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RESEARCH ARTICLE

Spatiotemporal changes in vegetation coverage and its causes in China since the Chinese economic reform

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Abstract
With the rapid development of the economy over 40 years since the initiation of Chinese economic reform, terrestrial ecosystems in China have undergone large-scale changes. In this study, we investigated vegetation dynamics in China and their relationships with climatic factors and anthropogenic drivers over 15 progressive periods of 18–32 years starting in 1982. This was accomplished by using the third-generation global satellite Advanced Very High Resolution Radiometer (AVHRR), Normalized Difference Vegetation Index (NDVI) dataset, night-time satellite data, and climate data. Across China, NDVI increased significantly during 1982–2013; especially significant increases were observed in all periods during the growing season and spring. At the pixel scale, 21–38% of the vegetated area in the 15 periods experienced a significant positive trend in vegetation growth. This increase was mostly located in central and southern China. A significant negative trend was observed in 1–8% of the vegetated area pixels, and this pattern was mainly seen in northwestern China, the Yangtze River Delta region, and the Pearl River Delta region. The contribution of spring NDVI to vegetation improvement increased, while the contribution of summer NDVI decreased. Vegetation activity in China was mainly regulated by thermal factors, especially pronounced in mountainous regions of northern China. However, the restrictive effect of moisture factors was very marked to vegetation growth in areas with less than 400 mm of precipitation. Urbanization in China has led to vegetation degradation in most urban centers and surrounding areas in central and eastern China. The increase of agricultural plantations, the Grain for Green Project, and a series ecological restoration projects in some areas have promoted vegetation coverage.

Keywords NDVI · Dynamics · Climate changes · Human activities · Nighttime light data

Introduction

Understanding the spatial pattern and dynamic processes of vegetation changes and their causes is one of the key topics in research on global change of terrestrial ecosystems (Chen et al. 2019; Pan et al. 2018; Peng et al. 2012b, 2019; Piao et al. 2011; Xu et al. 2014a; Zhu et al. 2016). As one of the most important components of terrestrial ecosystems, vegetation can convert solar energy to chemical energy through the process of photosynthesis (Franklin et al. 2016; Yu et al.

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2012). Vegetation represents the primary source of food for Earth's heterotrophic organisms, including human beings (Imhoff et al. 2004). Furthermore, vegetation also provides important ecosystem services, such as reducing greenhouse gases and maintaining climate stability (Liu et al. 2019a; Peng et al. 2012b; Piao et al. 2011). Vegetation plays a vital role in global biogeochemical cycles of carbon, oxygen, water, and nitrogen (Franklin et al. 2016). Global environmental change is rapidly altering the dynamics of terrestrial vegetation, with consequences for the functioning of the Earth's ecosystems and the provision of ecosystem services (Zhu et al. 2016). As an integral measure of ecosystem services (Buyantuyev and Wu 2009; Pettorelli et al. 2012), vegetation production and its spatiotemporal changes are important for land carbon sequestration, natural resource management, and ecological research (Cao et al. 2004). Thus, monitoring vegetation activity dynamics and analyzing their causes have been crucial topics in global change research (Peng et al. 2012b; Piao et al. 2011). NDVI is a reasonable proxy for vegetation production and the best indicator for terrestrial plant communities (Burrell et al. 2017; Cao et al. 2004; Fensholt and Proud 2012; Lamchin et al. 2018; Peng et al. 2012a; Prince et al. 2009; Shen et al. 2011; Wessels et al. 2007), and it is also one of the most important metrics used to measure land degradation (Bai and Dent 2009; Fensholt and Rasmussen 2011; Prince et al. 2009).

Within the context of global warming, terrestrial average temperature in China has risen 0.9–1.5 °C during 1909–2011 and 1.38 °C during 1960–2009 (Change ECoNARoC 2014; Ding and Wang 2016; Ren et al. 2012; Yuan et al. 2016). These levels are higher than most places in the world and throughout northern hemisphere during same periods (Change ECoNARoC 2014; Ding and Wang 2016; Ren et al. 2012; Yuan et al. 2016). Significant trends in precipitation across China were not observed during the last 100 years or the previous 60 years, but there were marked spatial differences in precipitation changes, i.e., continued wetting in arid and semiarid regions in western China during the past 30 years (Change ECoNARoC 2014; Ding and Wang 2016; Yuan et al. 2016). Rapid warming and spatial changes in precipitation have caused serious impacts on terrestrial ecosystems, especially in terms of vegetation coverage changes (Liu et al. 2015a; Yuan et al. 2016). A deep understanding of the responses of vegetation to climate changes can provide scientific and practical instructions for sustainable utilization of ecosystem services (Fu et al. 2017; Hao et al. 2017).

Since the Chinese economic reform began in 1978, rapid economic development of China has resulted in a drastic disruption in vegetation from anthropogenic construction activities (Fang et al. 2018). On the one hand, swift urbanization and industrialization on a large scale elevated the urbanization level in China from 17.9% in 1978 to 57.35% in 2017 (China NBoSo 2017). This altered vegetation conditions in city centers and surrounding areas and produced impacts on natural ecosystems. On the other hand, the implementations of the Grain to Green Project, the Natural Forest Protection Project, the Three-North Shelter Forest Project, and other similar projects have promoted vegetation growth (Lu et al. 2018; Ouyang et al. 2014; Ouyang et al. 2016; Qian et al. 2019; Zhao et al. 2019; Zheng et al. 2019). An in-depth analysis on the impacts of human factors and ecological protection activities on the terrestrial vegetation since the Chinese economic reform is critical to project future ecosystem dynamics and the adaptation of ecosystems to global change (Xu et al. 2014b). A summary of the effects of past economic development and ecological efforts can provide support and reference for dealing with tradeoffs between future economic development and ecological protection.

At present, there are some deficiencies in the literature on vegetation change trends and their causes in China. Few studies have focused on the changes of NDVI and its causes in different seasons and the contributions of each season to the changes of NDVI in the growing season. Furthermore, previous research has not sufficiently investigated NDVI change comparisons between various periods and the persistence of NDVI trends. In addition, some studies have integrated GIMMS NDVIg and MODIS NDVI datasets to extend the study period (Li et al. 2014; Liu et al. 2015a; Mao et al. 2012; Peng et al. 2011; Zhang et al. 2016; Zhou et al. 2014), but the differences between different satellites can introduce uncertainty regarding data continuity (Liu et al. 2018). For example, there are some discrepancies between studies that combined GIMMS NDVIg and MODIS and those that employed GIMMS NDVI3g (Du et al. 2016, 2017).

In this study, spatiotemporal changes in seasonal NDVI, the causes of these changes, and the contributions of seasonal NDVI to NDVI rates in the growing season were analyzed during 1982–2013 with GIMMS NDVI3g datasets, nighttime light data, socioeconomic statistical data, and meteorological data. Linear regression model and correlation analysis during nested periods were used to detect the NDVI trends and explore its relationships with climate variables and human activities. The goal of this article is to comprehensively assess patterns of vegetation trends since the initiation of Chinese economic reform, monitor current conditions of vegetation coverage in China, and prepare for future ecological management.

Materials and methods

Data sources and processing

The AVHRR GIMMS NDVI3g is the most frequently used, primarily because it provides longest temporal coverage since the early 1980s (Beck and Goetz 2011; de Jong et al. 2011;

Fensholt et al. 2009; Qi et al. 2019; Zhou et al. 2018). The data quality of the GIMMS NDVI3g dataset has been recognized as meeting the general requirements for regional vegetation monitoring (Pinzon and Tucker 2014; Wang et al. 2014; Xu et al. 2014b; Zeng et al. 2013), and it is even more accurate than GIMMS NDVIg (Wang et al. 2014). GIMMS NDVI3g dataset covering 1982–2013 was acquired from the NASA Goddard Space Flight Center. The spatial resolution is 0.083° × 0.083°, and the temporal resolution is 15 days. The common maximum value composite tool was used to compile a monthly NDVI dataset, as it could minimize cloud contamination and reduce the influence of the phenological cycle (Fensholt et al. 2012; Fensholt and Proud 2012). In order to avoid the influence of negative values of water bodies and the low values of non-vegetated areas, annual average pixel values below 0.05 were excluded from this work according to the relevant studies (Du et al. 2015; Mohammat et al. 2013; Myneni et al. 1997; Zhao et al. 2011a, b).

Version 4 of the nighttime light (NTL) data from 2013 was obtained from the National Oceanic and Atmospheric Administration's National Geophysical Data Center website (http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html, accessed October 15, 2016). To confirm the continuity and comparability of NTL data, an empirical procedure introduced by Elvidge et al. (2014), Elvidge et al. (2009), and Liu et al. (2012) was followed to process the annual composite images.

Seasonal surface air temperature, maximum air temperature, minimum air temperature, ground temperature, precipitation, sunshine duration, and relative humidity at a spatial resolution of 0.083° were generated using a Kriging-Linear interpolation algorithm from daily records collected at 813 meteorological stations across China. These datasets were acquired from the China Meteorological Data Sharing Service System.

Socio-economic data regarding effective irrigated area, the amount of fertilizer applied, and total power of agricultural machinery were obtained from the China Urban Statistical Yearbooks (China NBoSo 1985-2014) and the China Rural Statistical Yearbooks (China NBoSo 1985-2014).

Methods

Growing season NDVI was defined as the average of NDVI from April to October each year. In order to describe the characteristics of NDVI changes in each season, the growing season was divided into three seasons: spring (April and May), summer (June–August), and autumn (September and October). NDVI of spring, summer, and autumn were calculated as the average of NDVI values during the corresponding months. To detect the trend of NDVI and climate variables during a given period, a least-squares linear regression was applied. Furthermore, the contribution to total NDVI change due to an individual season equals the ratio of the change in NDVI in a single season to the change over the entire growing season (Du et al. 2017). The amount of NDVI change in each season and the entire growing season was calculated as the product of NDVI slope and the number of months.

To further explore the climatic factors driving NDVI change, interannual correlations between NDVI and contemporary climatic variables were calculated via Pearson correlation analysis. To reflect NDVI dynamic processes and the trend continuity, NDVI trends and correlations between NDVI and climatic factors were estimated over fifteen time periods: 1982–1999, 1982–2000, …, 1982–2013. Based on the results of significance tests, these trends and correlations were classified into three ranks: very significant ($p < 0.01$), significant ($p < 0.05$), and not significant ($p \geq 0.05$).

Cities are the most concentrated areas of human economic and social activities (Liu et al. 2014; Zhang and Seto 2011), and they are also the most concentrated areas of buildings and engineering projects that displace vegetation. To investigate the effects of urban expansion on vegetation, the 2013 NTL data was adopted to delineate built-up areas in the main cities of China. Then, the NDVI trends in built-up areas were isolated. Because the gross domestic product (GDP) is an important indicator of the level of regional economic development, the prefecture-level cities with a 2015 full-year GDP greater than 500 billion RMB (approximately 80.28 billion US dollars) and any other provincial capitals were chosen for this analysis. This included a total of 46 cities. The most commonly used threshold technique (Pandey et al. 2013) was applied to delineate the boundary of built-up areas in the main cities in China (He et al. 2014; Liu et al. 2012; Xu et al. 2016).

Since the onset of Chinese economic reform, China's agricultural production management practices have undergone tremendous changes, such as increases in fertilization and tillage(Zhao et al. 2018). Therefore, this paper also discusses the impact of ecological restoration measures such as agricultural production level and afforestation on vegetation growth.

Results

NDVI changes

NDVI trends across China

Seasonal and growing season NDVI significantly increased during 1982–2013 (growing season: R^2 = 0.49, spring: R^2 = 0.41, summer: R^2 = 0.17, and autumn: R^2 = 0.33). These increases were very significant in the growing season, spring, and autumn (Fig. 1). Significant NDVI increases were also observed in the growing season and spring during all the

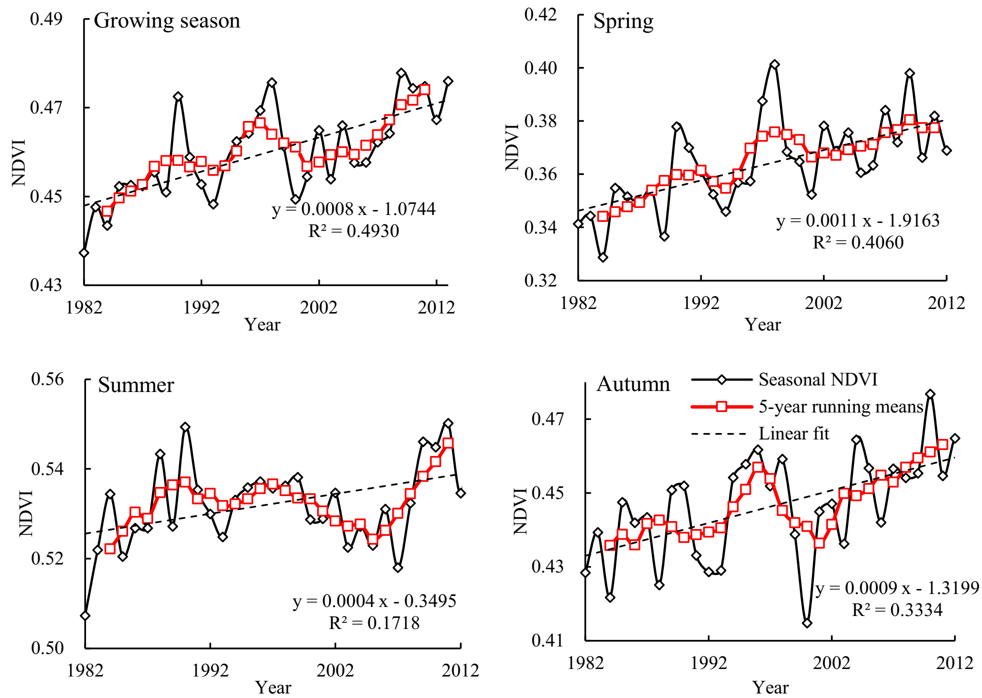

Fig. 1 Interannual variations NDVI in China during summer, spring, autumn, and the growing season

previous fourteen periods, during summer in the first few periods, and during autumn in the first and the last few periods (Fig. 1). As the NDVI record increases in temporal extent, NDVI rates and the percent NDVI changes in the growing season, spring, and summer decreased very significantly (R^2 = 0.43, R^2 = 0.78 and R^2 = 0.42; n = 15), and they slightly increased in autumn (Fig. 2a, b).

Although the total amounts of NDVI change in summer were the maximum among these three seasons during all periods, the ratios of summer NDVI to growing season NDVI markedly decreased during all periods (Fig. 3a). Significant decreases in these ratios were found during the last ten periods ($R^2 > 0.24$; $P < 0.05$; n = 23–32), while the spring-to-growing season NDVI ratios significantly increased during all periods ($R^2 > 0.21$; $P < 0.05$; n = 18–32; Fig. 3b). The autumn-to-growing season NDVI ratios insignificantly decreased during the first six periods and slightly increased during the last nine periods (Fig. 3b).

Spatial patterns

The interannual growing season NDVI variability in China exhibits high spatial heterogeneity (Fig. 4). The most significant restoration of vegetation occurred in central, eastern, and southern China during 1982–2013. There were also some areas of significant vegetative restoration in northwestern and northeastern China. In contrast, regions of vegetative degradation were concentrated in the Three River Plain of northeast China, some areas of Inner Mongolia and Xinjiang, and urban agglomeration areas such as the Yangtze River Delta and the Pearl River Delta. From 1982 to 2013, the significant decrease in growing season NDVI was only significant in 7.98% of China's vegetated area, and the decrease (including significant and insignificant decreases, the same as below) occupied 27% of the same area. The increase of growing season NDVI accounted for 73% of the vegetated area, and the trend was significant in 37.69% of the same area.

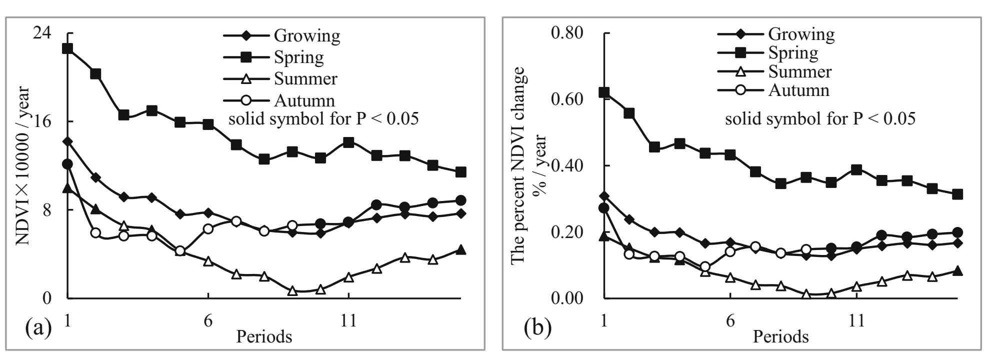

Fig. 2 Variations of seasonal NDVI **a** interannual slope and **b** percent NDVI change during 15 periods

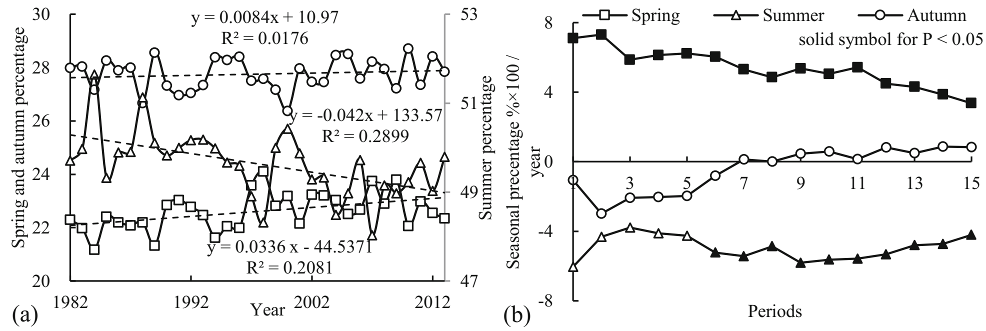

Fig. 3 Trends of **a** seasonal NDVI ratios to growing season NDVI and **b** their significance levels

Seasonal NDVI trends also show strong spatial heterogeneity, particularly the contrasts between northern and southern China and between western and eastern China (Fig. 5). Most of central and southern China exhibited a continuous increase in vegetation activity during 1982–2013, especially in spring. Similar to the pattern found for the growing season, the majority of the NDVI pixels with negative and significant trends were scattered in the Yangtze River Delta, the Pearl River Delta, and northwestern China. Among the three seasons, the maximum proportion of both significant increase and decrease occurred in spring. The proportion of decrease in summer was relatively high compared with that of increase, while the magnitude of the increase in the spring NDVI was larger than in summer and autumn.

For the first 14 times periods, areas with a significant change in NDVI (both positive and negative) were usually small for the growing and for all seasons compared with the 1982–2013 period (Table 1), but the spatial distributions were more concentrated in the prior 14 periods (Figs. 4 and 5). With the increase in the study period, there was an increase in the number of very significant and significant pixels that exhibited increases and decreases in NDVI. This pattern was observed in all seasons except for a significant increase in summer. However, there was a decrease in the number of areas with very significant NDVI increases as the study duration was extended. This pattern was seen in all seasons except for autumn.

Effects of climate change on NDVI trends

Effects at a national scale

Overall, the thermal factors of average temperature, maximum temperature, minimum temperature, and ground temperature were strongly positively correlated with NDVI, especially significant correlations were found in the growing season and spring during all periods, and they were observed in summer and autumn during some periods. NDVI was weakly positively correlated with water conditions, including precipitation and relative humidity (Table 2). Correlations between NDVI and moisture factors in spring and summer were stronger than in the growing season and autumn. Significant correlations between NDVI and relative humidity were observed in spring during 1982–2002 and 1982–2003 and in summer during 1982–2007. The correlations between NDVI and sunshine hours were not significant in any season or period.

Pixel scale

Given that the thermal variables are highly correlated with temperature, we only present the correlations between NDVI and temperature.

Areas characterized by significant positive correlations between NDVI and temperature included central and southern China, the Great Higgnan Mountains, and some areas of northwestern China. Significant negative correlations between NDVI and temperature are mainly located in northern China (Fig. 6), while the correlations between NDVI and precipitation are mostly positive and significant in this area (Fig. 7). Among the four seasons, spring has the largest area (an average of approximately 26.57% from the 15 periods) with positive and significant correlations between NDVI and temperature. This is followed by the growing season (12.13%). Summer has the largest area (5.1%) for negative and significant correlation, followed by the growing season (3.84%; Fig. 6 and Table S1). The most pixels with positive and significant correlations between NDVI and precipitation are observed in the growing season (12.85%), followed by summer (9.15%), and autumn (7.07%). Spring (5.15%) had the highest number of pixels with negative and significant correlations between NDVI and precipitation (Fig. 7 and Table S1).

Pixels with significant positive correlations between NDVI and relative humidity in all seasons were mainly distributed in northern arid areas and the southwestern Tibetan Plateau. However, significant negative correlations were concentrated in the southeastern humid region and the Great Higgnan Mountains (Fig. S1). Summer had the largest area (about 16.32%) with a significant positive correlation between NDVI and relative humidity, followed by the growing season (13.51%). Spring had the largest area (about 12.44%) with a significant negative correlation, followed by autumn (8.34%; Fig. S1 and Table S1).

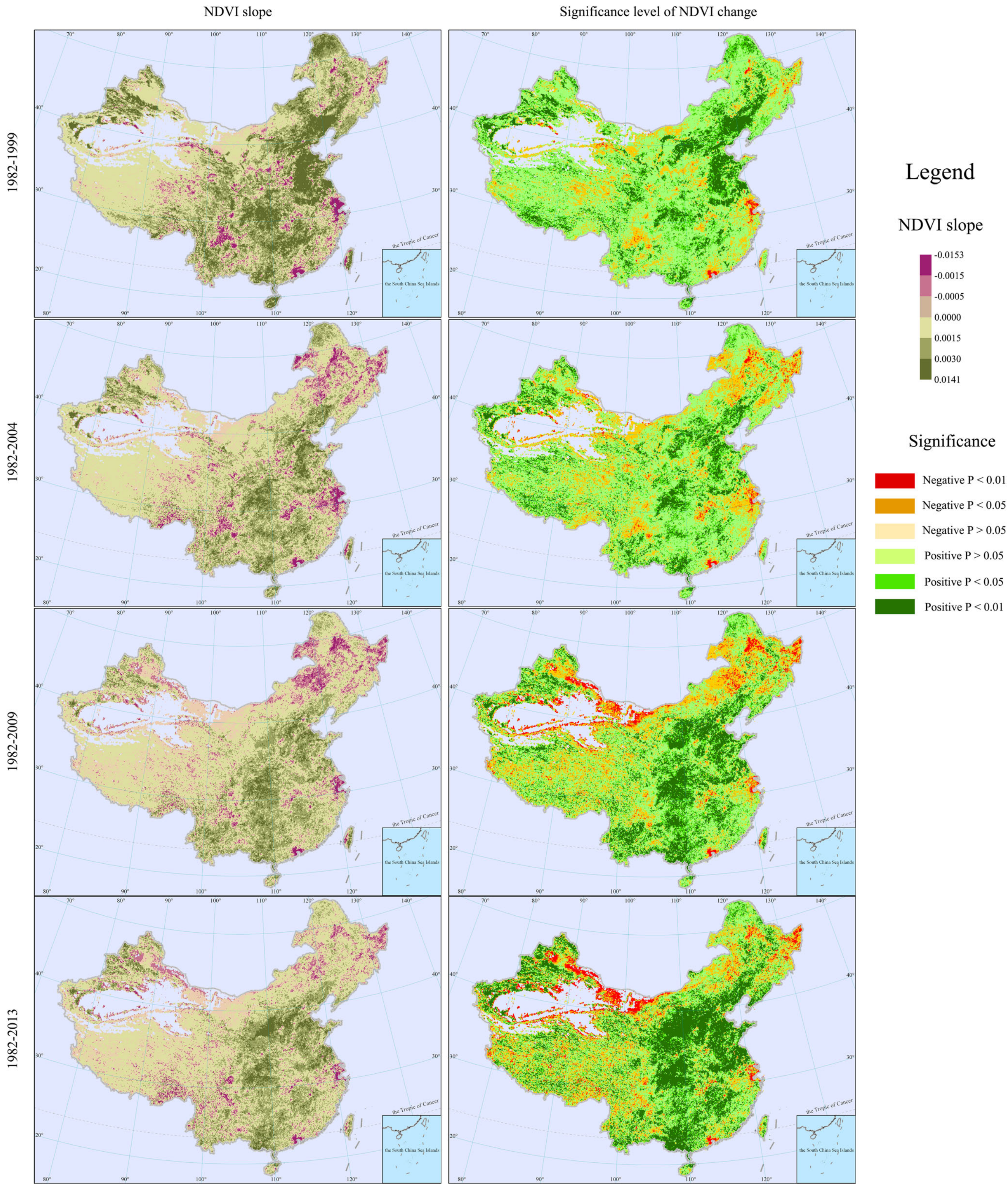

Fig. 4 Trends in growing season NDVI during a subset of study periods (1982–1999, 1982–2004, 1982–2009, and 1982–2013)

There are some differences in spatial patterns of correlations between NDVI and sunshine duration among seasons (Fig. S2). Spring has the largest area (15.31%) with significant positive correlation between NDVI and sunshine duration, which is mainly distributed in southeastern and northeastern China. Autumn has the second largest area (13.72%), and these areas are mainly located in central, southwestern, and northeastern China (Fig. S2 and Table S1). The spatial

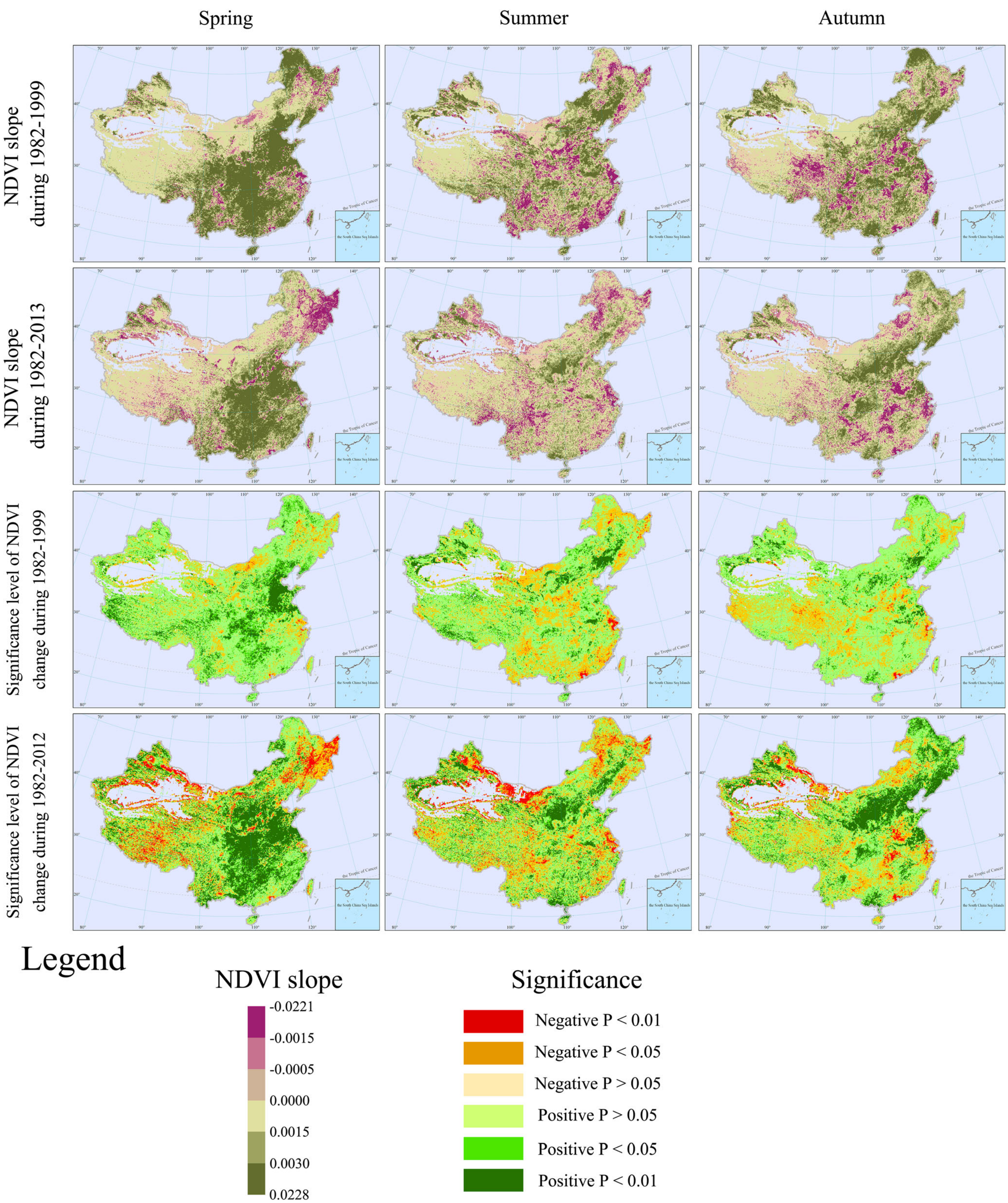

Fig. 5 NDVI trends in spring, summer, and autumn during a subset of study periods (1982–1999 and 1982–2013)

distributions of significant positive correlations in the summer and the growing season were similar, and these areas are mainly distributed in the middle and northeast regions (Fig. S2).

Generally, areas characterized by significant positive correlations between NDVI and thermal factors, such as temperature and ground temperature, were the largest in spring.

Table 1 The proportion of pixels characterized by different levels of statistical significance during fifteen periods (%)

	Growing season			Spring			Summer			Autumn		
	PNP	PSP	PP	PNP	PSP	PP	PNP	PSP	PP	PNP	PSP	PP
P1	1.18	27.90	84.83	0.69	23.66	83.60	2.07	15.40	69.80	1.24	11.31	75.09
P2	1.51	24.75	81.63	0.75	22.52	83.68	2.44	15.62	68.19	1.91	9.01	65.93
P3	1.65	23.39	78.97	0.94	20.81	81.88	2.51	13.44	66.81	1.80	9.75	65.66
P4	1.89	24.29	79.74	1.10	24.38	81.87	2.99	13.51	66.64	2.16	9.94	64.63
P5	2.40	21.42	76.44	1.59	24.47	79.24	4.27	12.12	62.50	2.63	9.94	61.98
P6	2.94	23.62	75.38	2.08	26.57	78.01	5.44	11.97	59.91	2.67	12.58	64.78
P7	3.83	23.42	72.35	2.97	25.15	74.72	6.65	10.93	56.03	2.93	14.99	65.86
P8	4.90	22.83	70.01	4.49	24.64	71.32	7.87	11.14	55.17	3.60	14.61	63.69
P9	5.88	23.78	69.50	5.24	25.54	70.39	9.57	9.89	51.81	4.11	16.97	64.34
P10	6.90	24.98	68.58	7.04	27.87	68.63	10.23	10.54	51.85	4.85	17.80	63.78
P11	6.81	29.40	70.66	7.11	32.18	70.99	10.15	13.09	55.08	5.38	19.14	64.15
P12	6.62	32.93	72.69	8.35	32.29	69.56	9.19	14.77	57.39	5.18	24.00	68.43
P13	7.15	35.82	73.68	9.88	33.85	68.53	9.59	17.65	60.30	5.72	25.20	68.47
P14	7.58	35.86	72.74	11.12	34.72	67.66	10.74	18.36	58.70	5.69	27.92	69.48
P15	7.98	37.69	73.01	11.66	35.61	67.68	10.82	21.54	60.37	6.13	29.19	69.57

P1, P2, …, P15 indicate the periods 1982–1999, 1982–2000, …, 1982–2013, respectively. *PNP* and *PSP* stand for $R < 0$ and $R > 0$, and statistical significance of correlation less than 0.05 level, respectively, and PP indicates increasing NDVI, including both significant and insignificant increases

However, the areas with significant positive correlations between NDVI and water conditions, such as precipitation and relative humidity, were largest in summer.

As the NDVI study period grew in length, pixels with significant positive and negative correlations between NDVI and most climate factors significantly increased, especially for temperature and relative humidity (Table S1). This indicates that the longer the period, the more obvious the effect of climate on vegetation.

Impacts of human activities on vegetation

Urbanization process

Over all cities, growing season NDVI significantly decreased during all 15 periods ($R^2 \geq 0.15$; $P < 0.05$; $n = 18–32$; Fig. 8). The NDVI in the two largest urban agglomerations (i.e., the Yangtze River and the Pearl River deltas) significantly decreased during all periods (Fig. 8). Areas with significant negative trends in NDVI during 1982–2013 represented 68% and 37% of vegetated area for the Yangtze River and the Pearl River deltas, respectively. Pixels characterized by significant vegetation degradation were also found in built-up areas of Beijing, Wuhan, and Chengdu, which may have resulted from the construction of industrial parks or new urban districts (Fig. S3). These results show the very obvious negative effects of urban expansion on vegetation, especially when analyzing all cities in aggregate and those cities located in central and eastern China.

Agricultural production and ecological restoration

Highly significant positive correlations between cultivated land NDVI and effective irrigated area, the amount of fertilizer applied, and total power of agricultural machinery during 1982–2013 were found ($R^2 = 0.53$, $R^2 = 0.55$, and $R^2 = 0.52$; $n = 32$; Fig. 9). Forest NDVI exhibited a highly significant positive correlation with cumulative afforestation area during 1986–2013 ($R^2 = 0.20$, $n = 28$). These results demonstrate that human activities such as the improvement of agricultural production conditions and ecological restorations have also promoted vegetation. Irrigation practices and large-scale vegetation restoration such as the Grain for Green Project initiated in 1999, the Natural Forest Conservation Program started in 1998, the Three-North Shelter Forest Project started in 1978, etc., benefit the vegetation promoting over the majority of affected areas (Fang et al. 2019a; Ouyang et al. 2016; Qian et al. 2019; Zhang et al. 2016; Zhao et al. 2019).

Discussion

NDVI trends

Although there are some differences in data, methods, and research periods among different studies, the greening trends in NDVI were identical across China (Fang et al. 2019b; Liu et al. 2015a, 2018; Liu and Lei 2015; Liu et al. 2015b; Peng

Table 2 Correlations between seasonal NDVI and climate factors at national scale

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
NDVI and mean temperature															
Gro	*0.49*	*0.34*	*0.28*	*0.29*	*0.28*	*0.30*	*0.27*	*0.25*	*0.26*	*0.27*	*0.33*	*0.34*	*0.36*	*0.37*	*0.40*
Spr	*0.29*	*0.29*	*0.26*	*0.28*	*0.29*	*0.32*	*0.31*	*0.31*	*0.36*	*0.37*	*0.43*	*0.40*	*0.41*	*0.40*	*0.40*
Sum	*0.30*	*0.21*	0.16	0.17	0.15	0.14	0.09	0.08	0.03	0.03	0.05	0.09	0.13	*0.13*	*0.18*
Aut	0.16	0.11	0.11	0.11	0.09	0.10	0.13	0.11	0.12	0.14	*0.16*	*0.17*	*0.18*	*0.16*	*0.18*
NDVI and maximum temperature															
Gro	*0.52*	*0.37*	*0.30*	*0.31*	*0.31*	*0.33*	*0.31*	*0.27*	*0.28*	*0.29*	*0.36*	*0.34*	*0.37*	*0.38*	*0.40*
Spr	*0.27*	*0.26*	*0.24*	*0.24*	*0.24*	*0.27*	*0.27*	*0.27*	*0.32*	*0.33*	*0.39*	*0.35*	*0.37*	*0.36*	*0.37*
Sum	*0.27*	0.20	0.15	0.15	0.15	0.15	0.10	0.09	0.04	0.04	0.05	0.09	0.13	*0.13*	*0.17*
Aut	0.21	0.19	0.19	0.18	0.16	*0.18*	*0.22*	*0.17*	*0.18*	*0.19*	*0.21*	*0.20*	*0.20*	*0.19*	*0.21*
NDVI and minimum temperature															
Gro	*0.44*	*0.31*	*0.25*	*0.27*	*0.25*	*0.26*	*0.23*	*0.21*	*0.22*	*0.24*	*0.29*	*0.33*	*0.36*	*0.37*	*0.40*
Spr	*0.33*	*0.32*	*0.29*	*0.33*	*0.34*	*0.36*	*0.35*	*0.34*	*0.39*	*0.39*	*0.45*	*0.45*	*0.46*	*0.43*	*0.44*
Sum	*0.28*	0.20	0.16	0.17	0.13	0.12	0.06	0.06	0.02	0.02	0.03	0.07	0.11	0.11	*0.16*
Aut	0.14	0.08	0.08	0.07	0.06	0.06	0.09	0.08	0.10	0.11	0.13	*0.18*	*0.19*	*0.18*	*0.19*
NDVI and precipitation															
Gro	0.10	0.10	0.10	0.11	0.11	0.06	0.06	0.06	0.05	0.05	0.01	0.03	0.00	0.01	0.02
Spr	0.00	0.00	0.01	0.03	0.03	0.04	0.04	0.04	0.02	0.02	0.01	0.01	0.00	0.00	0.00
Sum	0.08	0.08	0.09	0.09	0.08	0.08	0.08	0.07	0.07	0.07	0.03	0.03	0.01	0.01	0.01
Aut	0.00	0.03	0.03	0.03	0.04	0.08	0.09	0.08	0.08	0.08	0.10	0.02	0.02	0.01	0.01
NDVI and RHU															
Gro	0.10	0.09	0.09	0.11	0.09	0.02	0.01	0.01	0.00	0.00	0.05	0.05	0.09	0.10	0.12
Spr	0.15	0.15	0.15	*0.20*	*0.21*	0.10	0.09	0.06	0.00	0.00	0.03	0.02	0.04	0.05	0.05
Sum	0.11	0.11	0.11	0.12	0.10	0.11	0.13	0.10	*0.16*	0.13	0.02	0.00	0.00	0.00	0.01
Aut	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.03	0.05	0.05	0.07	0.03	0.04	0.06	0.08
NDVI and GST															
Gro	*0.49*	*0.33*	*0.26*	*0.28*	*0.27*	*0.30*	*0.26*	*0.21*	*0.22*	*0.24*	*0.31*	*0.34*	*0.38*	*0.39*	*0.42*
Spr	*0.33*	*0.31*	*0.28*	*0.30*	*0.30*	*0.32*	*0.31*	*0.30*	*0.35*	*0.36*	*0.43*	*0.41*	*0.43*	*0.41*	*0.41*
Sum	*0.25*	0.18	0.13	0.14	0.14	0.13	0.07	0.06	0.01	0.02	0.04	0.08	0.13	*0.13*	*0.18*
Aut	0.15	0.11	0.11	0.11	0.09	0.11	0.15	0.11	0.13	*0.15*	*0.18*	*0.21*	*0.22*	*0.22*	*0.24*
NDVI and SSD															
Gro	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spr	0.05	0.06	0.07	0.01	0.00	0.01	0.01	0.01	0.02	0.02	0.03	0.02	0.04	0.04	0.04
Sum	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.03	0.03	0.02	0.02	0.01	0.01
Aut	0.00	0.01	0.01	0.01	0.01	0.03	0.03	0.03	0.01	0.00	0.00	0.01	0.01	0.01	0.00

Italicized typeface represents statistical significance at the 0.05 level

RHU relative humidity, *GST* ground surface temperature, *SSD* sunshine duration

et al. 2011; Wang et al. 2017; Yao et al. 2019). This research agrees with those previous results about NDVI overall trends. In terms of spatial patterns of NDVI changes, spatial distributions of significant greening and browning in this article were very similar to results in some studies (Liu et al. 2015b; Peng et al. 2011); yet, they were dissimilar to those found by Liu et al. (2018) and Wang et al. (2017). The possible reasons include differences in data sources and methods. Liu et al. (2018) adopted integrated GIMMS NDVIg and MODIS NDVI, while Liu et al. (2015a) and Wang et al. (2017) calculated yearly NDVI from the full year of GIMMS NDVI3g data rather than from the growing season. Moreover, Liu et al. (2018) and Wang et al. (2017) did not remove nonvegetated area, and this may have also introduced disparities.

Our research draws some novel and useful results. The extension of the NDVI time series has also updated our understanding of the trend of vegetation change in China. In northern China and the Tibetan Plateau, NDVI exhibited greening during 1982–1999 and significant browning

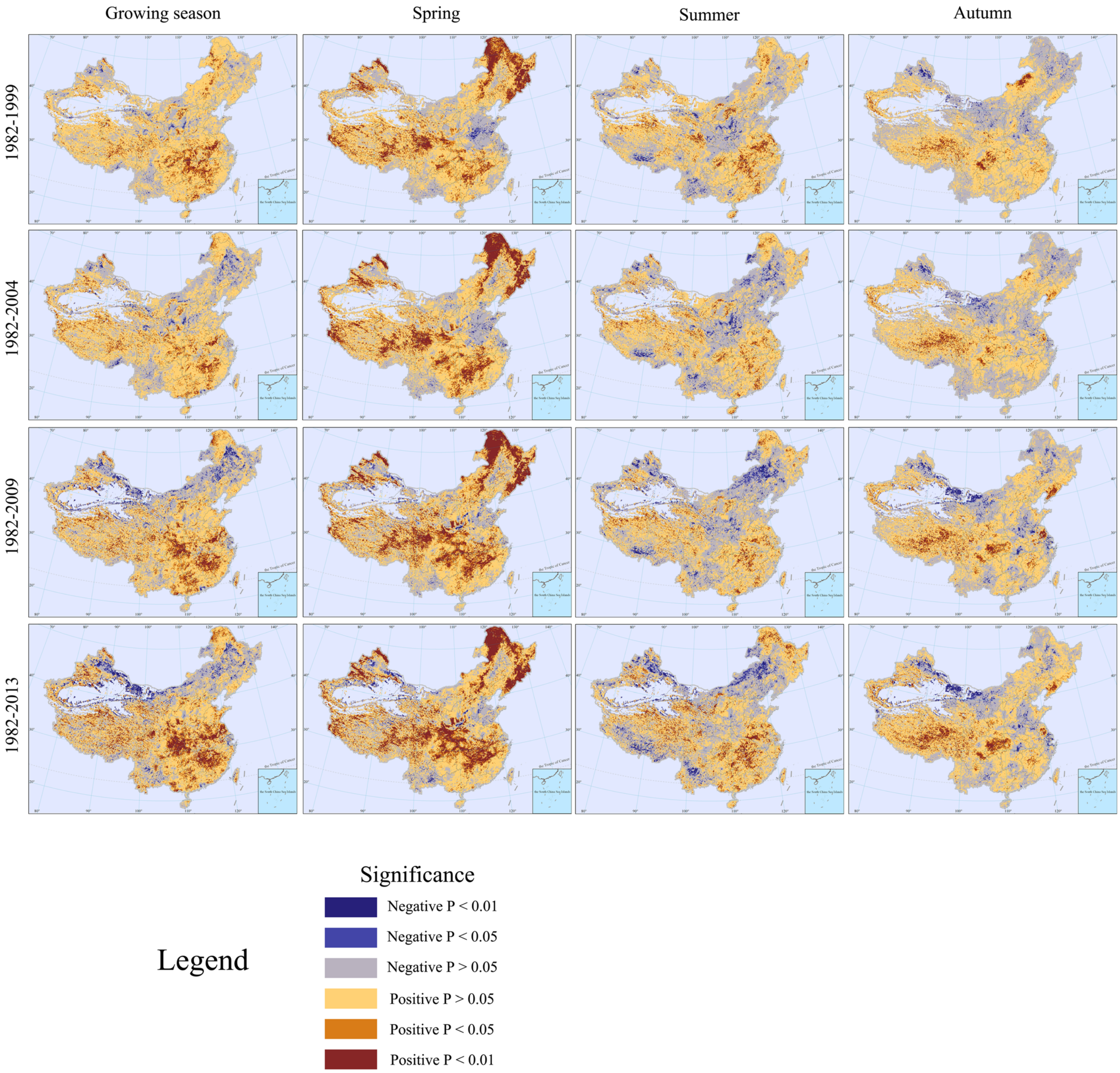

Fig. 6 Correlations between NDVI and temperature (1982–1999 and 1982–2013)

during 1982–2013. This indicates that NDVI experienced a large drop. In light of our findings, the rates of NDVI increase across China prominently declined as the study period was extended, which indicates that the NDVI was stagnant and vegetation activity tended to stabilize for China as a whole. However, a 'polarization' phenomenon was observed at the pixel scale, i.e., areas characterized by significant positive and negative trends in NDVI exhibited highly significant increases in most seasons as the study time extended. This may imply the importance of studying multiple spatial scales because the regional average may obscure phenomena that occur at the pixel scale. Furthermore, this study found that the periods of studied time span are shorter, the proportions of pixels with significant changes in NDVI in the growing season and seasons are smaller, and the spatial distributions of these pixels are more concentrated. The comparisons between the proportions and spatial patterns of pixels with significant positive and negative trends in growing season and seasonal NDVI were much more obvious in the first and last period (Table 1, Figs. 4 and 5). The polarization phenomenon reminds policy-maker and eco-environment superintendent to pay more attention to areas with significant reduced vegetation cover, and this also increased the

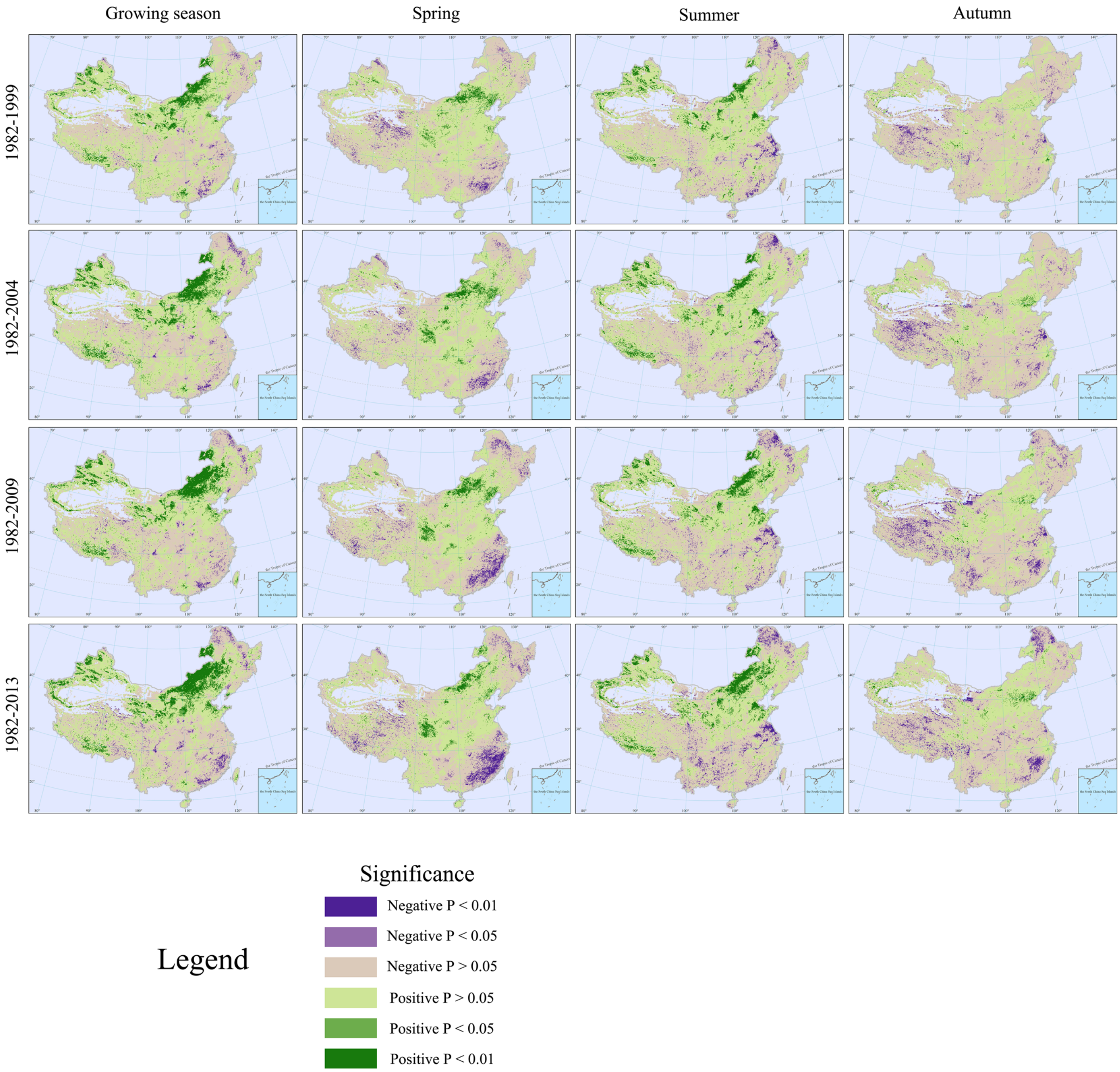

Fig. 7 Correlations between NDVI and precipitation (1982–1999 and 1982–2013)

spatial heterogeneity of vegetation greenness, which has a series of implications for environment and human activities (Yao et al. 2019).

Changes in NDVI rates and seasonal NDVI contributions as the study period was extended demonstrate that spring NDVI contributions to growing season NDVI were the largest and continuously increased. However, summer NDVI contributions were the smallest and continuously decreased. For vegetation in China, the advanced growing season in spring and the delay in the end date of the growing season in autumn made greater contributions to vegetation promotion than accelerated vegetation growth in summer.

Analysis of influencing factors

We found that pixels characterized by significant positive correlations between NDVI and precipitation during all periods were mainly concentrated in areas with less than 400 mm of precipitation. Pixel numbers with significant positive correlations in these areas accounted for 83% and 82% of all pixel numbers with the same feature, in 1982–1999 and 1982–2013, respectively. The ratio of pixels with significant positive correlations between NDVI and precipitation in each precipitation contour zone compared to the total number of pixels with positive correlations between NDVI and precipitation in all contour zones across China rapidly dropped with

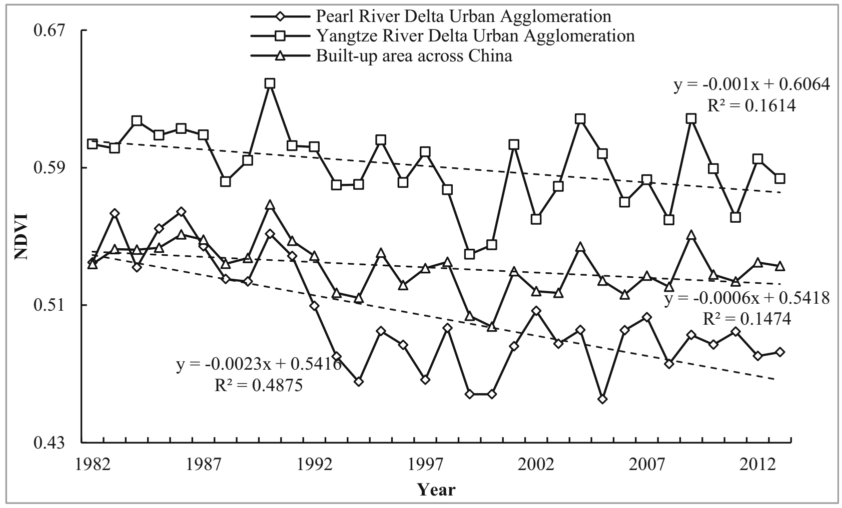

Fig. 8 NDVI Trends in built-up areas of China, the Yangtze River, and the Pearl River deltas

movement to precipitation contours greater than 400 mm (Fig. 10). This demonstrates that the effect of precipitation is significant to vegetation growth in this area. The strong correlations between NDVI and relative humidity as well as the significant negative correlations between NDVI and temperature in these areas also confirmed this viewpoint. Correlations between NDVI and temperature in these areas are mostly negative in the growing season and summer. This indicates that warming intensified drought (Qi et al. 2019), and the vegetation growth was inhibited by water shortage in these areas.

Pixels with a significant positive correlation between NDVI and temperature in spring and the growing season were mainly distributed in the northern forest and grassland, especially in the Great Hinggan Mountains, the Xiao Hinggan Mountains, Changbai Mountain of northeastern China, the Altai Mountains and Mt. Tianshan of northwestern China, as well as the Qinling Mountains and Wuling Mountain of central China. Areas with significant greening in forest and grassland accounted for 43% and 37%, respectively, of all significant greening area during 1982–2013. This indicates that the advance in on-set of the growing season caused by spring warming resulted in enhancement of vegetation activity in forest and grassland.

Areas with significant correlations between growing season and seasonal NDVI and almost all climatic factors, including both positive and negative, significantly increased as the study period was increased (Table S1). This illustrates that the effects of climate on vegetation status are more obvious over longer time spans. A certain length of time is required to obtain an objective and reasonable judgment on the impacts of climate change on vegetation conditions.

In the context of climate change beneficial to vegetation activity, NDVI in built-up areas across China decreased in the past. This indicates that urban development and construction activities offset the improvement of vegetation coverage caused by climate variation and also further reduced vegetation coverage in urban areas and surrounding areas. China experienced a rapid and large-scale process of urban expansion during this study period, and urban land in China expanded mainly by converting cropland(Cui and Shi 2012; Liu et al. 2015c; Seto et al. 2011; Xu et al. 2016). This reduced land areas covered by dense crops and lead to a decline in NDVI.

With the gradual increases in ecological protection awareness and investment in ecological restoration projects, the vegetation coverage in China has been increasing in the years after the late 1990s to the late 2000s. This means that ecological protection and restoration efforts such as afforestation and agricultural production investment have begun to play an important role in improving vegetation activity (Liu et al. 2019b; Lu et al. 2018; Tong et al. 2017; Xu et al. 2011; Yuan et al.

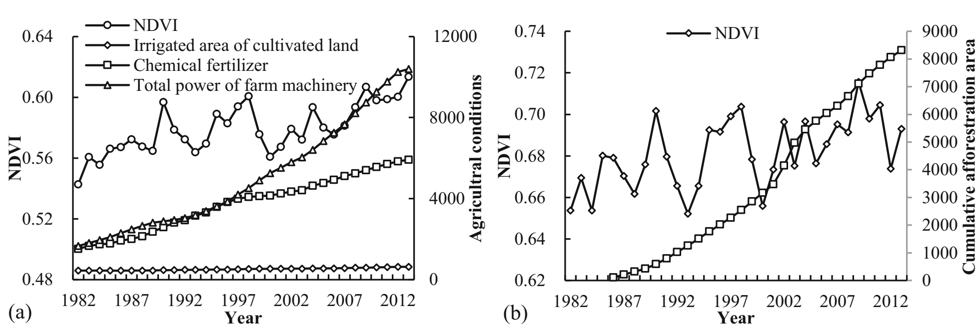

Fig. 9 Trends in NDVI and its related factors in farmland and forest during 1982–2013 (irrigated area of cultivated land: 10^5 hm^2, chemical fertilizer: 10^4 t, total power of farm machinery: 10^8 W, and cumulative afforestation area: 10^4 hm^2)

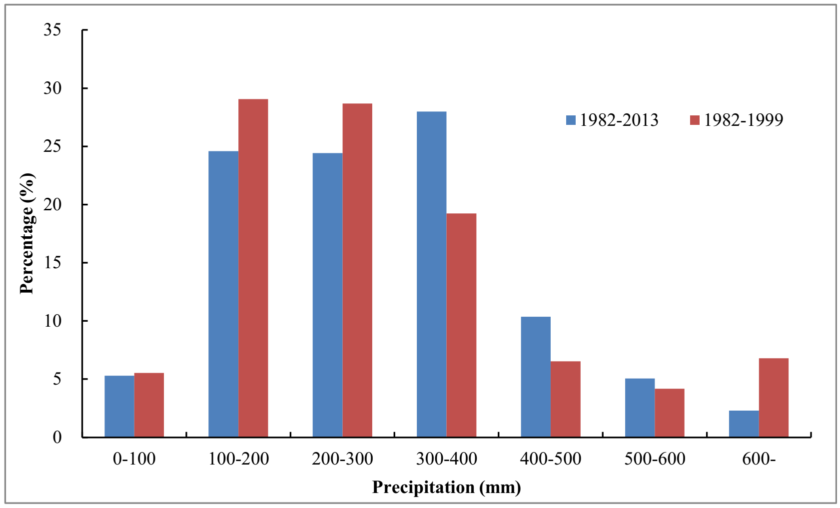

Fig. 10 Ratio of areas with significant positive correlation between NDVI and precipitation to areas with significant correlations for different water conditions

2018; Zhang et al. 2016; Zhou et al. 2016, 2018). In contrast to climate change, the impacts of human activity are mostly concentrated in population centers and associated areas such as cities, towns, farmlands and regions implemented ecological restoration project.

There are a few limitations in this work. The spatial resolution of GIMMS NDVI3g used in this research was relative rough. This data can reflect general trends for whole China and large region but may not have enough resolution to accurately distinguish ecological processes. Another shortcoming is that the relative contributions of climate change and human activities to NDVI changes have not been quantitatively determined yet. Future researches can (1) use higher spatial resolution data of remote sensing to better characterize vegetation trends; (2) disentangle the impacts of external factors such as warming, drought, extreme weather, urbanization, ecological restorations, and so on, on vegetation changes; (3) further analyze and validate the changes in spatial heterogeneity in vegetation cover and its implications for natural ecosystem and human society.

Conclusions

At the national scale, the growth of vegetation has increased significantly in the growing season and each season studied since the initiation of the Chinese economic reform. With the prolongation of the study period, the spatial heterogeneity in the growth trend of terrestrial vegetation in China generally increased. There is a polarization trend, i.e., the number of pixel with significant NDVI greening and browning significantly increase in all seasons (except for the significant increase in summer). The general pattern of vegetation changes is pixels with significant greening widely distributed in the central, eastern, and southern China, and the significant browning are concentrated in the Three River Plain, parts of Inner Mongolia and Xinjiang, as well as the Yangtze River Delta and the Pearl River Delta. The spatial pattern of NDVI changes in different seasons exhibits slight variations.

The increase of NDVI in the growing season mainly occurred in spring and autumn. Spring made the maximum contributions to the increases of NDVI in the growing season, while summer made the smallest contributions during all periods. The contributions of spring vegetation to the improvements of NDVI increased over longer study periods, while summer contributions decreased. These results indicate that the contributions of advancing the onset and delaying the termination of vegetation growth were greater than that due to accelerations in vegetation growth during summer.

The influence of thermal factors on the growth of vegetation in China was more significant, especially in the growing season, spring, and autumn. This phenomenon was particularly prominent in areas with relatively low temperatures in woodlands and grasslands in mountainous areas of Northeast China, Northwest China, and central China. The significant positive correlations between precipitation and NDVI were mainly located in northwest China, which experiences below 400 mm of average precipitation in many years. The development and construction activities with high intensity and high density in urban areas have led to a significant reduction in the vegetation coverage in cities and surrounding areas, especially in the Yangtze River Delta, the Pearl River Delta city group, and several other large cities. The ecological protection measures of agricultural production, conversion of farmland to forest, and grassland enclosure have promoted the improvement of vegetation cover.

Although the overall vegetation coverage in China has been improving, the intensification of the spatial heterogeneity in the vegetation change trend requires the management department to be highly vigilant. The degradation of vegetation in the highly urbanized area and the northwest arid region requires attention. The enhancement of vegetation in large cities and surrounding areas as well as the protection and restoration of vegetation in the fragile ecological areas of northwestern China should be the focus for future ecological protection measures in China.

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