Spatiotemporal Distribution and Driving Factors of Net Primary Productivity in Anhui Province, 2000-2015: Postprint

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Abstract

Anhui Province is a major agricultural province in China, and the dynamic changes in its ecosystem are directly related to food security. Changes in vegetation NPP can effectively reflect ecosystem variations. Based on MOD17A3 NPP data, meteorological data, and land use type data, this study investigates the spatiotemporal patterns, change trends, and driving factors of vegetation NPP in Anhui Province from 2000 to 2015 using deviation analysis, coefficient of variation, trend analysis, and correlation analysis. The results show: (1) The average vegetation NPP in Anhui Province from 2000 to 2015 was 476.6 gC/m^2, with a fluctuation range of 396.6–531.8 gC/m^2; vegetation NPP exhibited strong spatial heterogeneity, showing an overall trend of higher values in the south and lower values in the north; (2) The annual average NPP differed significantly among different land cover types, with forest land being the highest at 535.5 gC/m^2, and the interannual variation amplitude of NPP varied among different land types, mainly manifested in relatively larger variation amplitudes for forest land and grassland; (3) Vegetation NPP is jointly influenced by multiple factors including climate, environmental changes, and human activities, among which rainfall in climatic factors has a relatively large influence, but as human activities become increasingly frequent, urbanization has gradually become the main driving force of NPP change.

Full Text

Preamble

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Spatio-temporal Variations in Vegetation Net Primary Productivity and Their Driving Factors in Anhui Province from 2000 to 2015

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Abstract

Anhui Province is a major agricultural province in China, and dynamic changes in its ecosystems directly affect food security. Changes in vegetation net primary productivity (NPP) can effectively reflect ecosystem changes. This study used MOD17A3 NPP data, meteorological data, and land use type data to investigate the spatiotemporal patterns of vegetation NPP and their driving factors in Anhui Province from 2000 to 2015. The data were analyzed using bias analysis, coefficient of variation, trend analysis, and correlation analysis. The results showed that: (1) Between 2000 and 2015, the average annual NPP for Anhui Province was 476.6 gC/m^2, ranging from 396.6 to 531.8 gC/m^2. Vegetation NPP exhibited strong spatial variability, with higher values in the southern part and lower values in the northern part of the province. (2) The average NPP varied among different land cover types, with forest land having the highest NPP at 535.5 gC/m^2. The amplitude of annual NPP change also varied by land cover, with the largest values recorded for forest and grassland. (3) Vegetation NPP changes were driven by multiple environmental factors such as climate change and human activities, with rainfall playing the most important role. However, the increasing intensity of human activities and urbanization has gradually become the main force driving NPP changes.

Keywords: Anhui Province; NPP; temporal and spatial distribution; driving factors; land use type

1. Study Area

Anhui Province is located in eastern China, between 114°54′E–119°27′E and 29°41′N–34°38′N. The Yangtze and Huai Rivers run across the province from west to east, dividing it into five natural regions: the Huaibei Plain, Jianghuai Hills, Dabie Mountain Area, Yangtze River Plain, and Southern Anhui Mountain Area. The province’ s topography is high in the west and low in the east, with significant spatial distribution differences. Anhui lies in the East Asian monsoon region, in the transition zone between subtropical and warm temperate zones, with a warm and humid climate. The province’ s average annual temperature is 14–16°C, average precipitation is 800–1600 mm, and the average frost-free period is 200–250 days. Its unique geographical location and climate characteristics create prominent regional agricultural features. Crop types and multiple cropping indices differ significantly between the north and south of the Huai River. Anhui is one of China’ s important agricultural production bases, with major products including rice, wheat, and corn holding important positions nationally. Located in a transition zone with large temperature fluctuations, drought and flood disasters occur alternately, making agricultural yields highly unstable.

2. Data

The vegetation net primary productivity data used in this study is the MOD17A3 NPP product (http://www.ntsg.umt.edu/project/mod17), released by the Numerical Terradynamic Simulation Group at the University of Montana. This product is an upgraded version of MODIS LAI-FPAR data, with a spatial resolution of 30 arc-seconds (0.0083°) and a temporal resolution of one year. The data product includes a quality control dataset (NPP_{QC}). Studies have proven its validity and reliability in the region, with medium-to-high quality data accounting for 99.46% of the cumulative percentage, making it suitable for related research.

Land use data are 1:100,000 land cover datasets for 2000, 2005, and 2010 from the Earth System Science Data Sharing Platform (http://www.geodata.cn). Based on Anhui' s land use patterns and analysis accuracy requirements, the study area' s land use types were reclassified into six first-level categories: farmland, forest, grassland, water area, urban area, and unused land.

Meteorological data include gridded annual average precipitation datasets and gridded annual average temperature datasets from the Earth System Science Data Sharing Platform. The 2011-2015 meteorological data were obtained by interpolating observations from Anhui meteorological stations, sourced from the China Surface Meteorological Elements Monthly Value Dataset (http://data.cma.cn/data/).

3. Methods

3.1 Bias Analysis

Bias is defined as the difference between the annual NPP value and the multi-year average NPP value. A positive value indicates above-average levels, while a negative value indicates below-average levels. Bias reflects the degree of deviation from the multi-year average during a specific period. The calculation is performed pixel by pixel using the formula:

$$D_{ij} = NPP_{ij}^{t} - \overline{NPP_{ij}}$$

where D_{ij} represents the bias value for row i and column j, NPP_{ij}^{t} represents the NPP value for row i and column j in year t, and t is the year.

3.2 Trend Analysis

Trend analysis uses linear regression to estimate the temporal trend of NPP as it changes over time, often manifested as an overall increasing or decreasing trend in the time series and changes in distribution patterns. The pixel-based calculation formula is as follows:

$$slope = \frac{n \times \sum_{i=1}^{n}(t_i \times NPP_i) - \sum_{i=1}^{n} t_i \times \sum_{i=1}^{n} NPP_i}{n \times \sum_{i=1}^{n} t_i^2 - (\sum_{i=1}^{n} t_i)^2}$$

where *slope* is the linear trend value, $n = 16$, t is the year, and NPP_i is the net primary productivity in year i. A slope > 0 indicates that NPP increases over time, while a slope < 0 indicates a decreasing trend. The magnitude of the slope value reflects the rate of increase or decrease.

3.3 Coefficient of Variation

The Coefficient of Variation (CV) is a statistical measure reflecting the degree of variation in observed values, calculated as the ratio of the standard deviation to the mean. To more intuitively reflect NPP changes in Anhui Province, CV values were categorized into four levels: low variation ($CV \leq 0.1$), moderate variation ($0.1 < CV \leq 0.2$), high variation ($0.2 < CV \leq 0.3$), and very high variation ($CV > 0.3$).

3.4 Correlation Analysis

Correlation analysis reveals the degree of closeness between variables. This study used pixel-based correlation analysis to calculate the relationships between vegetation NPP and meteorological factors. Partial correlation coefficients were calculated to examine the relationship between two variables while controlling for other factors.

First, the correlation coefficient is calculated as:

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

where x_i and y_i represent the values of variables x and y in year i, n is the sample size, and $\bar{x}$ and $\bar{y}$ are the means of variables x and y.

The partial correlation coefficient formula is:

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

where z is the controlled variable, and $R_{xy,z}$ is the partial correlation coefficient between dependent variable x and independent variable y after controlling for z.

The significance of partial correlation coefficients is generally tested using the t-test, with the statistic calculated as:

$$t = \frac{R_{xy,z}\sqrt{n-m-1}}{\sqrt{1-R_{xy,z}^2}}$$

where m is the number of independent variables.

Since changes in one factor are often influenced by multiple factors, and factors are interrelated and mutually influential, simple correlation and partial correlation analyses cannot reflect the comprehensive impact of various factors. Therefore, multiple correlation analysis can be used to study the relationship between several factors and a particular factor. The multiple correlation coefficient is calculated as:

$$R_{x,yz} = \sqrt{1-(1-R_{xy}^2)(1-R_{xz}^2)}$$

where $R_{x,yz}$ is the multiple correlation coefficient between x and y, z. The significance test uses the F-test, with the statistic calculated as:

$$F = \frac{R_{x,yz}^2/k}{(1-R_{x,yz}^2)/(n-k-1)}$$

where k is the number of independent variables.

4. Results

4.1 Temporal Variation Characteristics of Vegetation NPP

Statistical analysis of annual average NPP values in Anhui Province shows that from 2000 to 2015, vegetation NPP ranged from 396.6 to 531.8 gC/m^2, with an average of 476.6 gC/m^2. The maximum value occurred in 2015 (531.8 gC/m^2), exceeding the average by 11%. Except for 2000, all other years were above the average level. Overall, vegetation NPP showed a slight fluctuating increasing trend during 2000–2015. The total NPP in Anhui Province ranged from 55.23 to 74.06 TgC (1 Tg = 10^{12} g), with an average of 62.03 TgC, indicating small interannual fluctuations.

Significant differences exist in multi-year average annual NPP among cities. Xuancheng and Chizhou showed higher NPP due to their typical mountainous climate characteristics, while Lu' an had the lowest NPP. Located in the Dabie

Mountains, Lu’ an is one of the areas with the most severe forest resource destruction in Anhui, mainly due to unreasonable afforestation and cultivation practices and serious land resource waste.

Analysis of different land use types shows that NPP trends were generally consistent across types, showing a fluctuating increase. However, significant differences existed in average annual NPP values: forest land (535.52 gC/m^2) > grassland (487.23 gC/m^2) > farmland (471.63 gC/m^2) > water area (462.51 gC/m^2) > urban area (447.61 gC/m^2) > unused land (396.27 gC/m^2). The fastest growth rate occurred in unused land, while the slowest was in water areas. The interannual variation amplitude differed among land types, with forest and grassland showing relatively large variations of 5.37 gC/m^2 and 3.96 gC/m^2, respectively.

4.2 Spatial Variation Characteristics of Vegetation NPP

The spatial distribution of average annual NPP from 2000 to 2015 shows strong spatial heterogeneity, with an overall pattern of high values in the south and low values in the north. NPP values ranged from 55.1 to 1250.2 gC/m^2. The Huaibei Plain generally had lower NPP (420–450 gC/m^2) due to low rainfall and large farmland area, mainly planted with seasonal crops like winter wheat and summer corn. The middle-value areas were in the Jianghuai Hills, also dominated by seasonal crops. In the southern Anhui mountainous area, high forest coverage with evergreen broad-leaved mixed forests and suitable hydrothermal conditions for vegetation growth resulted in higher NPP.

The coefficient of variation across cities ranged from 0.071 to 0.124, with an average of 0.118, indicating stable variation in vegetation NPP. The most obvious variation occurred in Lu’ an and Anqing. Areas with CV > 0.3 were mainly distributed in the Dabie Mountains and along the Yangtze River.

The linear regression slope analysis shows that most areas of Anhui Province had increasing rates greater than 5 gC/m^2, indicating good vegetation growth conditions, particularly in the Huaibei Plain. However, significant decreasing trends occurred in some areas along the Yangtze River, such as Chizhou and Ma’ anshan. The changing percentage analysis reveals that areas with >10% increase accounted for 67.1% of the province’s land area; areas with -10% to 10% change accounted for 29.8%; and areas with <-10% change (mainly distributed along the Yangtze River and around water bodies) accounted for 3.5%.

4.3 Relationship Between Vegetation NPP and Meteorological Factors

Vegetation growth is closely related to climate change, and their correlation is a major focus of global change research. From 2000 to 2015, annual precipitation showed an increasing trend with a rate of 4.181 mm/a, ranging from 1019.7 to 1539.9 mm. Annual temperature showed a decreasing trend with a rate of -0.022°C/a, ranging from 15.03 to 17.03°C.

Spatially, precipitation decreased from south to north, with more rainfall in the southern Anhui mountainous area, Dabie Mountains, and Jianghuai region, especially in Huangshan and Anqing cities. The Huaibei Plain had less rainfall. Temperature distribution was uneven, with lower temperatures in the mountainous areas and higher temperatures along the Yangtze River.

Partial correlation analysis between NPP and precipitation shows that 57.8% of the area had positive correlations, mainly distributed in the Dabie Mountains, Jianghuai region, and southern Anhui mountainous area, where altitude is higher and rainfall has greater impact on NPP changes. Negative correlations accounted for 42.2%, mainly in the area north of the Huai River. Only 3.77% of the area passed the significance test ($P < 0.01$).

Partial correlation between NPP and temperature shows positive correlations in 34.7% of the study area, concentrated in the Dabie Mountains and southern Anhui mountainous area, while negative correlations accounted for 65.3%, mainly in the area north of the Huai River. Only 1.23% passed the significance test ($P < 0.01$).

Multiple correlation analysis shows that areas with strong correlations between NPP and climate factors were concentrated in Huangshan and Xuancheng in southern Anhui, while weak correlations were mainly in the Huaibei Plain and Jianghuai region. These differences are mainly related to vegetation types and altitude.

4.4 Driving Force Analysis of Vegetation NPP Changes

Climate change and human activities are the main driving forces of NPP changes. Climate change, particularly precipitation and temperature, affects vegetation productivity by influencing photosynthesis and respiration. Human activities are mainly manifested through land use changes that directly alter ecosystem type, structure, and function.

Based on driving factor zoning principles from domestic scholars and the study area's characteristics, the classification criteria are shown in Table 1. The driving force zoning map shows that areas weakly driven by climate factors (temperature and precipitation) accounted for 89.28% of the study area, mainly distributed in the Dabie Mountains, Xuancheng and Huangshan in southern Anhui, and the Huaibei Plain. Areas strongly driven by temperature and precipitation accounted for 4.95%, concentrated in southern Xuancheng and northern Anqing. Rainfall-driven types accounted for 3.58%, mainly north of the Huai River and around Huainan City. Temperature-driven types accounted for 1.44%, and non-climate factor-driven types accounted for 0.75%.

The analysis shows that 89.28% of vegetation NPP changes in Anhui Province are mainly influenced by non-climate factors, indicating that as human activities become more frequent, urbanization has gradually become the main driving force of NPP changes.

4.5 Land Use Change in Anhui Province

Land use change statistics for 2000, 2005, and 2010 show that farmland and urban land were the main land use types in Anhui. Significant changes occurred in grassland and water area. Grassland mainly transferred to water area and farmland, while farmland mainly transferred to urban land and water area. Forest area changed little overall.

From 2000 to 2005, total land use transfer area was 1736.83 km^2 (1.22% of total land area), with farmland transfer accounting for the most at 793.74 km^2 (45.7% of total transfer), mainly converting to urban land (38.22%) and water area (57.27%). From 2005 to 2010, total transfer area was 4589.81 km^2 (3.23% of total land area), with farmland transfer of 3107.01 km^2 (67.7% of total transfer), mainly converting to urban land (76.63%). From 2000 to 2010, total transfer area was 3097.5 km^2 (2.19% of total land area), with farmland transfer of 2425 km^2 (78.3% of total transfer), mainly converting to urban land (86.36%) and forest (2.05%).

4.6 NPP Changes Under Different Land Cover Type Conversions

Different land use types correspond to different ecosystem structures and have different NPP values. Conversions between land use types directly affect regional ecosystem structure and thus NPP. The impact occurs in two ways: (1) conversion from high-NPP land cover types (forest, farmland) to low-NPP types (urban land, unused land) decreases NPP; (2) conversion from low-NPP types to high-NPP types increases NPP.

From 2000 to 2005, farmland-to-urban land conversion caused the largest NPP loss (-56,635.73 t/a), while construction land-to-forest conversion caused the largest NPP increase (9,453.1 t/a). From 2005 to 2010, farmland-to-water area conversion caused the largest loss (-42,225.99 t/a). From 2000 to 2010, farmland-to-urban land conversion caused the greatest loss (-37,254.93 t/a), while water area-to-farmland conversion caused the greatest increase (7,977.39 t/a). Overall, farmland-to-urban land conversion caused far greater NPP loss than other conversion types, indicating that urbanization is the main driver of NPP loss.

5. Conclusions and Discussion

Using MOD17A3 NPP data, meteorological data, and land use type data, this study investigated the spatiotemporal variation trends and driving factors of vegetation NPP in Anhui Province from 2000 to 2015. The main conclusions are:

(1) From 2000 to 2015, vegetation NPP in Anhui Province showed a slight fluctuating increasing trend, with an average annual value of 476.6 gC/m^2, ranging from 396.6 to 531.8 gC/m^2. Significant differences existed in multi-year average annual NPP among cities, and different land types showed

different interannual variation amplitudes, with forest and grassland showing relatively large variations.

(2) Vegetation NPP showed strong spatial heterogeneity, with an overall pattern of high values in the south and low values in the north. Most areas had increasing rates greater than 5 gC/m^2, with increases being the dominant trend.

(3) Vegetation NPP changes result from the combined effects of climate, environmental changes, and human activities. Climate change and human activities are the main driving factors. Climate factors influenced 10.72% of NPP changes, with rainfall being the most important factor. Non-climate factors accounted for 89.28%, mainly manifested through human-induced land use changes, with urban construction land increasing most significantly. This indicates that as human activities become more frequent, urbanization has gradually become the main driving force of vegetation NPP changes.

This study analyzed the spatiotemporal variation characteristics of vegetation NPP and its driving mechanisms, providing scientific references for vegetation productivity evaluation, land resource development, and natural resource management policy formulation. However, some limitations exist. Future research will further explore the impact of land policy changes on vegetation NPP and quantitatively assess how land cover conversion affects NPP under climate change conditions.

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Note: Figure translations are in progress. See original paper for figures.