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Research Article

Vegetation Dynamics and Their Response to Climatic Variability in China

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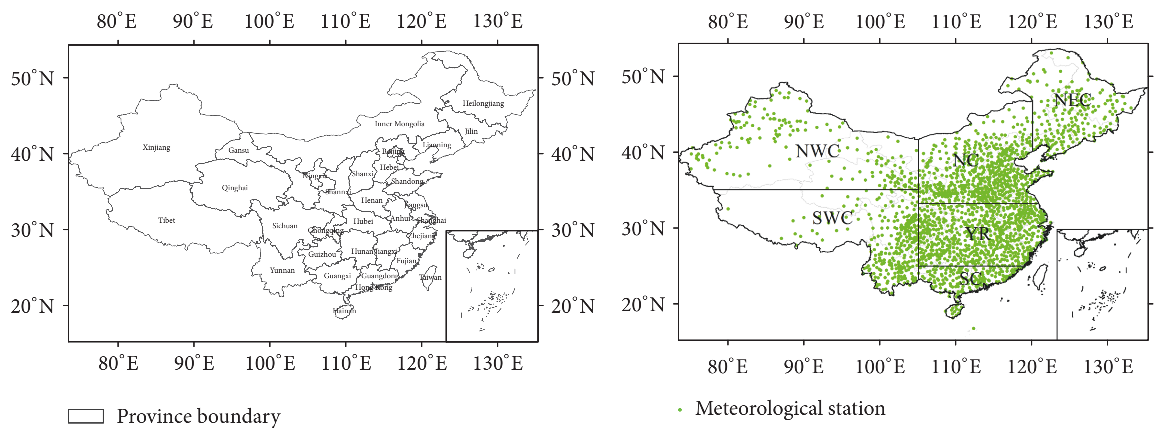
Based on SPOT VEGETATION data and meteorological data, NDVI (Normalized Difference Vegetation Index) and its response to temperature and precipitation in China and its different regions were investigated over the period 1998–2013 by using the maximum value composite and linear regression methods. The results showed that NDVI presented significant increase (0.0046/a) for all of China and all the regions over the last 16 years. Meanwhile, annual mean temperature of China presented a slightly increasing trend, while the annual precipitation showed a slightly decreasing trend over the last 16 years. Nevertheless, there were differences between temperature and precipitation in the subregions of China. The Annual NDVI had better relationships with precipitation ($r = 0.126$) compared to temperature ($r = -0.094$), and NDVI also had a good correlation with precipitation rather than temperature in different subregions of China. Additionally, human activities also made a difference to the trends of NDVI in some regions. This study is conductive to the effects of climate change on vegetation activity in future research.

1. Introduction

Vegetation, which dominates the carbon and water energy cycle of terrestrial ecosystems, has a pivotal position in global changes [1, 2]. The influence of vegetation change on climate system is mainly reflected in the surface albedo, aerodynamic resistance and regional evapotranspiration [3–6]. Therefore, as a comprehensive norm of environmental change, vegetation change becomes increasingly significant for the ongoing research about global change [7, 8]. It is well-known that NDVI, which is the ratio of infrared and near-infrared bands, can indicate vegetation dynamic excellently [9–12]. In recent years, many global and regional scale researches have utilized NDVI to investigate the vegetation change and land cover change [13–17].

Since the 1980s, relevant researchers have begun to focus on the vegetation dynamics and their correlation between vegetation and meteorological factors [18–22]. Globally, the NDVI in much of the surface of the land indicated great changes from 1982 to 2012, and about half of the change displayed seasonal dynamics [23]. For example, the Annual NDVI had a slightly increasing trend in Central Asia from 1982 to 2012 [24]. However, the monthly and seasonal NDVI in China had gone through an obvious increase from 1982 to 1999, and the fastest growth appeared in spring [14]. From a regional perspective, the NDVI in Yangtze River Basin showed an increasing trend, which was affected by the vegetation types of the whole basin [25]. The annual maximum NDVI of desert vegetation in Hexi region increased from 1982 to 2013, and the most obvious increase of maximum NDVI appeared in most of the typical desert vegetation areas [26].

Over the past thirty years, vegetation increased significantly in China, and climate dynamics were the dominant reason of this appearance [27]. Constant warming is regarded as an important influence on vegetation development in China, particularly in Northeastern China, in which temperature limits the growth of vegetation. In Northern China, water limits the increase of vegetation, and precipitation determines largely vegetation growth. Vegetation growth in this region was mainly motivated by continuously increasing precipitation before 2000 [28]. However, this increase was affected by persistent increasing drought in the last ten years



(a) (b)

FIGURE 1: The administrative division (a) and the locations of 2043 meteorological stations (b) in this study.

in Northern China [28]. Other factors, such as CO_2 fertilization, ecological reserve, recovery, rising solar radiation, and human activities, cause increasing vegetation coverage in China [28, 29]. The correlation between NDVI and climate dynamics has been indicated to have spatial heterogeneity [30–32]. Nevertheless, the connection between vegetation growth and climate change in China, particularly dynamics in these correlations, has not been fully analyzed. Additionally, impact of human activities such as afforestation and returning land for farming to forestry should also be considered [33].

Although the correlation between NDVI dynamics and climate factors in China has been discussed in previous studies [28, 29, 34], a holistic study with the recent SPOT/NDVI data and meteorological data at 2043 meteorological stations is still necessary. Hence, this study utilized SPOT/NDVI data and meteorological data to analyze the spatial and temporal variation of NDVI and their correlation with climate factors in all of China and its subregions from 1998 to 2013. The purpose of the study is to explore the correlation between vegetation change and climate in the past decade. The structure of this paper is as follows: firstly, it describes the dataset and methodology in Section 2; secondly, it analyzes the spatial and temporal characteristics of NDVI dynamics and their correlation with climatic factors and discussion in Section 3; finally, it provides a summary of the main conclusions in Section 4.

2. Datasets and Methods

2.1. Datasets. SPOT VGT-S10 composite is developed by France, the European Union, Belgium, Sweden, and Italy, whose spatial resolution is 1 km and this study utilizes the data from 1998 to 2013 [35, 36]. SPOT/NDVI products provide atmospheric correction of surface reflectance data and the use of multiband synthesis technology to obtain the resolution of the normalized vegetation index dataset. Download data on the site "http://free.vgt.vito.be" has completed a series of preprocessing, such as atmospheric correction, radiometric and geometric correction, and setting the value of −1 to −0.1. This study uses the original data SPOT VGT-S10 which contains a total of 576 images covering all of China from April 1998 to December 2013. The spatial resolution of this data is 1 km, and the time resolution is in every ten days. In this paper, the NDVI image data of the study area is extracted by using the boundary map of China, and the projection transformation, cutting processing, and spatial analysis are mainly done in ArcGIS 9.3 software. The attribute value of the original data has been converted into the gray value (DN) of 0–250, and the following formula must be converted into the true value of DN [37]:

$$\text{NDVI} = 0.004 * \text{DN} - 0.1. \quad (1)$$

Climatic data on monthly precipitation and temperatures were from the National Meteorological Information Center/China Meteorological Administration (NMIC/CMA) with a time span from 1998 to 2013. Finally, 2043 meteorological stations in month and the data series that covered periods during 1998–2013 were used which had passed quality control. China's administrative divisions and the distribution of selected meteorological stations were shown in Figure 1. The 2043 stations are not evenly distributed, most of them are located in the Central, Eastern, and Southern China, and their distribution was sparse in some areas of Western and Northeastern China, where deserts or bare lands are the most popular land types. Given that the urbanization has some influence on vegetation, the meteorological stations we choose largely exclude the stations in big cities, so the urbanization has minor effect on vegetation in this paper. There were 652 stations in Yangtze River (YR) basin, 584 stations in Northern China (NC), 173 stations in Southern China (SC), 167 stations in Northwest China (NWC), 269 stations in Southwest China (SWC), and 198 stations in Northeast China (NEC).

2.2. Methods

2.2.1. Maximum-Value Composite Method. In order to make NDVI data more reasonable and effective, the international general MVC (Maximum Value Composites) procedure was applied to the calculation of NDVI values from each 10-day interval to get the maximum NDVI monthly, seasonally, and yearly to further minimize the effects of cloudiness and/or geometrical changes in sensor view [38].

$$\mathrm{NDVI}_i = \max\left(\mathrm{NDVI}_{ij}\right), \tag{2}$$

where NDVI_i is the NDVI data of month i or year i and NDVI_{ij} is the NDVI data of jth 10-day interval or month j in month i or year i.

2.2.2. Linear Regression. According to the trend change and amplitude of vegetation cover in the past period, the linear regression analysis can be used to fit the NDVI's trend of each pixel. The advantage of this method is that it can eliminate the influence of abnormal factors on vegetation growth in the study period by using the data of each year and more accurately reflect the evolution trend of vegetation cover [39]. The formula is as follows [40]:

$$\text{slope} = \frac{n \times \sum_{i=1}^{n} i \times \mathrm{NDVI}_i - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} \mathrm{NDVI}_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}, \tag{3}$$

where slope is the slope of the pixel NDVI regression equation, i is the number of years from 1 to 16 in the study period, n is the year range. The slope value reflects the trend of change in China NDVI data from 1998 to 2013. When slope > 0, it indicated that the vegetation cover increased in the past 16 years, and the larger the value of slope, the more obvious the trend. Otherwise, the trend is reduced. With classification method based on standard variance, the change of vegetation cover (slope) is divided into five grades: significant increase (slope/a $\geq$ 0.005), increase (0.002 $\leq$ slope/a < 0.005), no trend (−0.001 $\leq$ slope/a < 0.002), decrease (−0.004 $\leq$ slope/a < −0.001), and significant decrease (slope/a < −0.004).

2.2.3. Correlation Analysis. The correlation between vegetation and climatic factors (temperature and precipitation) was calculated by the correlation coefficient. For each pixel in the study area, the linear relationship model between NDVI and climatic factors was established to calculate the single correlation coefficient of NDVI and climatic factors in China from 1998 to 2013. The relationship between NDVI and temperature or precipitation based on meteorological stations was mainly done in Excel 2013 and ArcGIS 10.2 software.

The formula of correlation coefficient is as follows [23]:

$$r_{xy} = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)\left(y_i - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2}}. \tag{4}$$

In this formula, $\overline{x}$ and $\overline{y}$ represent the average values of the two factors. r_{xy} is the correlation coefficient between x and y, which indicates the correlation degree between the two factors, and its value is in the range from −1 to 1. When $r_{xy} > 0$, it means that they are positively correlated; when $r_{xy} < 0$, they are negatively correlated. Moreover, the larger the absolute value of the correlation coefficient, the stronger the correlation of the two factors at the pixel. Finally, 0.05 significant tests were performed [41].

3. Results and Discussion

3.1. NDVI Change. The annual variation rates of the NDVI were calculated using the annual mean maximum NDVI of each pixel for China and different regions during 1998–2013. Figure 2 shows the temporal trends of the annual max NDVI in China and its subregions. It is clear that there is a significant growth rate of average Annual NDVI of 0.0046/a ($r^2 = 0.82$, $P < 0.001$) as shown in Figure 2.

The results showed that the NDVI in all the subregions in China increased significantly. The most significant increase is in SC, which had an increasing rate of 0.0048/a ($r^2 = 0.89$, $P < 0.001$). The reason may be that the continuous warming of climate provides the condition for the development of tropical monsoon rain forest and increases the vegetation coverage [42]. The second significant increase is in YR, which had an increasing rate of 0.0049/a ($r^2 = 0.84$, $P < 0.001$). The region increased significantly mainly due to the enough moisture from Yangtze River, the heat from low latitude, and vegetation from the mountains. In NC, which had an increasing rate of 0.006/a, $r^2 = 0.62$ and $P < 0.001$. In NWC, the NDVI also had an increasing rate of 0.0039/a ($r^2 = 0.61$, $P < 0.001$). The slowest increase is in SWC but also very impressive, which also had an increasing rate of 0.0029/a ($r^2 = 0.66$, $P < 0.001$). The areas are the extremely arid deserts and Gobi but afforestation was also mainly implemented in the area to improve the vegetation during the past decades, which is confirmed by the previous study [43].

The year's linear trend of NDVI was calculated in order to assess the spatial heterogeneity of NDVI trends. It can be inferred from Figure 3 that the regions with annual maximum value of NDVI increases were primarily distributed in the northeast plain, Sanjiang plain, middle regions of Inner Mongolia, northern part of Shaanxi Province, southern part of Qinghai province, and western part of Xinjiang Uygur Autonomous Region, which is consistent with the previous study [40]. On the contrary, Figure 3 presents the diminishing trend of vegetation during the regions of hulunbuir pasture land, Great Khingan, Lesser Khingan Mountains, Changbai mountains, southern part of Gansu province and Shannxi province, northwestern part of Xinjiang Uygur Autonomous Region, Yangtze River Delta, Yun-Gui plateau, and some parts of other areas. The results of the linear regression are showed in Table 1. On the whole, vegetation activity increased from 1998 to 2013. The proportion of growing annual maximum value of NDVI in the entire survey region is 60.61%, but the decrease is just 3.98%. As for vegetation cover in 35.42% of the area before, now there is no significant change. The areas of NWC and SWC have no change because they are full of high mountains and desert, for example, arid desert and Gobi Desert regions [40].

3.2. Climate Change. The annual variation rates of the temperature and precipitation were calculated using the annual

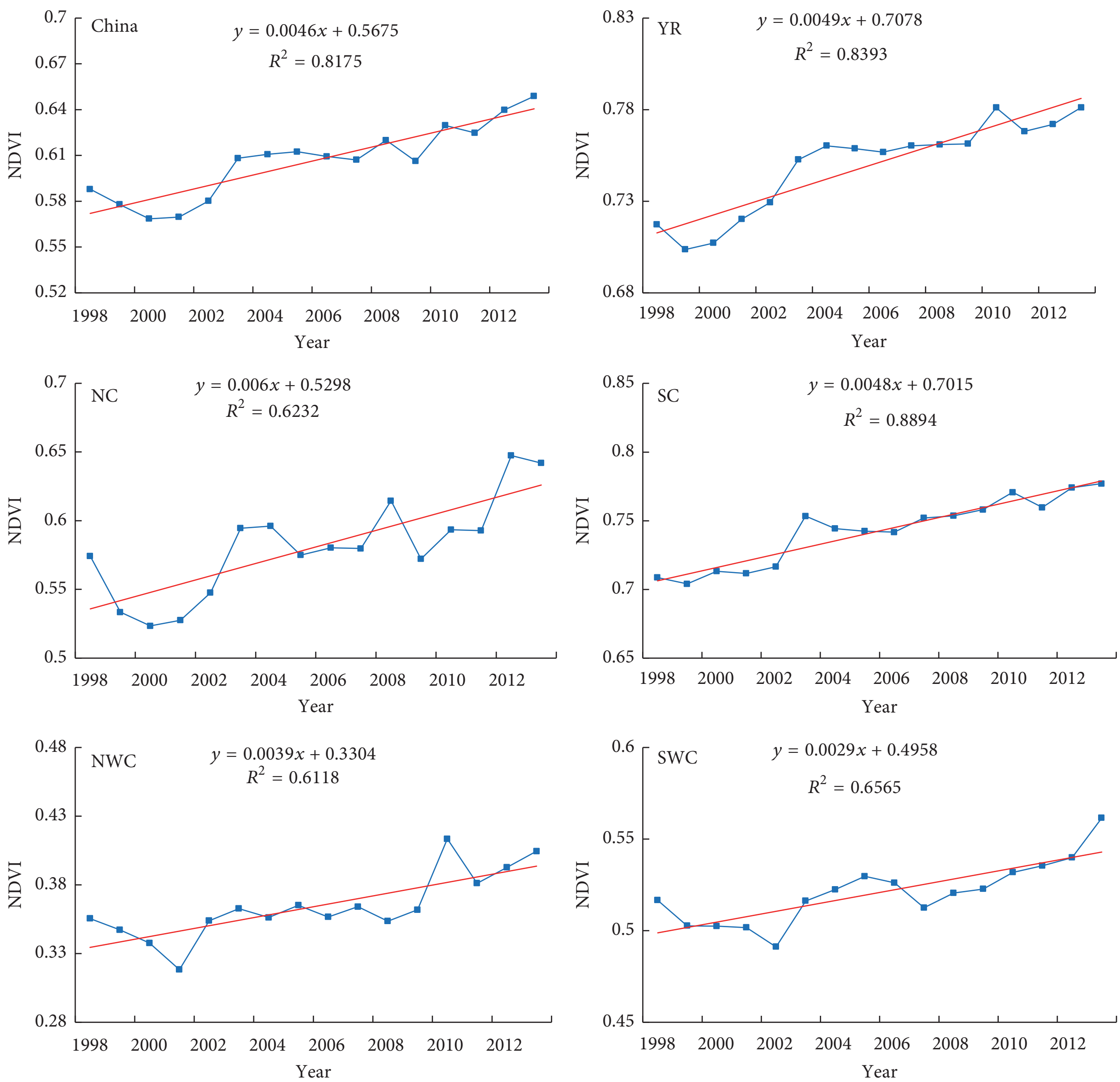


FIGURE 2: Time series of NDVI for China and its subregions.

mean temperature and precipitation of each pixel for China and different regions during 1998–2013 (Figures 4 and 5). Although the temperature of all China increased in the past 16 years, most of the subregions of China have a decreasing trend in China, and this study was in accordance with the previous study. The results showed that the temperature in most of the subregions decreased slightly, while the precipitation had a slight increase. Among them, the temperature in NEC, NC, and SC decreased generally, the temperature showed a slight decrease with different proportion of −0.011/a ($r^2 = 0.065$, $P < 0.001$), −0.026/a ($r^2 = 0.018$, $P < 0.001$), and −0.031/a ($r^2 = 0.213$, $P < 0.001$), while the precipitation in NEC, NC, and SC was generally increased, and the precipitation revealed a poor rising at various proportions of 6.719/a ($r^2 = 0.129$, $P < 0.001$), 2.051/a ($r^2 = 0.029$, $P < 0.001$), and 2.568/a ($r^2 = 0.004$, $P < 0.001$). The temperature and precipitation in NWC were increasing, the temperature revealed a poor rising at various proportion of 0.019/a ($r^2 = 0.172$, $P < 0.001$) and the precipitation also revealed a poor rising at various proportion of 0.355/a ($r^2 = 0.01$, $P < 0.001$). In contrast, both the temperature and precipitation had slight decrease, with the difference of −0.0082/a ($r^2 = 0.015$, $P < 0.001$) and −9.873/a ($r^2 = 0.128$, $P < 0.001$). In SWC, the temperature had a poor increase and the precipitation had a poor decrease, rising at various proportion of 0.016/a ($r^2 = 0.126$, $P < 0.001$) and −4.854/a ($r^2 = 0.355$, $P < 0.001$). On the whole, the precipitation increased basically in the northern region of China, especially in NEC and NC.

3.3. Correlations between NDVI and Principal Climatic Dynamics. It is well-known that climate change has an important effect on vegetation [16, 18, 25]. In this study,

Table 1: Annual max NDVI change trend from 1998 to 2013 in China and its different regions.

Regions	Pixel statistics	Significant increase	Increase	No trend	Decrease	Significant decrease
China	Number of pixels	1398389	5922814	4278827	422499	57396
	Percent of total area	11.58	49.03	35.42	3.5	0.48
YR	Number of pixels	42993	393374	806013	414920	27033
	Percent of total area	2.62	23.93	49.03	25.24	1.64
NEC	Number of pixels	18370	322610	837153	442289	127818
	Percent of total area	1.08	18.98	49.26	26.02	7.52
NC	Number of pixels	109642	563586	737848	519435	168615
	Percent of total area	5.31	27.29	35.73	25.15	8.16
SC	Number of pixels	9358	69245	198404	209672	67465
	Percent of total area	1.73	12.83	36.77	38.86	12.5
NWC	Number of pixels	274604	2361421	654802	181404	27348
	Percent of total area	7.92	68.11	18.89	5.23	0.79
SWC	Number of pixels	60608	532593	1130610	744500	271650
	Percent of total area	2.28	20	42.46	27.96	10.2

Table 2: Results of correlation test of different subregions.

Correlation	YR	NEC	NC	SC	NWC	SWC	China
NDVI and temperature	−0.013	−0.407	−0.467	−0.321	0.056	0.204	−0.094
NDVI and precipitation	−0.351	0.296	0.557*	−0.089	0.54*	−0.391	0.126

*Statistically significant at the 0.05 level.

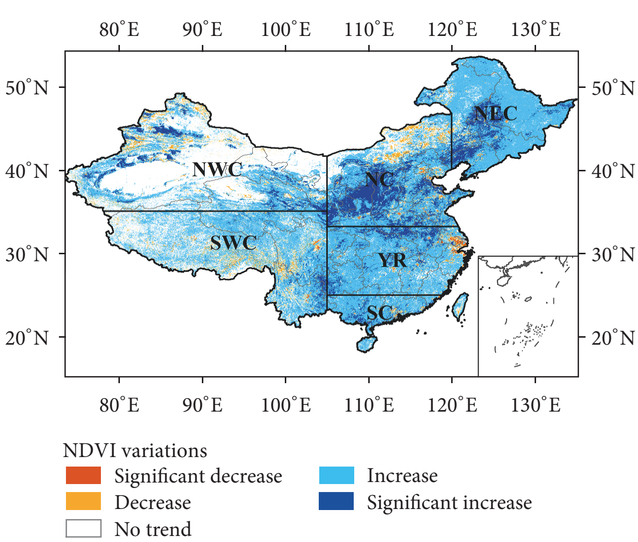


Figure 3: Spatial distribution of linear regression in the study area from 1998 to 2013.

the relationship between NDVI and temperature and precipitation in China from 1998 to 2013 were discussed at the annual scales (Table 2). The results showed that NDVI was positively correlated with precipitation and negatively correlated with temperature, but the correlation was not significant. The relationship between precipitation and NDVI was more obvious than temperature, which was consistent with the previous study [24, 29, 44]. The correlation coefficient between Annual NDVI and annual temperature was −0.094, which was a negative correlation, while there was a positive correlation between NDVI and precipitation and the correlation coefficient between them was 0.126. However, both of the correlation between NDVI and temperature and precipitation were poor. In YR and SC, there was a weak negative correlation between NDVI and temperature and precipitation. The correlation between NDVI and temperature and precipitation in the west of Daxingan Mountains was more obvious than in eastern parts, which indicates that Daxingan Mountains had a great influence on the growth of vegetation [33]. In NEC, NDVI was negatively correlated with temperature and positively correlated with precipitation. The reason is that the decrease of precipitation in recent years in the region and the drastic action of human activities reduce the vegetation coverage of the region [45]. In NC, NDVI was negatively correlated with temperature, while being positively correlated with precipitation. The results showed that precipitation was the main influencing factor of vegetation growth in NC area; the NDVI increase may be due to the region including the North China plain area; with the improvement of the level of modern farming, crop growth has been greatly improved, leading to the increase of NDVI in farming area [44]. In NWC, NDVI was positively correlated with temperature and significant positively correlated with precipitation. The main reason may be the climate wetting and the second reason may be the construction of the three North Shelterbelts in China significantly improving the vegetation conditions in the region [33, 46, 47]. In SWC, NDVI was weakly positively correlated with temperature, while being weakly negatively correlated with precipitation. The possible reason is that this region has high altitude and low latitude and is warm throughout the year as spring, and climate warming make Tibet Plateau temperature generally

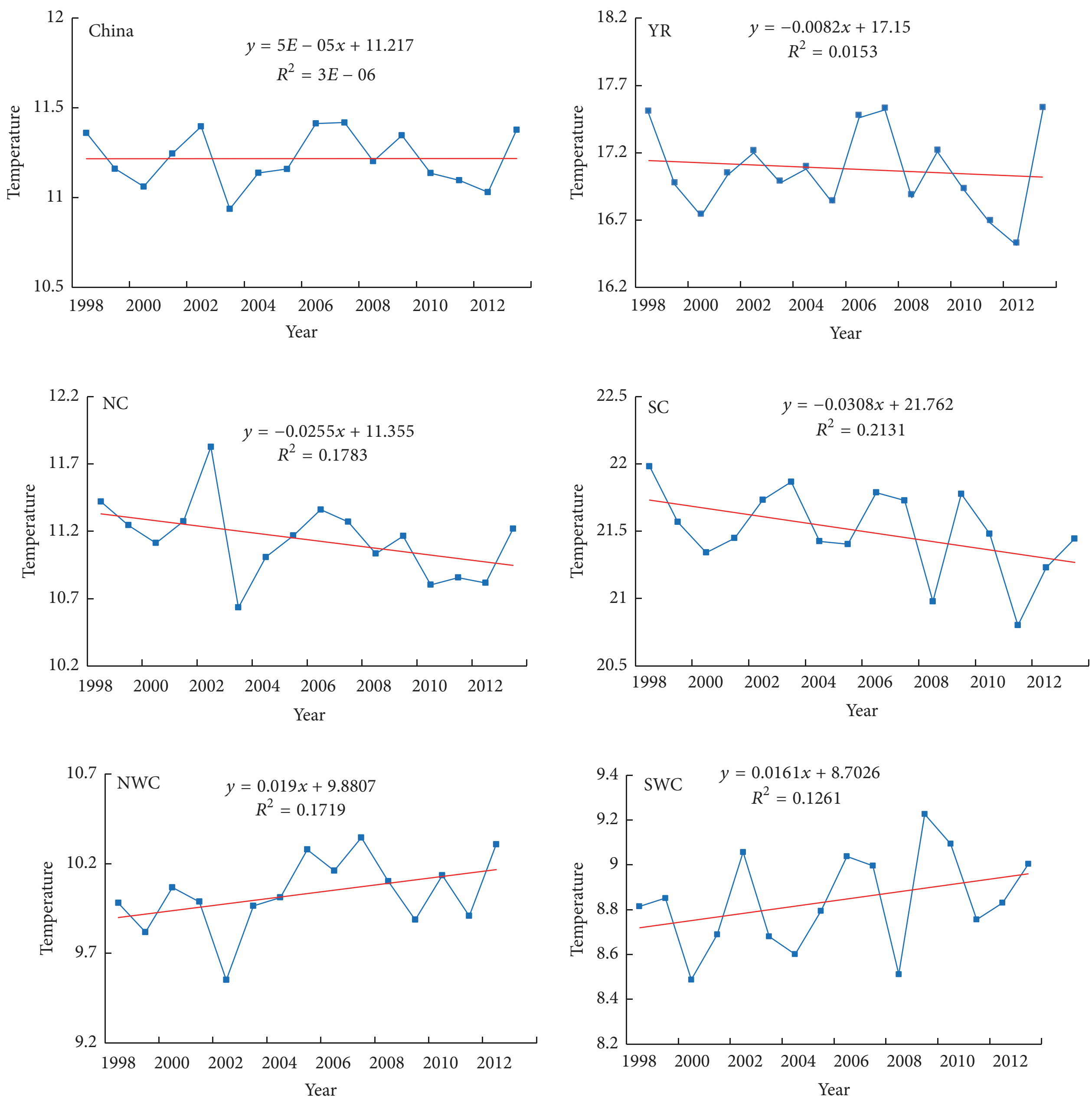


FIGURE 4: Time series of temperature for China and its subregions (unit: °C).

increased, so vegetation growth has heat conditions, while the temperature rise increases the glacier and snow melt water and so forth, which provides moisture condition for vegetation [31].

The correlation of vegetation NDVI with temperature and precipitation is not significant, and the distribution of correlation coefficient is quite different due to the influence of human activities and topography. In SC, the vegetation condition is affected significantly by human activities because of the water and heat conditions, and the relationship between the temperature and precipitation changes is not obvious. In NEC, due to the decrease of the temperature and the increase of the precipitation, the precipitation becomes the limiting climatic factors affecting the vegetation growth. In NC and NWC, water limits the growth of vegetation, and the vegetation improved obviously due to the increase of precipitation. The increase of temperature in the Tibetan Plateau can offer both heat and moisture conditions to vegetation growth, so temperature limits the growth of vegetation. At the same time, NDVI was positively correlated with precipitation in most parts of China but negatively correlated with precipitation in water-rich irrigation area, which is consistent with the former study [48]. Overall, the temperature increase in China has provided heat conditions for vegetation growth, and water has become a limiting factor affecting vegetation development.

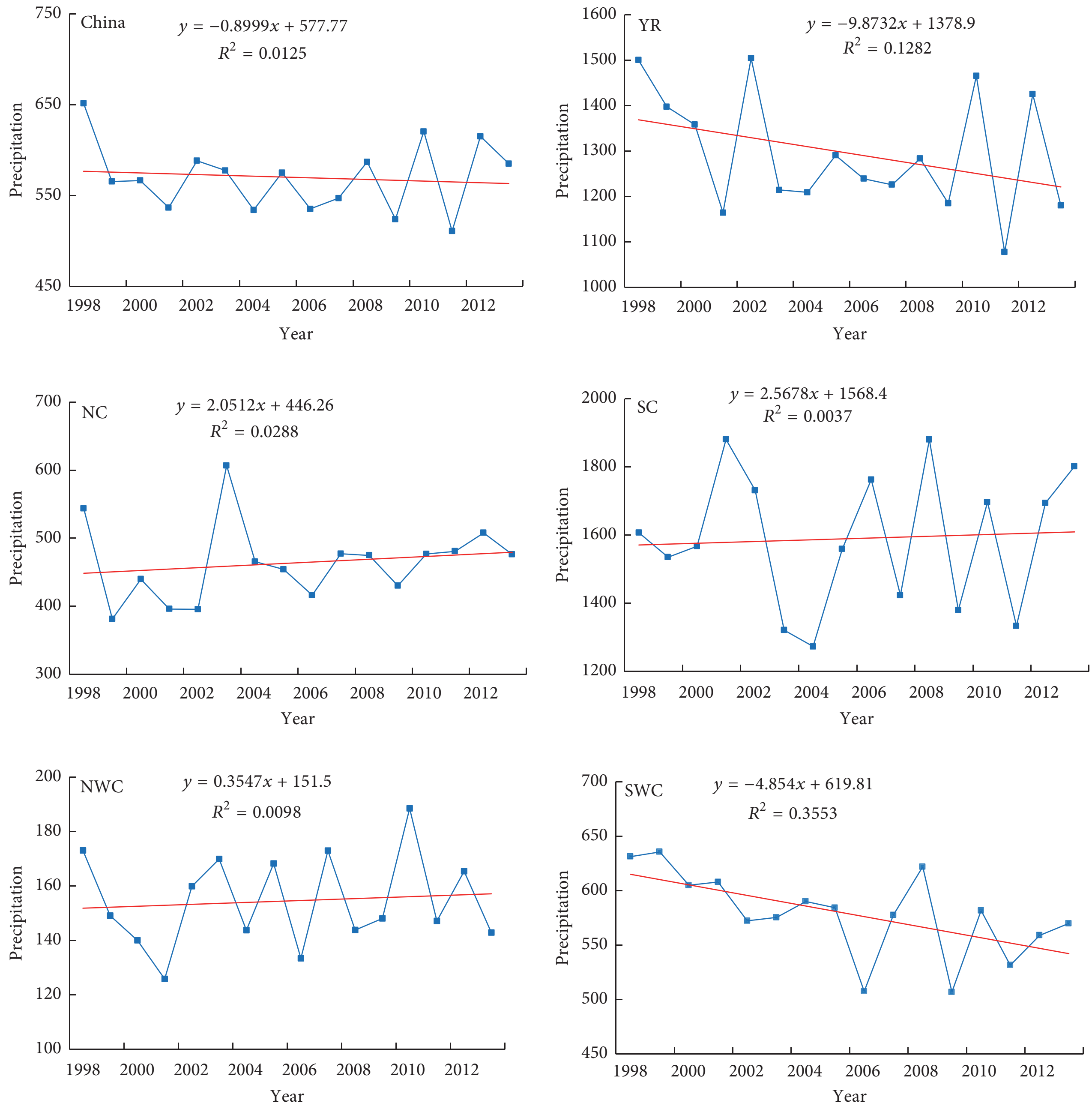


Figure 5: Time series of precipitation for China and its subregions (unit: mm).

The correlation between NDVI and temperature and precipitation at each meteorological station is shown in Figure 6. In Figure 6, the results show that there are significant differences between the two sides with significant correlation and no correlation, and the distribution of typical boundary coincides with the boundary line of humid and arid areas. According to the results, it can be known that the humid and arid areas are mainly semihumid, semiarid, and arid. Therefore, there was no obvious distribution law between vegetation NDVI and temperature, but distribution law was significant positively correlated with precipitation. Due to the abundant water and heat conditions, there is no obvious law in the humid areas south of China. The vegetation growth and the distribution of temperature and precipitation were not obvious, and the annual max NDVI was basically stable at about 0.7–0.8.

4. Conclusions

This study analyzes the spatial distribution and variation coverage of China and the correlation between vegetation NDVI and the main factors (temperature and precipitation) through SPOT/NDVI data from 1998 to 2013. The results showed that sufficient basic resources can provide a good

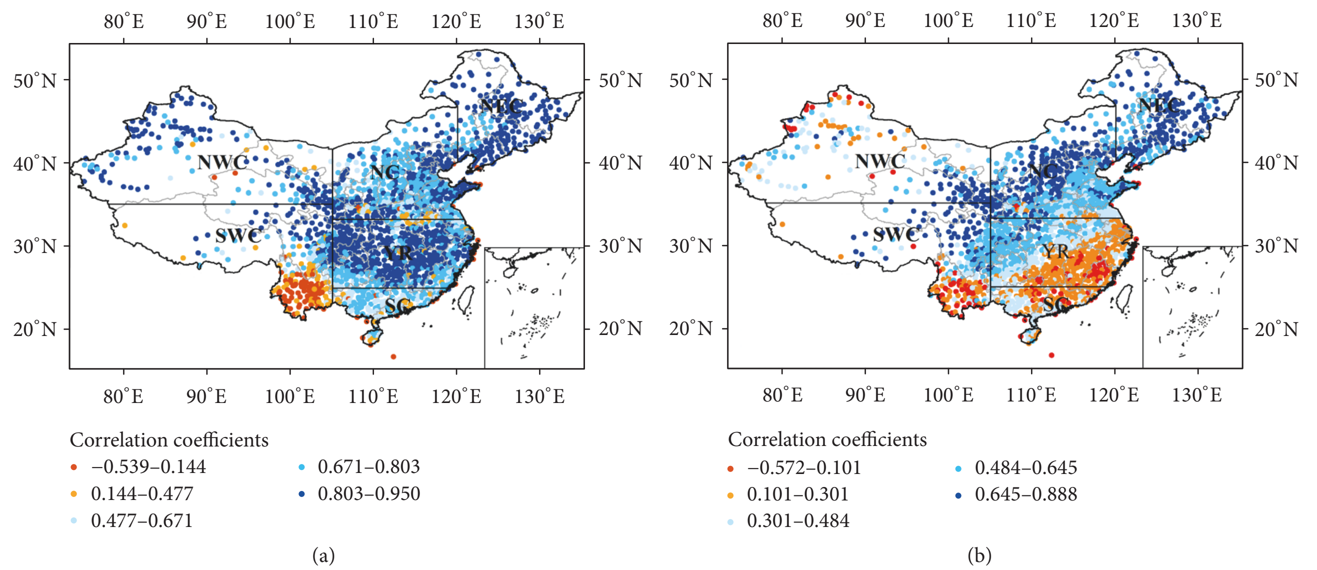


Figure 6: Distribution of correlation coefficient between NDVI and temperature (a) and precipitation (b) at meteorological stations throughout the study area.

foundation for the study of surface vegetation change. In general, the following is the representation of the outcome: (1) China's climate is getting warmer and drier from 1998 to 2013. Similarly, the annual maximum NDVI was significantly increased throughout the study region, as well as the NDVI in different subregions. (2) Through the analysis of the correlation between NDVI and temperature and precipitation, it was found that there was a positive correlation between NDVI and precipitation. (3) On the whole, the overall increase in the temperature of China provides heat for vegetation growth, which makes the water the limiting factor of vegetation growth, especially in the humid and arid area, which is relatively dry, and the distribution of NDVI and precipitation is positively related. The vegetation growth of the humid area in the south area is little affected by temperature and precipitation distribution, and human activity is the key factor affecting the vegetation growth condition. (4) In this research, though the SPOT/NDVI data were imprecise, these results provide a good foundation for the following research about the correlation between NDVI and temperature and precipitation and other related research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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