carried out by Li showed that the vegetation response to the temperature had no lag effect in the Nanyang Basin and the Jianghan Plain, and the response to precipitation lagged by 20 days [45]. Different spatial-temporal scales of studies may cause the discrepancy.

4.3 Response of vegetation cover to human activities

Through investigation and evaluation, the vegetation growth in the Nanyang Basin and its surrounding areas at different stages may be mainly affected by hydraulic engineering construction, and the direct impact was from the water pipeline construction [46]. During the construction process, the surface vegetation would be directly eradicated in the operation area, resulting in the reduction of forest and grassland. But after the construction, the operation area gradually turned into bare land, and vegetation could be restored after a period of natural succession. Meanwhile, the water storage was increased due to the Danjiangkou Hydraulic Project

after October 2005, which submerged the surrounding croplands, forest lands, and grasslands and had a significant effect on the vegetation cover [47–49]. Moreover, due to the ecological benefit brought by the hydraulic engineering construction [50,51], the regional and local climate formed, and the growth conditions of forest lands and grasslands became better [49]. Besides, the implementation of ecological engineering projects such as returning farmland to the forest reduced the negative effect that human activities had on the vegetation cover, and the vegetation cover increased significantly [52,53]. Therefore, the negative effect of human activities on the vegetation cover weakened gradually, and the vegetation cover increased significantly.

After 2009, the water source for the middle route of South-to-North Water Transfer witnessed mass immigration, which had an important impact on the regional vegetation cover changes [54]. On the one hand, in the migrating-out areas, due to the policy of returning farmland to forest, a large amount of farmland reclaimed from wasteland had been turned into forest again [55]. On the other hand, in the resettlement areas, large amounts of wood were used in house construction, resulting in a decrease in the forest area [56]. In addition, immigration had changed people's production and lifestyles, especially the farming system and farming methods, which also had an impact on the vegetation cover changes [57].

Furthermore, the $NDVI_g$ residual generally exceeded 0 in the Jianghan Plain because the modern agricultural development, especially mechanization, had a positive effect on the regional vegetation. According to the data, the agricultural area decreased by 1451.58 km^2 between 2000 and 2015 in the Jianghan Plain [58]. However, in the same period, the total annual NPP of regional farmlands tended to be stable on the whole [59], which, to a certain extent, indicated that the realistic productivity of farmlands was improved. Compared to the data about the mechanization level in this period, the total power of agricultural machinery increased from 5.72×10^6 to 1.76×10^7 kW, and the grain yield increased from 6.6×10^6 to 8.0×10^6 t [60]. Without the interference of planting structure adjustment and crop variety change, mechanization may be the key in promoting the vegetation growth in the Jianghan Plain.

5 Conclusion

With the mid-lower reaches of the Hanjiang River Basin as the study object, this article, based on the MODIS NDVI time-series data from 2001 to 2015, discussed the response of the vegetation cover change to climatic factors and

human activities at different elevations under the pretext of hydraulic engineering construction and modern agricultural development. The following are the major conclusions:

(1) The vegetation cover in the study area was "high in the west and north, lower on both sides of Hanjiang River, and lowest in the center and southeast." It changed parabolically with increasing elevation: Vegetation cover increased below 1,900 m and then decreased steadily over 1,900 m.

(2) Over the 15 years, vegetation cover in the basin showed an increasing trend, and the increased and decreased areas were 90.72 and 9.23%, respectively. The extremely significantly increased and decreased areas were 41.8 and 1.26%, respectively.

(3) The response of vegetation cover to climatic factors varies greatly depending on increasing elevation. That is, the lag effect under the impact of temperature disappeared gradually, while it became more evident under the impact of precipitation.

(4) Human activities promoted vegetation cover on the whole, with an average slope of $0.07/15a$. Around the Nanyang Basin and the most parts of the Jianghan Plain, human activities played an inhibited and a promoted role, respectively, but both roles were gradually weakening.

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