Responses of the Yellow River basin vegetation: climate change

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Abstract

Purpose – This paper aims to study the temporal and spatial variation of vegetation and the influence of climate change on vegetation coverage in the Yellow River basin, China. The current study aimed to evaluate the role of a series of government-led environmental control projects in restoring the ecological environment of the Yellow River basin.

Design/methodology/approach – This paper uses unary linear regression, Mann–Kendall and wavelet analyses to study the spatial–temporal variations of vegetation and the response to climate changes in the Yellow River, China.

Findings – The results showed that for the past 17 years, not only the mean annual increase rate of the Normalized Difference Vegetation Index (NDVI) was 0.0059/a, but the spatial heterogeneity also yields significant results. The vegetation growth in the southeastern region was significantly better than that in the northwestern region. The variation period of the NDVI in the study area significantly shortened, and the most obvious oscillation period was half a year, with two peaks in one year. In addition, there are positive and negative effects of human activities on the change of vegetation cover of the Loess Plateau. The project of transforming cultivated land to forest and grassland promotes the increase of vegetation cover of the Loess plateau. Unfortunately, the regional urbanization and industrialization proliferated, and the overloading of grazing, deforestation, over-reclamation, and the exploitation and development of the energy area in the grassland region led to the reduction of the NDVI. Fortunately, the positive effects outweigh the negative ones.

Originality/value – This paper provides a comprehensive insight to analysis of the vegetation change and the responses of vegetation to climate change, with special reference to make the planning policy of ecological restoration. This paper argues that ecological restoration should be strengthened in areas with annual precipitation less than 450 mm.

Keywords Climate change, NDVI, Land use, Spatial–temporal variation, Environmental policy

Paper type Research paper

1. Introduction

The correlation between global climate change and the terrestrial ecosystem is one of the core subjects in scientific research on global climate change (Zhang, 1993). According to the Intergovernmental Panel on Climate Change (IPCC)'s AR5 report, between the period

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1983 to 2012, the world experienced the warmest 30-year period in the northern hemisphere in the last 800 years (IPCC, 2013). This drastic change in climate has had significant impacts on vegetation. Being the main component of the Earth's ecosystem, vegetation plays a significant role in the global cycle of matter and energy (Yi *et al.*, 2014). As a result, the vegetation in the Yellow River basin, China, is vulnerable to climate change. Vegetation is paramount for ecological research (Zhang *et al.*, 2008) because it helps not only to understand and simulate the dynamic changes in the ecosystem but also identify the correlation between climate change and changes in vegetation cover over time. Furthermore, it can also provide spatial information about and theoretical support to China's project to transform farmland into forest and grassland. Therefore, the spatial-temporal variations in vegetation in the Yellow River basin and the dynamic response to climatic factors (e.g. temperature and precipitation change) are scientific concerns.

The spatial-temporal patterns of vegetation and the response of vegetation to climate change have attracted extensive attention. Studies in drought and semi-arid regions have reported that the Normalized Difference Vegetation Index (NDVI) is positively correlated with precipitation, especially in central Asia (Yin *et al.*, 2017), South Africa and Australia (Ichii *et al.*, 2002). In different regions, researchers have carried out dynamic spatial-temporal analyses of vegetation over extended periods of time (Florian *et al.*, 2016; Luan *et al.*, 2018), analyses of vegetation cover changes under the influence of climate change and human activities (Shen *et al.*, 2015; Tian *et al.*, 2015) and analyses of the factors that drive change in vegetation cover (Amy *et al.*, 2016; Fu and Isabela, 2015). Several research groups have analyzed the relationship between vegetation and people whose livelihoods depend on forests (Angelsen *et al.*, 2014; Angelsen and Wunder, 2003). For instance, Jumbe and Angelsen analyzed the benefit from a devolution in the forest management of local people, especially vulnerable households, and demonstrated an increase in the income from the forest for female and low-income people (Jumbe and Angelsen, 2006). Dash *et al.* (2016) observed that the provision of non-farm employment and adequate farming land goes a long way in reducing household dependence on non-timber forest products and, thereby, promotes the outcomes of forest conservation. Ali and Bahadur (2017) utilized multivariate probit and propensity score matching methods to establish a relationship between poverty, household income and forest resources. They found that forest resources can increase a household's income. Heltberg (2004) discussed the determinants of household fuel usage and fuel switching and demonstrated that there is a direct relationship between electrification and the uptake of modern cooking fuels. Behera *et al.* (2015) showed that the age, gender and education level of the household's head has a close connection with the household's choice of energy sources. Heltberg (2005) discussed the factors that determine a household's choice of cooking fuels and demonstrated a strong dependence of household income on the choice of cooking fuel. However, one should note that income is not the only detrimental factor in this regard. It is worth mentioning that modern fuels cannot replace the utilization of fuel-wood in rural areas due to poverty. Rahut *et al.* (2016) claimed that rural households who are engaged in forestry-related activities have a higher income than those who do not exploit forest resources. However, the increase in forestry-dependent income is usually limited to a certain extent. Rahut *et al.* also observed that wood-based products are economically more viable and rewarding than non-wood-based products.

In China, studies on the spatial-temporal evolution of vegetation in the Yellow River basin and the response of vegetation to climate change have found that precipitation influences vegetation positively. Scholars have reported that vegetation has shown an increasing trend and that precipitation plays a leading role in interannual changes in

vegetation (Yang *et al.*, 2002). Li and Yang (2001) analyzed changes in the spatial pattern of the NDVI in the Yellow River basin from 1982 to 1998 and concluded that the average annual NDVI showed an increasing trend and that the variation within the year in the NDVI was positively correlated with precipitation.

Moreover, Liu *et al.* indicated that the grassland and shrub types of land use were significantly correlated with precipitation and temperature (Liu and Xiao, 2006). He and He (2012) analyzed the spatial-temporal variations, and the trend in the interannual variation, of the NDVI in the Yellow River basin based on Systeme Probatoire d'Observation de la Terre/VEGETATION data of 1-km resolution from 1998 to 2011. They concluded that the NDVI and the environment had been continuously improving since 1998. However, the abovementioned studies used between 7 and 12 years of NDVI analysis and low spatial resolution data.

In this paper, we adopt NDVI products with a spatial resolution of 500 meters, linear regression analysis, Mann-Kendall trend tests and wavelet analysis to study the spatial-temporal patterns and the evolution of vegetation in the Yellow River basin. We also explore the response of vegetation to climate and land use change. The factors that have an impact on NDVI changes have been analyzed from the perspectives of climate change and ecological engineering to provide a basis for the management and protection of the ecological environment in the Yellow River basin.

2. Methodology

2.1 Study area

The Yellow River, which originates from the Qinghai Tibetan Plateau in the Bayan Har Mountain in the Qinghai, flows east through nine provinces – Qinghai, Sichuan, Gansu, Ningxia, the Inner Mongolia autonomous region, Shaanxi, Shanxi, Henan and Shandong – and empties into the Bohai Sea in Connolly county in the Shandong province. It has a basin area of 752,443 km² (Yang *et al.*, 2003). The average elevation is above 4,000 m and is higher in the west than in the east (Figure 1). The ecological environment is fragile and seriously marked by soil erosion, and vegetation cover changes dramatically. The elevation toward the east is inferior to 100 m and mainly formed by the alluvial plain of the Yellow River (He and He, 2012). The northwestern region has a dry climate. The southeastern region has a semi-humid climate. The middle region has a semi-dry to dry climate. The average annual temperature and rainfall range between 4.3 and 14.3°C and 200 and 750 mm, respectively. Most importantly, approximately 60-70 per cent of the heavy rainfalls occur between July and September (rainy season) and vary per region.

2.2 Data sources

The temperature and precipitation data of 326 China's national ground meteorological stations in the Yellow River basin were collected from China's meteorological scientific data sharing service network (<http://cdc.cma.gov.cn>). The data used in this study were collected between 1998 and 2015 and belong to the daily value data set of China's surface climate data. For the remote sensing data, we adopted the monthly and annual vegetation index data set of the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (www.resdc.cn). This data set is based on the continuous time series of the SPOT/VEGETATION NDVI satellite remote sensing data. Raster data with 1-km resolution were collected from the earth system science data sharing platform of the Institute of Geographic Sciences and Resources, Chinese Academy of Sciences (www.resdc.cn).

Figure 1.
The map of the
Yellow River
basin in China

2.3 Data analysis

2.3.1 Trend analysis and correlation. Unary linear regression analysis can simulate the trend in variation at the pixel scale. Consequently, the characteristics of the spatial-temporal evolution of vegetation cover can be comprehended. The change trend formula is as follows:

$$\text{Slope} = \frac{n \times \sum_{i=1}^n i \times NDVI_i - \sum_{i=1}^n i \sum_{i=1}^n NDVI_i}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \quad (1)$$

where the slope represents the change trend, $NDVI_i$ is the NDVI value in the i th year, and n is the length of the time series. When the slope is > 0 , the NDVI shows an increasing trend; when the slope is < 0 , the NDVI shows a downward trend; and when the slope $= 0$, the NDVI does not change.

2.3.2 Correlation and significance test. The correlation coefficients between each pixel's NDVI value and years were calculated, and the trend in variation of vegetation growth was tested with the correlation coefficient r_{xy} . The calculation formula is as follows:

$$r_{xy} = \frac{\sum_{i=1}^n [(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (2)$$

2.3.3 Time-series analysis. The Mann-Kendall trend test is a nonparametric statistical test used to test the significance of the change trend; the samples do not have to have a certain

distribution, nor are they affected by a few outliers (Tošić, 2004). The formulas are as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{S(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{S(S)}} & S < 0 \end{cases} \quad (3)$$

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^n \text{sgn}(NDVI_j - NDVI_i) \quad (4)$$

$$\text{sgn}(NDVI_j - NDVI_i) = \begin{cases} 1 & NDVI_j - NDVI_i > 0 \\ 0 & NDVI_j - NDVI_i = 0 \\ -1 & NDVI_j - NDVI_i < 0 \end{cases} \quad (5)$$

$$S = \frac{n(n-1)(2n+5)}{18} \quad (6)$$

where $NDVI_i$ and $NDVI_j$ are the NDVI values of the pixels in the i th and j th years, respectively, n represents the length of the time series, sgn is a symbolic function, and the Z value is $(-\infty, +\infty)$. At the given significance level ($P < 0.05$), there is a significant change when $|Z| > u_{1-\alpha/2}$.

2.3.4 Detection of periodicity and abrupt changes. A wavelet analysis is often used to reveal the characteristics of multi-temporal geographic phenomena and to detect the periodicity of and abrupt changes in a time series. The Morlet wavelet has been widely used in meteorology and hydrology. In this paper, the wavelet analysis method was adopted to study the period of change, abrupt points of change, and phase structure of the average monthly NDVI of the Yellow River basin over the last 18 years. Details of the method's steps can be found in Yi and Shu (2012).

3. Results

3.1 Change trends of NDVI, temperature and precipitation in the Yellow River basin

The characteristics of the change in NDVI over time were studied in the vegetative covered area based on the monthly and interannual scale changes in the NDVI (Figure 2a) as well as the monthly average temperature and precipitation (Figure 2b) from 1998 to 2015. A unimodal pattern change was observed in the NDVI values. The peak was reached in the months of July and August, and the annual NDVI showed yearly periodic changes. The average NDVI value steadily increased and ranged between 0.15 and 0.5. Even though the change in the monthly scale of the vegetation cover was generally constant, as indicated by the fluctuating monthly average NDVI values, the periodic change was significant. The vegetation showed a decreasing trend from 1998 to 2001, followed by a rapid increase from 2001 to 2004, a slight decrease from 2004 to 2006, and finally a slow increase afterward.

Figure 2. The trends of the monthly and interannual average Normalized Difference Vegetation Index (NDVI) (a, c), temperature, and precipitation (b, d), and changes in the Yellow River basin during 1998-2015

From 2013 to 2015 (Figure 2c), the amount of vegetation significantly decreased. The annual precipitation of the Yellow River basin showed a gradually increasing trend, especially in the summer and autumn seasons of 1998, 2003 and 2013 (Figure 2d). The temperature did not show significant changes in general, except for extremely low temperatures in the years 2000, 2008 and 2011.

3.2 The spatial pattern and the spatial-temporal changes in the NDVI

3.2.1 The spatial distribution of vegetation. The amount of vegetation significantly decreased from southeast to northwest, and the high-vegetation areas were mainly distributed in the eastern and central parts of Shanxi, south-central Shaanxi, the lower reaches of the Yellow River, the southeast of Qinghai, the southwest of Gansu and most of Henan and Shandong. The medium-vegetation areas were mainly distributed in the north of Shaanxi, the west of Shanxi, the east of Inner Mongolia and the southeast of Gansu. The low-vegetation areas were mainly distributed in the northwest of Inner Mongolia and north-central Ningxia. Due to the humid climate in the southern and southeastern regions, the vegetation type of the middle and lower reaches of the Yellow River was found to be

temperate broad-leaved forests, while coniferous forests were found upstream. The areas with NDVI > 0.6 were mainly distributed in the eastern and southern regions (Figure 3).

The northwest region of the study area is far from the sea and has extremely low vegetation cover. The mean NDVI value is significantly lower in the estuary and the surrounding area of the Yellow River. The reason for this phenomenon is that waves of the sea and river have washed the estuary of the Yellow River for a long time, resulting in poor vegetation growth conditions. In addition, as an alluvial plain of the Yellow River, Hetao plain, which is located in the northwest of the study area, is an important grain production base. The NDVI value of this region was significantly higher than that of surrounding regions. This is due mainly to its fertile soil, flat terrain, and proximity to the Yellow River for irrigation.

3.2.2 The spatial-temporal dynamics of the NDVI. The spatial distribution of the variation in vegetation from 1998 to 2015 (Figure 3) and the areas of different change levels (Table I) were obtained through the unary linear regression trend analysis. The NDVI of most of the regions exhibited an increasing trend, where the increasing slope in most of the studied areas ranged from 0 to 0.007/a. From the results of this study, few regions reached the value of 0.02/a, and the maximum slope was 0.056/a (Figure 4). This indicates that the increase in the NDVI in those areas that had less than 450 mm of precipitation was significantly higher than that in the other study areas. These results show that, since the 21st century, China's large-scale ecological restoration in this region has achieved obvious results and the environment has been gradually restored.

Figure 3. The average annual NDVI values in the Yellow River basin from 1998 to 2015 (0 for no vegetation; close to +1 (0.8-0.9) indicates the highest possible density of green leaves)

NDVI variance tread	Area (km ²)	Proportion (%)	NDVI variance tread	Area (km ²)	Proportion (%)
Slope < -0.05	1	0.00	0 ≤ Slope < 0.01	531,848	64.69
-0.05 < Slope < -0.04	3	0.00	0.01 ≤ Slope < 0.02	180,071	21.90
-0.04 ≤ Slope < -0.03	18	0.00	0.02 ≤ Slope < 0.03	8635	1.05
-0.03 ≤ Slope < -0.02	644	0.08	0.03 ≤ Slope < 0.04	415	0.05
-0.02 ≤ Slope < -0.01	6,268	0.76	Slope ≥ 0.04	22	0.00
-0.01 ≤ Slope < 0	94,252	11.46			
Total	101,186	12.3		720,991	87.7

Table I. The linear regression analysis of NDVI variations in the Yellow River from 1998 to 2015

On the Qinghai-Tibet plateau (the southwest of the study area), the average annual precipitation was greater than 450 mm, but the vegetation degradation was more obvious. Ecological restoration project measures in areas with an average annual precipitation value between 270 and 450 mm were found not to be very effective. The ecological restoration effects have achieved obvious results south of the 400 mm isohyet and general results in the north. Changes in the NDVI values to a low degree were scattered in the southeastern and northwestern regions of the study area. Areas with an average annual precipitation value below 270 mm and the lower reaches of the Yellow River were the areas with the most serious vegetation degradation.

The reduction in the southeastern region's vegetation was mainly due to the enlargement of construction areas during an urban construction process. These regions include Xi'an city, Luoyang city, Jiaozuo city and Jincheng city. Furthermore, the reduction in the vegetation cover of the northwestern region was due to the poor climate conditions coupled with long-term overgrazing and reclamation, among other things (Liu *et al.*, 2018).

NDVI values with negative slopes covered 12.3 per cent of the total area (101,186 km²), while those with positive NDVI values covered 87.7 per cent of the total area (720,991 km²; Table I). The NDVI has been increasing in recent years, and the added value has generally been between 0 and 0.02/a. The area with a slope between 0 and -0.01 is 94,252 km² and accounts for 11.46 per cent of the total area. The area with a slope between 0 and 0.01 is 531,848 km² and accounts for 64.69 per cent. The area with a slope between 0.01 and 0.02 accounts for 21.9 per cent, while the area with a slope between -0.02 and -0.01 accounts for 0.76 per cent.

3.2.3 Significant changes in NDVI. A correlation analysis between the NDVI in different years and the corresponding years was conducted to quantitatively analyze the degree of variation in the NDVI in the study area as well as to obtain the regression coefficient (*R*) between each pixel. The significance level of 0.05 was tested ($p < 0.05$), and the trend of variation in the average annual NDVI was obtained (Figure 4b). Significant increases in the NDVI were found in the Qinling mountains, Hetao plain and the southeastern edge of the Qinghai-Tibet plateau; areas with a significantly reduced NDVI were distributed sporadically in the northwestern region. The NDVI showed an increasing trend in most regions of the study area (87.72 per cent of the total area).

3.2.4 The Mann-Kendall abrupt changes and mutation test. According to the Mann-Kendall test, only UF or UB lines are required to analyze an upward or a downward trend of a time-dependent NDVI value. If $UF > 0$ or $UB < 0$, the sequence exhibits an upward trend and vice versa. When UB or UF exceed the critical line, the upward or downward trend becomes significant. If UF and UB intersect within the critical region ($|Z| < 1.96$), then

Figure 4. One-dimensional linear regression slopes of the NDVI distribution (a) and a significance test (b) of the change in the NDVI in the study area from 1998 to 2015

mutation begins at that time. The vegetation mutation time is the time at which the degree of change in vegetation is significant. Since 1998, the NDVI of vegetation in the study area has had an increasing trend, and after the mutation point (the year when UF and U intersect), the NDVI of vegetation has shown a tendency to increase significantly. The abrupt point of change in the NDVI in the time series was reported by using the yearly NDVI of the Yellow River basin from 1998 to 2015 (Figure 5).

The UF curve indicates a significant upward trend of the yearly NDVI in the research area. Moreover, the Z value of the UF curve changed from less than 0 to greater than 0 in 2003, indicating that the NDVI increased year-by-year from 2003 onward. The NDVI trend experienced a clear vibration and large wave amplitude from 1998 to 2004. After 2004, the overall fluctuation became relatively more stable. The $|Z|$ values of the UF curve from 1998 to 2000 and from 2013 to 2015 were >1.96 ($\alpha < 0.05$), indicating that the NDVI values of the study area significantly increased during this period. In 2007, the UF and UB curves intersected in the critical region ($|Z| < 1.96$), which indicates that the time of intersection was the beginning of the mutation.

3.2.5 Characteristics of the periodic variation in the NDVI. A Morlet wavelet analysis was performed to test the periodic evolution of the NDVI. The results of the wavelet analysis of the NDVI clearly show the time series change and phase structure of the NDVI (Figure 6). There are two peaks in the NDVI each year, with obvious seasonal changes. The most significant oscillation period in the study area is half a year (with two peaks per year). In the Figure 6a timescale, there are two obvious low-value centers and one high-value center to the low peaks and a high peak, corresponding to 2000, 2003, and 2006, respectively. There are three low-value centers in the Figure 3a timescale, corresponding to 2011, 2012, and 2014, which indicate that the NDVI value is lower in these years than in adjacent years.

3.3 Response of vegetation to climatic factors

Temperature and precipitation are two major climatic factors that influence vegetation change (Fu *et al.*, 2007). To analyze the response of vegetation to temperature and precipitation, we analyzed the spatial distribution of the correlation of the average annual NDVI with temperature and precipitation from 1998 to 2015. Figure 7a shows the highly significant positive correlation between the NDVI and temperature in the southeastern

Figure 5. The Mann-Kendall test curves of yearly NDVI from 1998 to 2015 (The vegetation mutation time is the time at which the degree of change in vegetation is significant)

region of the Yellow River basin ($p < 0.01$), mainly in the Shaanxi and Shanxi provinces, while a significant positive correlation ($p < 0.05$) was found at the source of the Yellow River in the south of Qinghai province.

Significant negative correlation centers were observed in the northern areas of Shaanxi and Nei Mongol, northwestern and northern regions of the Yellow River basin, and the region near the upstream of the Yellow River in the northern areas of Qinghai, Gansu and Ningxia. The region containing a positive correlation between the NDVI and temperature is larger than the region with a negative correlation, indicating that the average annual temperature and the NDVI have a positive correlation. Significantly, the region that shows a negative correlation between the NDVI and temperature is distributed in the central parts of Shanxi province.

The region that exhibits a negative correlation between the NDVI and precipitation is distributed mainly in Shanxi, Shaanxi, Qinghai and Gansu (Figure 7b). The center of the significant positive correlation between the NDVI and precipitation has the same special distribution as the center of the negative correlation between the NDVI and temperature, which indicates that precipitation promotes vegetation growth in Ningxia and Nei Mongol, while lower temperatures reduce vegetation growth.

Figure 6.
The Morlet wavelet of the NDVI in the Yellow River basin from 1998 to 2015 (Low means that the wavelet coefficient is low, indicating that the NDVI is low; High means that the wavelet coefficient is high, indicating that the NDVI is high)

Figure 7.
The spatial distribution of the significance of NDVI change with temperature (a) and precipitation (b) in the Yellow River basin from 1998 to 2015

3.4 Response of vegetation to changes in land use

The vegetation in the Yellow River basin has greatly changed in the period 1998–2015 due to the frequent changes in land use in the farming–pastoral transitional zone (Table II). In that period, the area of the land use types that changed was 18,394 km², which accounts for 2.23 per cent of the total basin area. The largest transformed area during the study period was cultivated land that turned into construction land, which accounts for 1.47 per cent of the total cultivated area.

The main reasons for the reduction in cultivated land and the increase in forest and grassland are the return of farmland to forest and grass project (Feng *et al.*, 2005), the “Tianbao” project for the planting and protection of large natural forests (State Forestry Administration, 2015) and the “Sanbei” shelterbelt project (State Forestry Administration, 2015). It should be noted that, with the increasing demand for urban construction, farmland, forest land and grassland have transformed into construction land.

Because this transformation of land use is significant for estimating the degree of vegetation cover of different land types, the average NDVI value and pixel number were calculated for 2000 and 2015 (Table III). The area of grassland is the largest in the study area, followed by cultivated land and forest land, while the area covered by water is the smallest. The area of cultivated land, grassland, and unutilized land exhibited a downward trend with a decreasing proportion of –2.62 per cent, –0.81 per cent and –0.59 per cent, respectively, whereas the area of construction, water and forest land demonstrated an

Land use type	Grassland	Cultivated land	Construction land	Forest land	Water	Unutilized land	Total
Grassland	377,387	2,005	1,710	1,720	471	2,390	385,683
Cultivated land	2,746	213,121	3,279	1,526	870	392	221,934
Construction land	39	28	19,189	10	34	9	19,309
Forest land	367	146	223	107,107	80	88	108,011
Water	237	378	94	40	12,848	270	13,867
Unutilized land	1,801	598	564	322	297	69,708	73,290
Total	382,577	216,276	25,059	110,725	14,600	72,857	822,094

Table II.
The land use change
matrix in the Yellow
River basin from
2000 to 2015

Types of land use	Value	2000	2015	(%)
Cultivated land	NDVI	0.50	0.61	18.03
	Area (km ²)	221,934	216,276	–2.62
Forest land	NDVI	0.67	0.77	12.99
	Area (km ²)	108,011	110,725	2.45
Grassland	NDVI	0.47	0.52	9.62
	Area (km ²)	385,683	382,577	–0.81
Water	NDVI	0.39	0.45	13.33
	Area (km ²)	13,855	14,588	5.02
Construction land	NDVI	0.51	0.49	–4.08
	Area (km ²)	19,309	25,059	22.95
Unutilized land	NDVI	0.31	0.31	0.00
	Area (km ²)	73,285	72,852	–0.59

Table III.
The NDVI of
different types of
land use in 2000 and
2015 (P-N: the
average pixel value
of the NDVI)

upward trend. The area of construction land has been increased significantly, with a rate of increase of 22.95 per cent between 2000 and 2015.

The NDVI value of forest land is the largest, followed by cultivated land and grassland, while the NDVI of unutilized land is the lowest. The NDVI of cultivated land, forest land and grassland increased by 18.03 per cent, 12.99 per cent and 9.62 per cent, respectively.

4. Discussion

The amount of vegetation on the Loess plateau gradually increased from northwest to southeast. Moreover, the amount of vegetation in the arid and semi-arid regions remained low, whereas the amount of vegetation in the semi-humid regions became high. The current study shows a gradually increasing trend in vegetation, which is consistent with the results of [Gou et al. \(2018\)](#). Gou et al. demonstrated that the vegetation coverage of the Loess Plateau gradually increased. However, in the middle and lower regions of the Yellow River, the vegetation around large and medium-sized cities exhibited a decreasing trend, which is directly related to the city's one-sided pursuit of development scale.

The results reveal that vegetation is negatively related to temperature in most of the arid areas, which explains the vegetation degeneration phenomenon in the drought area during the last 20 years. Without obvious changes in rainfall, the increase in temperature accelerates the leaf transpiration of vegetation, which leads to an increase in evaporation, a reduction in soil moisture, and, subsequently, a reduction in vegetation growth and photosynthesis ([Dai et al., 2011](#)). The correlation coefficient between vegetation and rainfall is higher in arid and semi-arid areas, and lower in semi-humid areas, indicating that rainfall plays a critical role in vegetation growth in water-deficient areas.

This observation is also consistent with previous reports on the relationship between vegetation and rainfall in the Yellow River basin ([Nemani et al., 2003](#); [Zhao et al., 2011](#)). Moreover, the vegetation in areas with annual precipitation of higher than 450 mm has shown an increasing trend over last two decades, which can be ascribed to the implementation of the Returning Farmland to Forest and Grass project, which was initiated in 1999. Hence, we can conclude that the significant increase in vegetation coverage is mainly related to the positive impact of human activities (The Grain for Green Program). On the other hand, the deterioration of the environment in the Yellow River basin is related to residents' lack of environmental awareness and the utilization of wood as fuel in rural households ([Lang et al., 2014](#)).

In addition, irrational farming practices, the exploitation of resources and excessive deforestation have also contributed to vegetation degradation. Furthermore, the spatiotemporal changes in regional hydrothermal resources, caused by global climate change, have a significant impact on vegetation growth. Consequently, since the middle and upper regions of the Yellow River basin are located in the transition zone from a humid and semi-humid climate to an arid and a semi-arid climate, the extremely fragile ecological environment has become an important reason to induce vegetation degradation.

To restore the environment of the Yellow River basin, we make the following recommendations for future strategies and policies:

- To achieve the sustainable development of the environment and utilization of natural resources, the Chinese government needs to craft strict regulations to ban and inhibit deforestation in river areas. In addition, each community should be advised to initiate voluntary, paid and nongovernmental organization (NGO)-sponsored and government-sponsored reforestation and vegetation initiatives in the Yellow River basin. At the same time, it is worth mentioning that fuel-wood is an important energy source for rural households. The Chinese government should

focus on the development of alternative energy sources, such as solar, wind, natural gas, and electricity, for rural areas. Moreover, the government should actively promote the utilization of clean energy sources instead of fuel-wood to minimize deforestation.

- Overgrazing, urbanization, the overexploitation of natural resources and over-reclamation have played a critical role in the ecological deterioration. Hence, rational planning and utilization of natural resources should be carried out to prohibit crude deforestation, which shall result in increased agricultural output. Moreover, agricultural production should be carried out by raising the level of agricultural mechanization and improving the soil fertility. In the urbanization process, more attention should be paid to the protection of the surrounding city's environment, which implies that the expansion of urban space should not be carried out at the cost of the ecological environment.
- This study revealed that the vegetation growth in arid regions that have less than 450 mm of precipitation was adversely affected by the low rate of precipitation, and this shortage of water resources was the main reason for the lower vegetation growth. Therefore, we suggest the maximum exploitation of prevailing precipitation conditions on short-term bases. For example, on a smaller scale, some experimental vegetation restoration belts should be developed by using an artificial irrigation system and a rain-fed system simultaneously according to local conditions. This strategy may help the soil to absorb and retain water, minimizing surface runoff and enhancing the conservation of soil to water. Therefore, it would be beneficial to ensure the effectiveness of the utilization of water resources.
- The most important measures for the restoration of vegetation on the Loess Plateau include banning deforestation, planting grass and afforestation. The area under afforestation accounts for 73.58 per cent of the total project area (Gao *et al.*, 2017), and afforestation measures can be taken to restore vegetation under different precipitation belts. Afforestation in water-deficient areas will aggravate the dry layer of soil beneath and can further restrict the vegetation restoration. Therefore, vegetation restoration measures should be taken according to the water conditions. As the vegetation restoration rate in areas with less than 450 mm of annual precipitation is relatively slow, it would be suitable to take mountain closure and forest prohibition measures to avoid the soil drying that afforestation renders. Vegetation restoration in the Yellow River Basin is a long-term and arduous task; therefore, if China were to continue to de-vegetate the Yellow River basin, sooner or later, it would turn into a desert. However, if the combined knowledge of environmentalists, botanists, pedologists and agricultural engineers is utilized, the Yellow River Basin can be turned into a green forest, and, thus, it would contribute significantly to the conservation of biodiversity and would protect the ridge-to-reef diversity of the river.

5. Conclusion

An investigation of the response of vegetation growth to climate change on the Loess plateau can help us to better predict the ecosystem's response to global climate change in the future. Herein, the change in vegetation and its relationship to temperature and precipitation from 1998 to 2015 were systematically studied. The major findings of the present study include:

- The NDVI data between 1998 and 2015 show a unimodal pattern change over time, peaking in July and August. The average monthly NDVI has obvious annual fluctuations with a small amplitude. The southeastern region has more vegetation than the other areas of the Yellow River Basin. The amount of vegetation significantly decreased from the southeastern to the northwestern region of the study area.
- The rate of increase in the average NDVI was 0.056 and ranged between 0.0 and 0.07/a. The maximum NDVI values were mainly distributed in areas with annual precipitation greater than or equal to 450 mm. The NDVI of most of the regions exhibited an increasing trend, and the increasing trend of NDVI passed the significance test ($P < 0.05$) in the study area.
- The NDVI values have a good correlation with precipitation and temperature in the Yellow River basin. The correlation coefficient of vegetation to temperature and precipitation has obvious spatial heterogeneity; that is, the coefficient changes with the change in space. The significantly positive correlation coefficient between the NDVI and precipitation is consistent with most of the areas of the negative center of the NDVI and temperature.
- Human activities have had an important impact on the growth of vegetation in the Yellow River basin. On the one hand, the Grain for Green Program can promote vegetation restoration, while large-scale urbanization, overgrazing, and mineral resource development will cause damage to a large area of vegetation.

However, although this paper has produced some significant results on the temporal and spatial changes in vegetation in the Yellow River basin, the relationship between vegetation, climate and human activities is equally important. Due to limitations in the resolution of the NDVI data, the length of the time series and the factors influencing vegetation changes, we put forward the following recommendations for further research. Firstly, as the effect of human activities on vegetation is obvious and important, quantitative and qualitative analyses based on interviews with Chinese citizens who live and depend upon the Yellow River Basin are necessary to evaluate the impact of human activities on vegetation change. Secondly, a study should be designed to quantitatively analyze the influence of climatic conditions on vegetation growth in different periods because the response of vegetation growth to climatic factors, such as temperature and precipitation, has a lag effect in time. Thirdly, as natural factors, such as soil, hydrology, insect infestation, radiation conditions, surface evapotranspiration, and carbon dioxide, nitrogen, and phosphorus deposition, also affect the vegetation in addition to topography, temperature and precipitation, these factors should also be taken into consideration in future studies on natural drivers of vegetation growth. Lastly, as soil and water loss in the Yellow River Basin, especially in the middle reaches of the Yellow River, have an important impact on vegetation restoration, quantitative monitoring, analysis and treatment of soil and water loss in the Yellow River Basin are needed on a regular basis – now and into the future.

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