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*Original Research*

# Temporal and Spatial Variation Characteristics of NDVI of Forest Ecosystem in China from 1998 to 2015 and its Driving Force of Climate Factors

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## Abstract

In recent years, research on the relationship between the Normalized Difference Vegetation Index (NDVI) and climate factors has gained significant interest. This study examines vegetation changes in different forest ecosystems in China using the NDVI dataset from 1998 to 2015 and corresponding climate factor data (temperature and precipitation). Trend line analysis and correlation analysis methods are employed to investigate the spatial and temporal change characteristics of NDVI in five representative Chinese forest ecosystems. The driving forces of the two climate factors are simultaneously analyzed. The results indicate that: (1) Over the 18-year study period, the annual maximum NDVI of China's forest ecosystems exhibited a significant increasing trend ($P<0.01$), with an average annual increase of 0.0043; (2) Vegetation cover changes demonstrated an overall upward trend, with the NDVI of 84.87% of the forest vegetation in the study area increasing. However, a minimal decrease was observed in 0.94% of the study area; (3) Vegetation coverage in China's forest ecosystems has increased over the past 18 years, exhibiting a greening trend. Across the entire study area, the correlations between NDVI and temperature and precipitation were insignificant.

**Keywords**: NDVI, climatic factors; relevance, forest vegetation, spatio-temporal variation characteristics

## Introduction

Vegetation is a crucial component of terrestrial ecosystems and often changes in response to climate, which in turn constantly influences the Earth's energy balance and plays a critical role in various cycles [1-2]. Vegetation serves as a link between soil, atmosphere, and water, thereby consistently affecting the energy balance of Earth's ecosystems and playing a vital role in numerous cycles [3]. As the core of terrestrial ecosystems, vegetation reflects ecological changes and responds to complex systems, such as hydrology and gas exchange [4-5]. Therefore, studying different vegetation types in regional and global trends can reveal the interrelationship between climate change and terrestrial ecosystems [6]. In general, continuous observation of vegetation trends at large scales is challenging for traditional ecosystems, prompting many studies to

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utilize remote sensing technology for observation [7]. Characterizing long-term vegetation changes based on remote sensing is a key direction for global and regional change research [8]. Global warming has become an increasingly pressing issue in recent years [9], indirectly regulating carbon cycle feedback between terrestrial and atmospheric systems by altering nitrogen, phosphorus, and water cycles [10]. As a result of global warming, climate change is evidently affecting terrestrial vegetation activity [11-12].

The Normalized Difference Vegetation Index (NDVI) is a parameter that indicates the growth and coverage of various vegetation types in remote sensing vegetation monitoring and is widely used in large-scale vegetation change research [13-18]. NDVI accurately reflects the status of surface vegetation cover, distribution, and growth. It provides data for areas with large spatial scales or difficult to reach by person. At the same time, long-term NDVI datasets can present the distribution and change of vegetation cover across spatial and temporal scales. This makes NDVI an essential reference for studying vegetation change dynamics, rational use of vegetation resources, and other ecological environment-related fields [19]. NDVI is an important indicator for evaluating a region's ecological health [20]. For example, NDVI is a good indicator of Net Primary Productivity of forests and they are mostly positively correlated [21]. Forest succession processes can also be analyzed according to NDVI [19]. It is very important for vegetation research and conservation [22]. Both domestic and international researchers have explored vegetation cover dynamics based on long time-series NDVI and developed several generalized analysis methods, such as principal component analysis, regression analysis, Theil-Sen median trend analysis, Mann-Kendall test, Fourier transform, and wavelet analysis [23]. NDVI is also used in different fields such as agriculture, ecology [24-26], etc.

Under the combined influences of ongoing climate change and increasing human activities, terrestrial vegetation cover in China has experienced significant and complex changes [27]. In order to investigate the patterns of vegetation changes in different terrestrial ecosystems in response to climate factors [28], several studies have examined the spatial and temporal distribution changes of NDVI. For instance, Liu et al. suggested that moisture was the limiting factor affecting vegetation development within a certain range of temperature variation, according to GIMMS NDVI and climate variables (temperature and precipitation) [29]. Cui et al. demonstrated that grassland NDVI values in eastern China during 1998-2007 increased, and the correlation between NDVI and climate variables in grasslands was most significant [30]. Li et al. proposed that overall terrestrial vegetation activity in China has tended to increase in the last 30 years and is clearly influenced by anthropogenic factors at the regional level [31]. Vegetation cover in China has also increased significantly in recent years due to the impact of climate change [32]. Furthermore, many researchers analyzed different vegetation types in various geographical units and even across the entirety of China [33-37], concluding that NDVI is correlated with climate factors across the area and represents the coverage of different vegetation types. In northeastern China, several studies have shown that over the past 20 years, vegetation NDVI has exhibited an increasing trend under the combined influence of climate and human activities. NDVI was positively correlated with temperature and precipitation, with precipitation exerting the strongest influence on NDVI [38]. Among them, forest vegetation NDVI was significantly influenced by minimum temperature and precipitation but was not closely related to the maximum temperature. Climate change resulted in a significant increase in minimum temperature and precipitation during the growing season [39].

Given the vastness of China, different regions have various natural conditions and diverse plant species, resulting in an extremely diverse range of forest plants and forest types. Forests are essential for mitigating climate change and ensuring human survival. They are an important part of terrestrial ecosystems and the foundation for human existence, playing a key role in mitigating climate change and maintaining ecological balance [40]. The quantity and quality of forest resources are directly related to human socio-economic development. With climate change influencing forest changes, the focus has shifted to ecological environment construction. Studying the vegetation change process of forest ecosystems and its relationship with climate change is crucial. In this study, SPOT NDVI data and meteorological station data from 1998–2015 were used to examine the spatial distribution of forest vegetation NDVI and its correlation with climate variables (temperature and precipitation). The NDVI of forest ecosystems mentioned in this paper refers to the annual NDVI maximum.

## Materials

### Study Area

China's territory spans from 49° of latitude to 62° of longitude, with the majority of its land located between 18°N and 53°N. The country's climate zones, which include the sub-frigid zone, temperate zone, subtropics, and tropics, are arranged from north to south. Eastern China experiences a typical inland climate under the influence of the southeast marine monsoon. Consequently, forest cover gradually decreases from southeast to northwest, with forest belts, grassland belts, and desert belts distributed along this gradient, exhibiting longitudinal zonality. Forest cover in the eastern, western, and central regions is 34.27%, 12.54%, and 27.12%, respectively. Although the northwest region comprises 32.19% of China's territory, its forest cover is only 5.86%. The distribution of forest vegetation exhibits a striking latitudinal zonality, with numerous plant species in tropical rainforests and fewer in sub-boreal forests.

This paper focuses on five forest types in China: broadleaf forests, planted broadleaf forests, needle-leaf forests, planted needle-leaf forests, and broadleaf-conifer mixed forests. The distribution of forest ecosystems in China is illustrated in Fig. 1.

## Data Sources

In this study, two datasets were utilized. The long-term NDVI data, collected from 1998 to 2015, were obtained from the Resource and Environment Science and Data Center (https://www.resdc.cn/). Meteorological factors, including mean temperature and annual precipitation data, span the same timeframe as the NDVI data. The NDVI dataset was downloaded with a spatial resolution of 1 km × 1 km. Meteorological data were resampled using bilinear interpolation to match the spatial resolution of the NDVI data. MODIS (Moderate Resolution Imaging Spectroradiometer) NDVI, AVHRR (Advanced Very High Resolution Radiometer) NDVI, and SPOT-VGT (SPOT-VEGETATION) NDVI datasets are widely employed in recent research. The SPOT-VGT NDVI dataset, originating from France, is specifically designed for vegetation and surface observations, offering advantages in spectral band design, spatial accuracy, and ensemble correction [41].

We analyzed the inter-annual variation of NDVI using linear trend analysis. ArcGIS 10.1 raster calculator was employed to examine the spatial and temporal variation characteristics of vegetation cover in forest ecosystems, revealing the NDVI changes in Chinese forest ecosystems. Subsequently, the correlation between mean temperature, annual precipitation, and NDVI was analyzed using the correlation analysis method.

This paper focuses on five forest vegetation types: broadleaf forests, planted broadleaf forests, needle-leaf forests, planted needle-leaf forests, and broadleaf-conifer mixed forests. We generated a vector map depicting the distribution of these five forest vegetation types. To obtain the NDVI data for different forest ecosystems, we cropped the 18-year NDVI raster data in the study area using the vector map. Meteorological factor data were resampled using nearest neighbor interpolation to maintain spatial resolution consistency with NDVI. Finally, ArcGIS 10.1 raster calculator was employed to analyze the spatial and temporal characteristics of vegetation cover changes in forest ecosystems across the nation over the 18-year period.

## Research Methods

### *Trend Line Analysis*

In this study, we examined the spatial distribution and characteristics of NDVI in Chinese forest ecosystems based on the overall trend of NDVI data over 18 years (1998-2015). We employed least squares

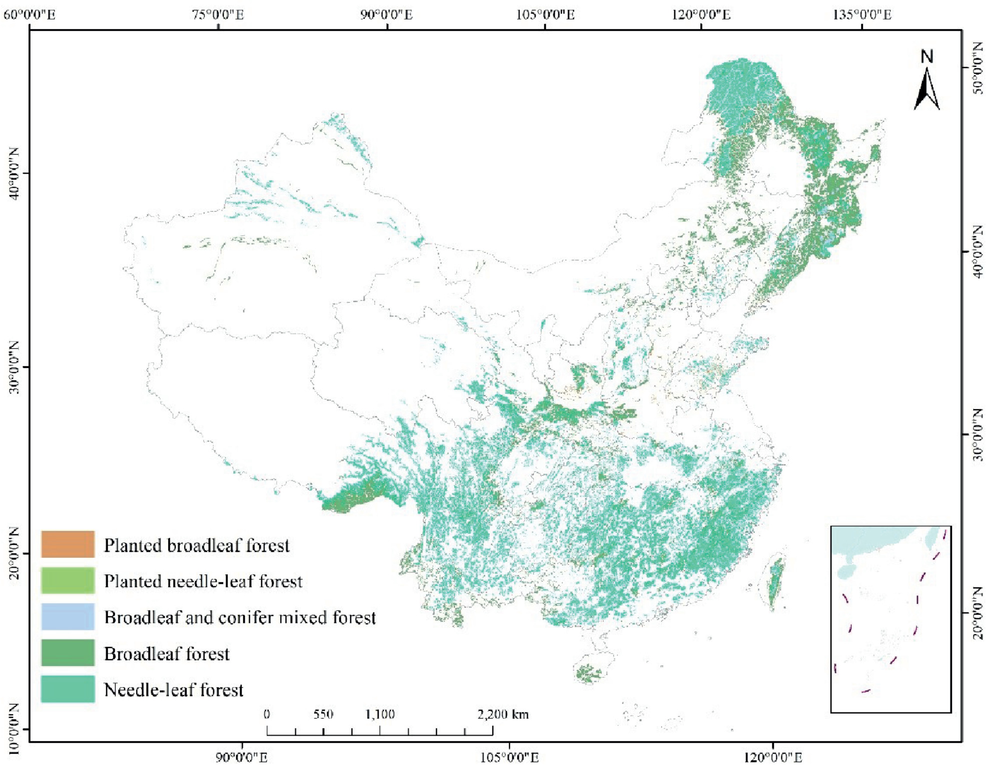


Fig. 1. Distribution map of forest ecosystem in China.

regression analysis to calculate NDVI values for forest vegetation and the inter-annual trends of meteorological factors. To test for significant changes in NDVI of forest vegetation, we used a 95% significance level ($P$<0.05). The linear regression equations are presented as follows. (Equations (1) and (2) [42]).

$$y = at + b + \varepsilon \tag{1}$$

$$a = \frac{\sum_{i=1}^{18}(y_i - \bar{y})(t_i - \bar{t})}{\sum_{i=1}^{18}(y_i - \bar{y})^2} \tag{2}$$

Where $y$ is the NDVI, $a$ is the inter-annual trends of annual mean NDVI during the growing season, $t$ is time, $b$ is intercept, $\varepsilon$ is random error, $\bar{y}$ and $\bar{t}$ are the average of $y$ and $t$ respectively.

To explore the trends of forest ecosystem NDVI, we analyzed linear trends of raster from 1998 to 2015 on a per-pixel basis. The expression is provided below (Equations (3) [43]):

$$Slope = \frac{n \times \sum_{i=1}^{n} i \times \overline{M}_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} \overline{M}_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \tag{3}$$

Where $Slope$ is the trend of a pixel's NDVI or meteorological factor, $n$ is equal to 18, $M_i$ is the NDVI value in $i$ year, $\overline{M_i}$ is the mean value of the NDVI in $i^{th}$ year, the order of year from 1998 to 2014. In general, the NDVI of the forest ecosystem exhibits an increasing trend when >0 and decreasing trend when $Slope$<0.

*Correlation Analysis*

Climatic factors, particularly temperature and precipitation, influence vegetation growth. In this study, inter-annual mean temperature and annual precipitation serve as key factors reflecting forest vegetation growth. Since vegetation NDVI changes are also impacted by a combination of temperature, precipitation, and other factors, we initially analyzed the relationship between NDVI and temperature and precipitation. We employed correlation analysis to evaluate their association and a t-test ($P$<0.05) to determine the trend of vegetation cover. Furthermore, we examined the extent to which each factor affects the percentage of the total area, with the final result indicating the magnitude of their contributions. Equation (4) represents the formula for the correlation coefficient [44]:

$$r_{xy} = \frac{\sum_{i=1}^{18}[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum_{i=1}^{18}(x_i - \bar{x})^2 \sum_{i=1}^{18}(y_i - \bar{y})^2}} \tag{4}$$

Where $r_{xy}$ represents the correlation coefficient for $x$ and $y$. $x_i$ and $y_i$ is the values of the two variables in $i^{th}$ year, $\bar{x}$ and $\bar{y}$ is the mean values of $x$ and $y$.

## Results

### NDVI Annual Trend of Forest System

*Spatial Distribution Pattern of Forest System Vegetation NDVI*

The spatial distribution map of NDVI from 1998 to 2015 (Fig. 2) demonstrates that the NDVI values for most pixels exceed 0.6, indicating healthy forest vegetation growth. In the northern regions, NDVI gradually increases from west to east. Moreover, most southern forest vegetation exhibits higher NDVI values compared to other areas.

According to Fig. 1, pixels with values below 0.2 constitute 0.56% of the forest vegetation. Pixels in the range of 0.2-0.4 represent 0.74%, while those in the 0.4-0.6 range account for 3.29%. Pixels in the 0.6-0.8 range make up 38.42% of the area, with the primary forest vegetation types being needle-leaf forests and planted broadleaf forests.

The largest area (approximately 59.99%) consists of pixels with values above 0.8. The main forest vegetation types in this range are broadleaf and conifer mixed forests, needle-leaf forests, and broadleaf forests. In areas with abundant water, plants thrive, resulting in high NDVI values and considerably greater forest vegetation coverage.

*Inter-Annual Dynamics of NDVI*

Fig. 4 illustrates the variations in the NDVI of forest ecosystem vegetation from 1998 to 2015. The total study area exhibited a notable increase from 0.7471 in 1998 to 0.7649 in 2015, with an average annual increment of 0.0046 year$^{-1}$ ($P$<0.01). The minimum value was 0.7457 in 2000, while maximum value reached 0.833 in 2015. NDVI increased at a faster pace, contributing to enhanced vegetation cover.

*Spatial Dynamics of NDVI at the Pixel Scale*

The spatial dynamics of forest vegetation NDVI reveal the trend of NDVI changes. In Fig 4a), positive values indicate an increasing trend in forest vegetation cover, while negative values signify a decreasing trend. During the study period, NDVI values in China were predominantly positive, indicating that the overall vegetation cover of forest ecosystems is increasing. Fig. 4b) demonstrates that the annual NDVI values of forest vegetation in the northeast, southeast, and southwest regions experienced a significant increase ($P$<0.01). Conversely, the annual NDVI in northwest

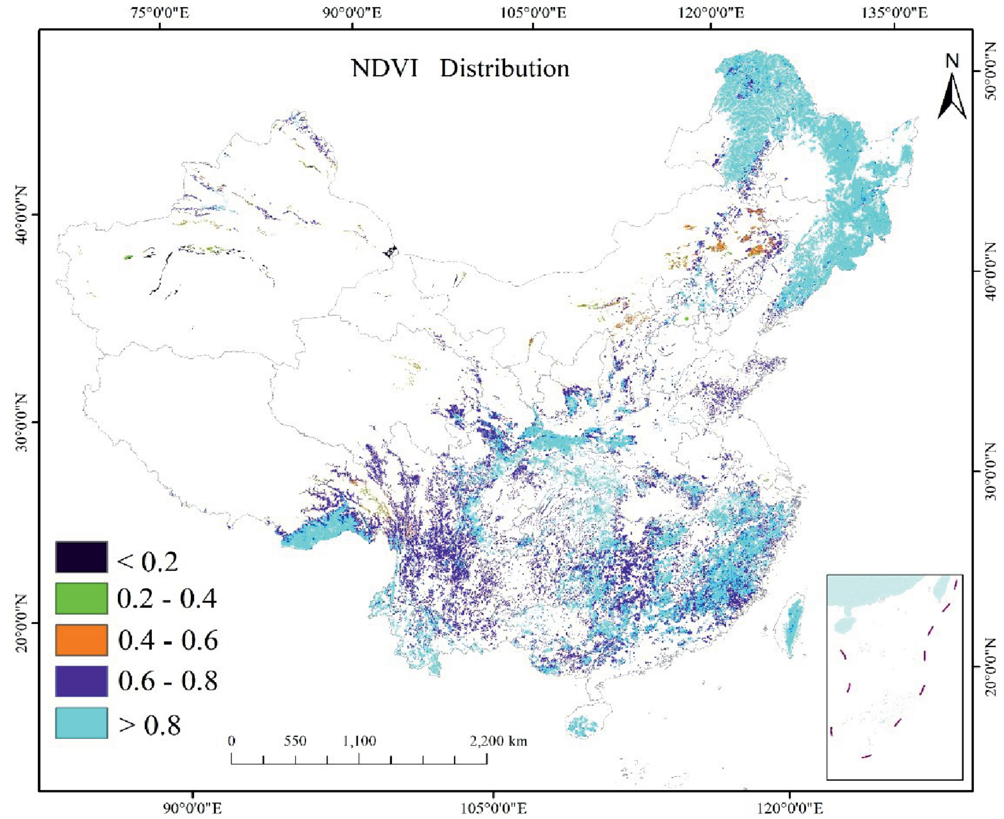


Fig. 2. NDVI spatial distribution map from 1998 to 2015 .

China increased insignificantly or even decreased. The northwest region is primarily composed of grasslands and deserts, with a smaller forest vegetation area and the potential presence of growing shrubs.

Fig. 3, derived from Fig. 4b), indicates that 84.87% of Chinese forest ecosystem exhibits an increasing trend. Within the study area, 74.8% demonstrates a highly significant increase ($P$<0.01), while only 0.94% shows a decreasing trend. The area of increased forest vegetation cover substantially exceeds the area of decrease. Thus, during the study period, the forest vegetation cover in China experienced a significant increase.

## Correlation Between Vegetation NDVI and Climate Factors

### *Correlation Between Chinese Forest Ecosystem NDVI and Climate Factors*

Forest ecosystems can potentially mitigate the impacts of climate change. The relationship between forest vegetation and climate factors is complex,

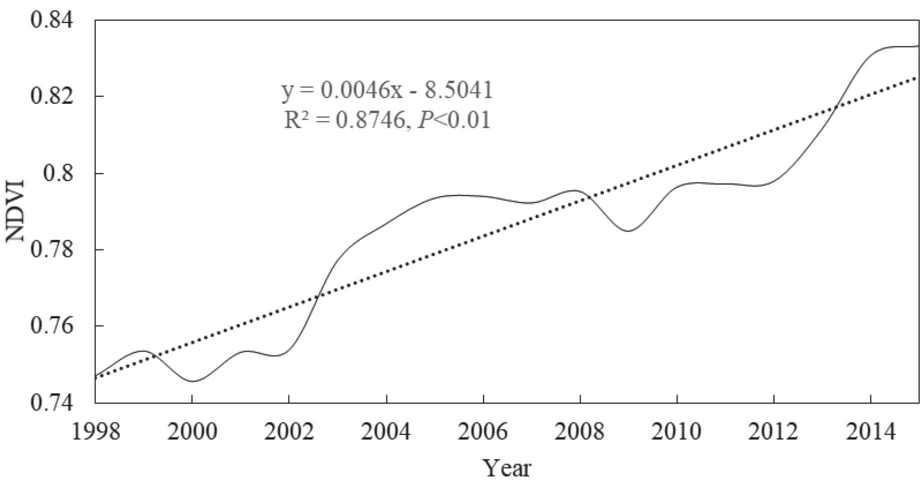


Fig. 3. Change trend of NDVI of forest ecosystem in China from 1998 to 2015.

as they often interact with one another. As shown in Table 4, the positive correlations between NDVI and temperature, as well as the negative correlations between precipitation, are not significant for the five typical forest vegetation types in China. However, we can map the spatial distribution of correlation coefficients and the significance of NDVI with temperature and precipitation to investigate their correlation further.

Table 1. Percentage of pixels in NDVI change trend of forest ecosystem in China from 1998 to 2015.

| NDVI | Pixel scale (%) |
|---|---|
| <0.2 | 0.56% |
| 0.2-0.4 | 0.74% |
| 0.4-0.6 | 3.29% |
| 0.6-0.8 | 38.42% |
| >0.8 | 59.99% |

Table 2. Annual NDVI change trend of forest ecosystem in China from 1998 to 2015 proportion of slope amplitude in pixels.

| Slope | Pixel scale (%) |
|---|---|
| <0 | 4.09% |
| 0-0.002 | 5.49% |
| 0.002-0.004 | 26.89% |
| 0.004-0.006 | 38.35% |
| 0.006-0.008 | 17.79% |
| >0.008 | 7.39% |

Table 3. Percentage of significant levels in pixels of annual NDVI change trend of forest ecosystem in China from 1998 to 2015.

| Sig. | Pixel scale (%) |
|---|---|
| Significant decrease (*P*<0.01) | 0.54% |
| Significant decrease (*P*<0.05) | 0.40% |
| Decrease but not significant | 3.16% |
| Increase but not significant | 11.04% |
| Significant increase (*P*<0.05) | 10.07% |
| Significant increase (*P*<0.01) | 74.80% |

Table 4. Correlation coefficient between annual NDVI of forest ecosystem and climate factors (precipitation and temperature) in China from 1998 to 2015.

| Correlation | NDVI |
|---|---|
| Temperature | 0.024 |
| Precipitation | -0.178 |

To further assess correlations between NDVI and climate variables, we calculated correlation coefficients between NDVI and the two climate factors in Chinese forest ecosystems, we created spatial distribution maps of correlation coefficients (Figs 5a) and 6a)) and significance (Figs 5b) and 6b)).

As shown in Table 5, NDVI of forest vegetation was not significantly correlated with temperature and precipitation in most of the study areas. However, there were still a small number of areas with significant correlations. There was a significant positive correlation between NDVI and temperature in 5.25% of the forest vegetation, and NDVI increased with increasing temperature. A significant negative correlation between NDVI and temperature existed in 3.01% of the forest vegetation, and NDVI decreased with increasing temperature. Temperature is the key factor in these two areas.

A significant negative correlation between NDVI and precipitation existed in 2.41% of the forest vegetation. 6.43% of the NDVI of the forest vegetation was significant positively correlated with the spatial variation in precipitation. Precipitation plays a more important role for forest vegetation in the above-mentioned areas.

## Variation Characteristics of NDVI Changes in Different Chinese Forest Ecosystems

The NDVI trends for various forest ecosystems enabled us to better understand patterns of NDVI change (Fig. 7). The NDVI of the five forest ecosystems showed an increasing trend, but with fluctuations. This reveals that the growth of the five forest vegetation types has continuously improved and ultimately stabilized over 18 years. Among the five forest vegetation types, the NDVI values of planted broadleaf forests and planted coniferous forests displayed a trough around 2002. These two planted forests exhibited substantial fluctuations during the study period. Needle-leaf forests, broadleaf forests, and broadleaf and conifer mixed forests experienced fewer fluctuations than plantation forests over the 18-year period. The NDVI of mixed and broadleaf forests showed a decreasing trend between 2007 and 2009. The NDVI of planted forest vegetation

Table 5. Proportion of significant level of temperature change trend of forest ecosystem in pixels in China from 1998 to 2015.

| Sig. | Pixel scale (%) |
|---|---|
| Significant decrease(*P*<0.01) | 0.74% |
| Significant decrease (*P*<0.05) | 2.27% |
| Decrease but not significant | 42.28% |
| Increase but not significant | 49.46% |
| Significant increase (*P*<0.05) | 3.32% |
| Significant increase (*P*<0.01) | 1.93% |

displayed a rapid increase between 2002 and 2008, with the curves of both forest vegetation types showing similar trends. Planted forest vegetation is influenced by human intervention in addition to climatic factors. The trends of the two planted forests were similar to those of natural forests. However, human intervention during the study period caused greater fluctuations in both planted forests compared to the other natural forests.

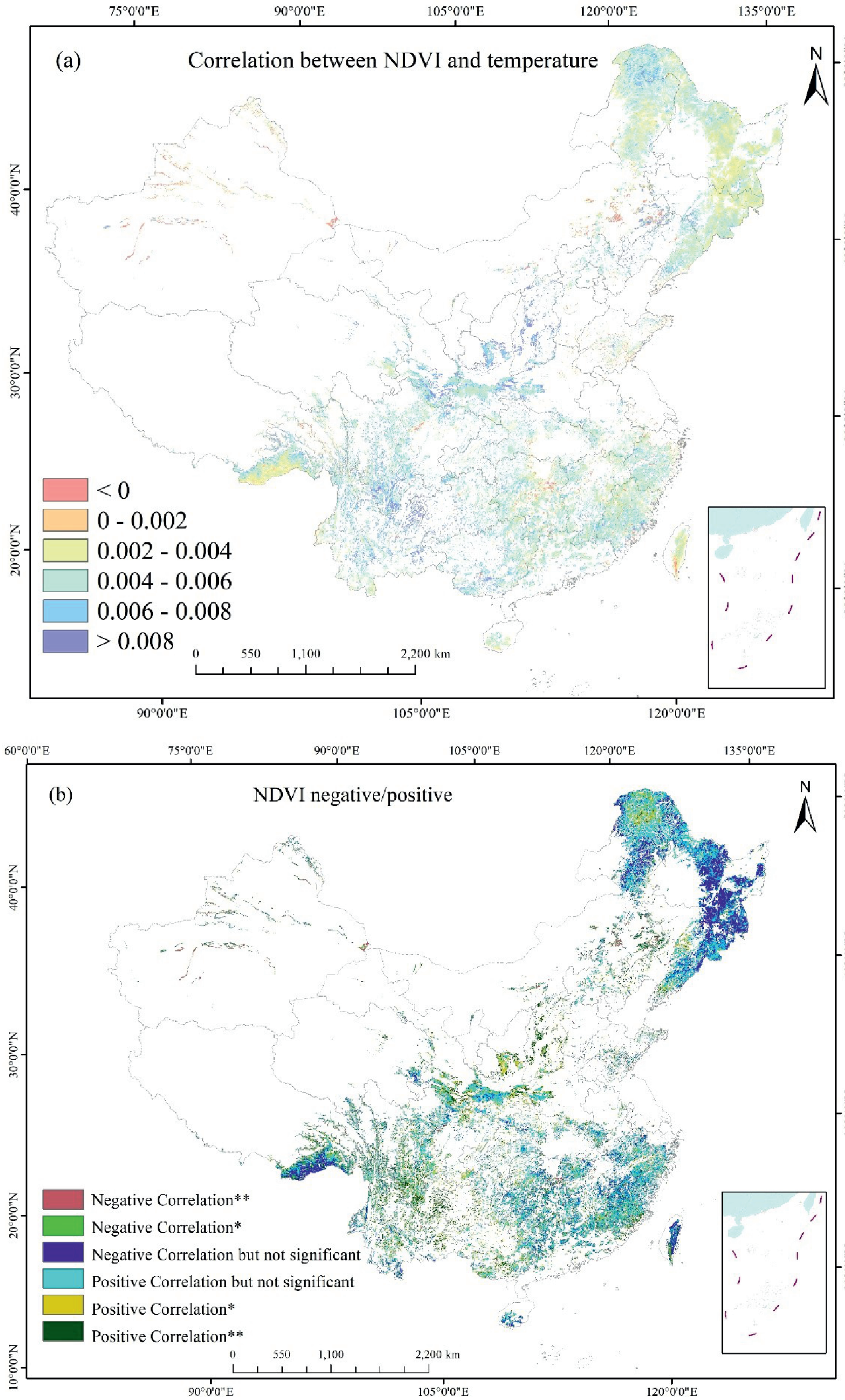


Fig. 4. Trend chart of NDVI change significance from 1998 to 2015.

## Discussion

In this study, we utilized SPOT NDVI data and meteorological station data from 1998-2015 to investigate the spatial and temporal variation characteristics of NDVI. In the north, the NDVI of the forest gradually increases from west to east, with higher NDVI values observed in most southern forest vegetation. This reveals

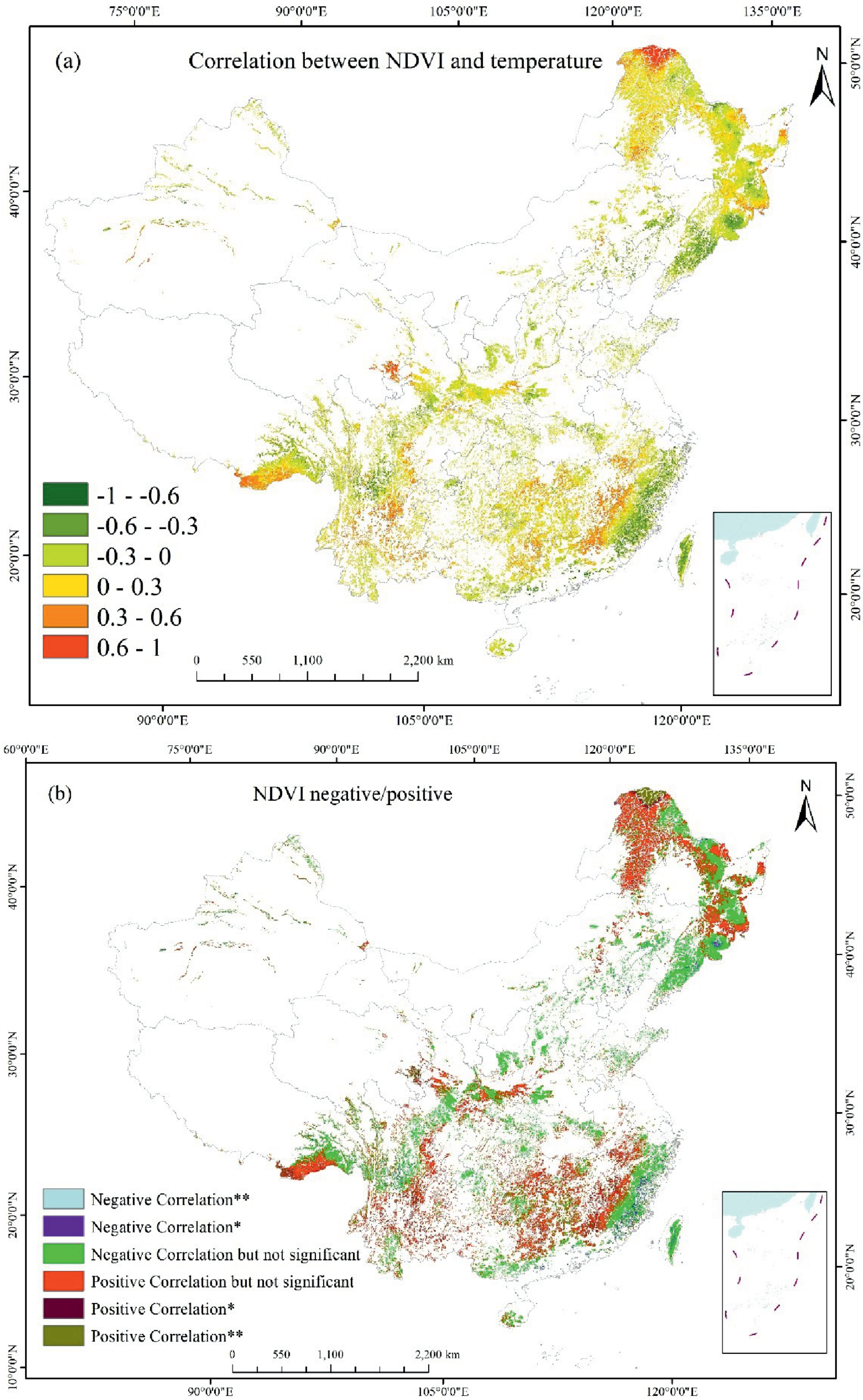


Fig. 5. Spatial distribution of correlation coefficients a) and significance b) between NDVI and temperature for forest ecosystems in China from 1998 to 2015.

a favorable status for the southern forests. Generally, forest vegetation in the southeast is healthier than in the northwest, and the vegetation coverage of forest ecosystems decreases from southeast to northwest.

Forests are closely related to the long-term effects on the local environment. In China, there are significant climatic differences between the north and the south, with higher temperatures and precipitation in the

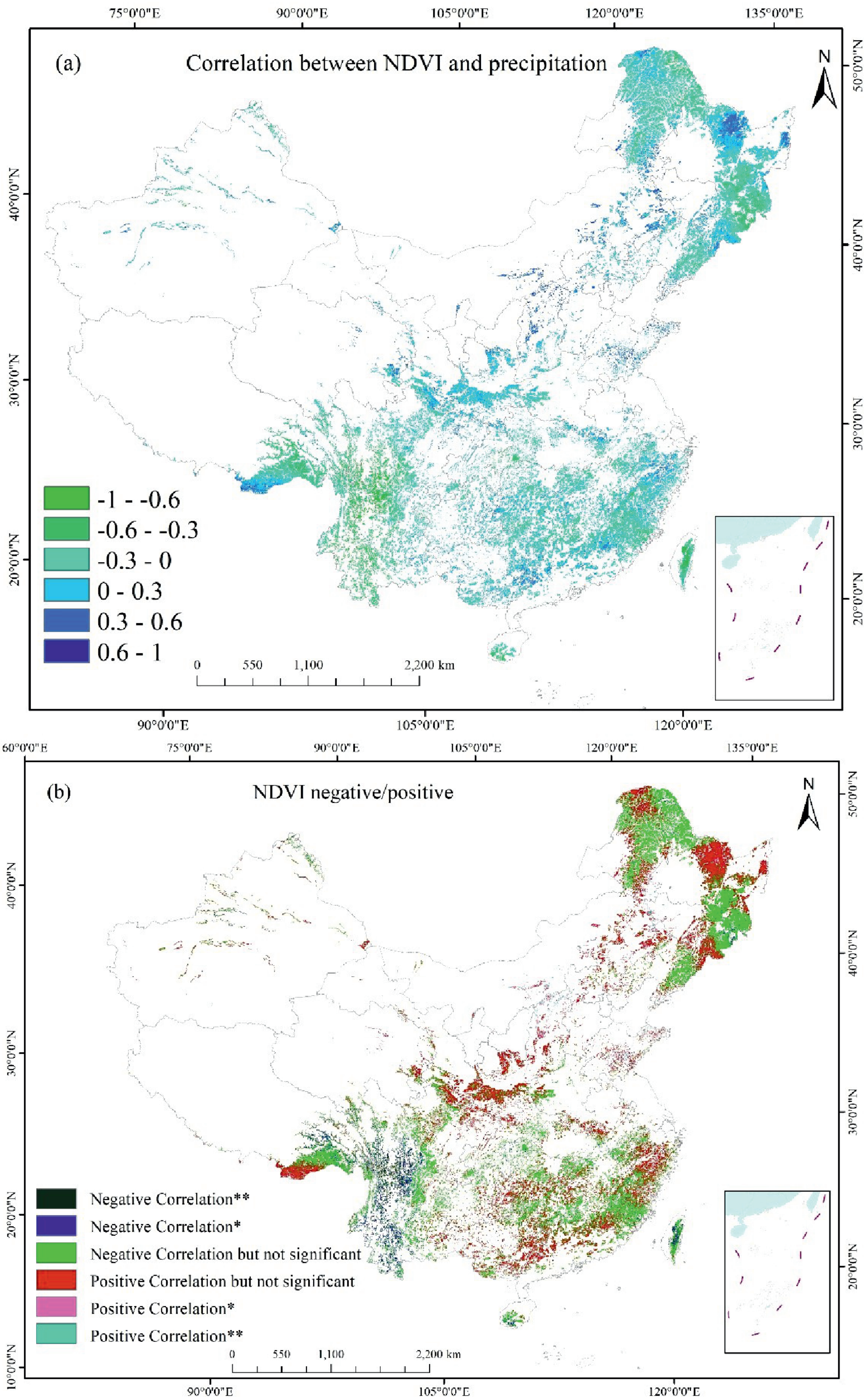


Fig. 6. Spatial distribution map of correlation coefficient a) and significance b) be-tween NDVI and precipitation of forest ecosystem in China from 1998 to 2015

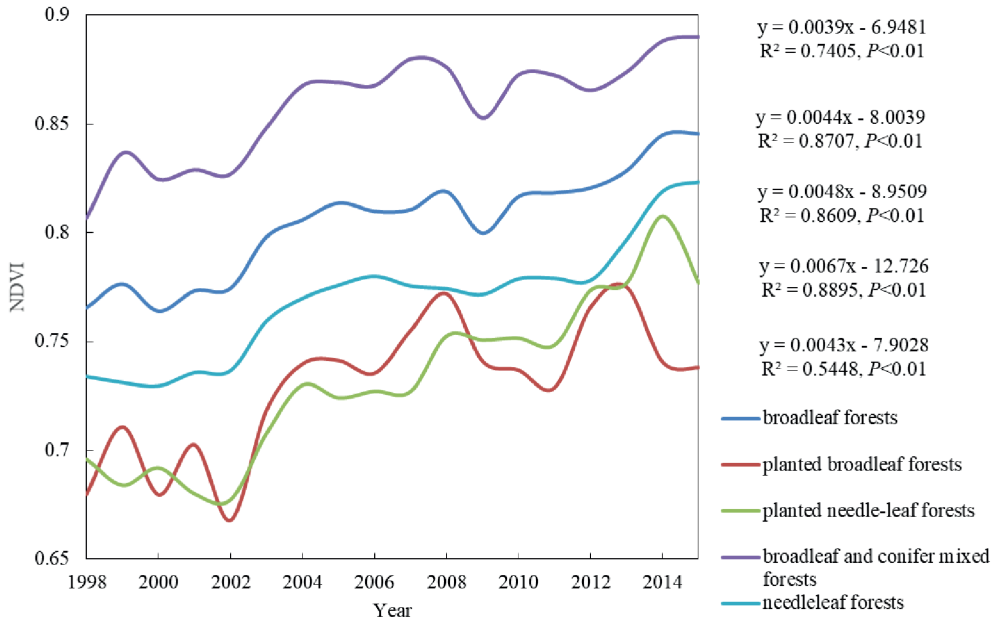


Fig. 7. Variation Characteristics of NDVI in different forest ecosystems.

southeast. Vegetation comprising more species grows rapidly in warm and humid conditions. In contrast, the northwest has fewer plant species compared to the south [45], with fewer macrophanerophytes and the possible presence of some shrubs. The better the plant growth, the higher the NDVI of the vegetation. Consequently, the forest vegetation cover is higher near the tropics. Additionally, healthy and lush forest vegetation can also improve the environment [46]. Among the five forest vegetation types, the NDVI values of planted broadleaf forests and planted coniferous forests displayed a trough around 2002.

The response of vegetation NDVI to climate is a complex process. Study results may vary depending on factors such as the study area, spatial and temporal scales, and data sources, among others [47]. In this study, the correlation between NDVI values of forest vegetation and temperature and precipitation was not significant. This is due to the large latitudinal span, multiple climate types, and complex and diverse topography in China. For example, vegetation cover in the growing season is greater than that in the non-growing season. In the non-growing season, evergreen broadleaf forest cover is higher than deciduous broad-leaved forest. Additionally, the NDVI of various forest vegetation types exhibits different spatial and temporal variation characteristics under different seasons within the growing season. In contrast, this paper analyzes the inter-annual variation trends of five forest vegetation types and their relationships with temperature and precipitation over a large time span based on annual NDVI maxima. This weakens the fluctuation of vegetation variation within small geographical units to a certain extent.

The heat demand of different forest vegetation types differs, but related studies have suggested that the NDVI values of coniferous, broadleaf and mixed forests were positively correlated with temperature throughout the season [48]. In the context of global warming, the overall NDVI values of forest vegetation in China have shown an increasing trend. NDVI exhibited a significant positive correlation with temperature in some southern regions of China (Fig 5(a)), indicating substantial effects of heat on forest vegetation activity. Jin et al. found that the NDVI of broadleaf forests in eastern central China increased rapidly under the influence of climate between 1982 and 2015, and that climate warming was an important cause of NDVI increase in China [49]. In the north, vegetation growth is primarily limited by moisture, and precipitation is more relevant to the growth of boreal forest vegetation than temperature [36, 50]. Coniferous forests had lower NDVI than broadleaf forests due to lower net primary productivity, but the growth trend was totally similar to broadleaf forests. The plantation forests had the lowest NDVI values and fluctuated greatly.

## Conclusion

This paper documents the spatiotemporal variations in NDVI and the correlation between NDVI and climate factors for five forest vegetation types in China. The main conclusions are as follows:

(1) From 1998 to 2015, the annual NDVI of Chinese forest ecosystems exhibits an overall increasing trend at a rate of 0.0046 year$^{-1}$($P$<0.01). Under the influence of climate change due to global warming, Chinese forest ecosystem vegetation is in good condition, and vegetation cover increases in a suitable growing environment.

(2) Owing to the diverse environments of different forest ecosystems, forest vegetation types exhibit distinct characteristics in different times and spaces. The correlation between the annual NDVI maximum and the annual mean temperature and the total annual precipitation was not significant overall. However, the correlation exhibited a certain degree of heterogeneity at the per-pixel scale. For instance, NDVI variation in some areas of southern China and the Greater Khingan Range showed a significant positive correlation with temperature.


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## Author Contributions

Nan Bai: substantial contributions toward the collection, processing, analysis and interpretation of data, plus manuscript preparation.

Jinting Guo: ensured integrity of the entire study, guidance for the ArcGIS software, data collection, final approval of the version for publication and as corresponding author to review, revise and finalize manuscripts, and contributed to the work equally and should be regarded as co-first authors with Nan Bai.

Shengqi Zhang and Guiquan Tian: data collection.

Jinting Guo: as corresponding author to review, revise and finalize manuscripts. Her email address is guojinting0517@163.com.

## Conflict of Interest

The authors declare no conflict of interest.

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