The Dominant Driving Force of Forest Change in the Yangtze River Basin, China: Climate Variation or Anthropogenic Activities?

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Abstract: Under the combined effect of climate variations and anthropogenic activities, the forest ecosystem in the Yangtze River Basin (YRB) has experienced dramatic changes in recent decades. Quantifying their relative contributions can provide a valuable reference for forest management and ecological sustainability. In this study, we selected net primary productivity (NPP) as an indicator to investigate forest variations. Meanwhile, we established eight scenarios based on the slope coefficients of the potential NPP (PNPP) and actual NPP (ANPP), and human-induced NPP (HNPP) to quantify the contributions of anthropogenic activities and climate variations to forest variations in the YRB from 2000 to 2015. The results revealed that in general, the total forest ANPP increased by 10.42 TgC in the YRB, and forest restoration occurred in 57.25% of the study area during the study period. The forest degradation was mainly observed in the Wujiang River basin, Dongting Lake basin, and Poyang Lake basin. On the whole, the contribution of anthropogenic activities was greater than climate variations on both forest restoration and degradation in the YRB. Their contribution to forest restoration and degradation varied in different tributaries. Among the five forest types, shrubs experienced the most severe degradation during the study period, which should arouse great attention. Ecological restoration programs implemented in YRB have effectively mitigated the adverse effect of climate variations and dominated forest restoration, while rapid urbanization in the mid-lower region has resulted in forest degradation. The forest degradation in Dongting Lake basin and Poyang Lake basin may be ascribed to the absence of the Natural Forest Conservation Program. Therefore, we recommend that the extent of the Natural Forest Conservation Program should expand to cover these two basins. The current research could improve the understanding of the driving mechanism of forest dynamics and promote the effectiveness of ecological restoration programs in the YRB.

Keywords: anthropogenic activities; climate variations; ecological program; forest; Net Primary Productivity; Yangtze River basin

1. Introduction

As one of the most substantial terrestrial ecosystems, forest covers more than 4.0 × 10⁷ km², accounting for about 31% of the Earth's land area. This vegetation type plays an important role in the global carbon cycle and contains approximately half of the vegetation biomass carbon [1]. In addition, the forest can provide crucial ecosystem services such as maintaining biodiversity, water and soil conservation, and air purification [2]. However, the forest ecosystems have experienced serious degradation resulting from climate variations and
unreasonable anthropogenic activities, which has threatened sustainable development at both regional and global scales [1,3,4]. In September 2015, the United Nations adopted the 2030 Agenda, the core elements of which are the 17 Sustainable Development Goals (SDGs) [5]. To implement SDG 15.3 (Land Degradation Neutralization Initiative) more effectively, it is important to explore the driving mechanism of forest dynamics.

Climate variations and anthropogenic activities have been regarded as two major driving forces of terrestrial ecosystem changes [1,6,7]. Climate variations could affect the rates of plant photosynthesis, respiration, and soil organic carbon decomposition, thus influencing the productivity of vegetation ecosystems [8]. Climate variations mainly exert influence on ecosystems through the change of temperature and precipitation. For instance, global warming has intensified and the frequency of precipitation events tends to increase, particularly in humid regions during the past decades [9,10]. The temperature has increased by up to 1.1 °C in China since the 1980s [11]. Climate warming can prolong the growing season, thereby promoting the productivity of vegetation ecosystems [12,13]. Meanwhile, warming without enough precipitation will result in severe drought events, which can exert an adverse effect on vegetation growth [8,14,15]. Anthropogenic activities can also significantly affect vegetation growth. For example, reasonable anthropogenic activities such as large-scale ecological restoration programs implemented in China in the past decades have dramatically changed the landscape, thus improving ecosystem services [12,16–18]. Meanwhile, economic development and rapid urbanization are characterized by expansion of construction land, which could lead to vegetation degradation by compressing the space of vegetation growth and thus altering the compositions, structures, and functions of the terrestrial ecosystem [19–23]. As vegetation growth is affected by both climate variations and anthropogenic activities, there are still challenges to quantitatively assessing their relative contributions.

Net primary productivity (NPP) is the accumulated amount of organic matter produced by vegetation per unit of time and space [24]. It is an important indicator to monitor the status of vegetation growth. The methods of estimating NPP can be mainly divided into three categories: field measurement, model simulation, and remote sensing estimations [25]. Compared with the other two kinds of methods, the remote sensing estimation method is more suitable for large-scale vegetation research due to its high efficiency and low cost [25]. Thanks to the rapid development of remote sensing technology, high-resolution remote sensing satellite products have been widely used in vegetation dynamics research on large scales in recent years [26–29]. Using NPP as an indicator, Xu, et al. [30] developed a method to quantify the contribution of climate variations and anthropogenic activities to vegetation ecosystems by comparing the slope coefficients of the potential NPP (PNPP), the actual NPP (ANPP), and the human appropriation on NPP (HNPP). This method converted a complex underlying mechanism of vegetation dynamics into a straightforward process by comparing the slope coefficients of these three kinds of NPP, which could avoid certain uncertainties compared with other methods to some extent [31–33].

The Yangtze River basin (YRB) is one of the most important regions due to its crucial position in the social-economic development of China [34]. Meanwhile, this basin is a region with a fragile ecological environment, which plays an indispensable role in maintaining regional ecological balance and security even the whole of China [35]. However, with economic development and rapid urbanization, many environmental and ecological problems including soil erosion, desertification, and loss of biodiversity have severely increased, posing a threat to ecological security during the past decades. To alleviate this serious situation, multiple ecological restoration programs such as the Grain to Green Program (GTGP) and the Natural Forest Conservation Program (NFCP) have been launched in the YRB [36]. The implementation of these ecological restoration projects has improved multiple ecosystem services in the past decades [17]. Meanwhile, population growth and economic development have posed pressure on vegetation growth. As the dominant vegetation type in the YRB, the forest ecosystem has undergone significant change under the
influence of climate variations and anthropogenic activities [23]. However, the contribution of climate variations and anthropogenic activities to forest change in YRB is still unclear.

The ecological programs are usually implemented in stages in China [37]. The Chinese government announced to expand the extent of the new round of GTGP in 2015 [38]. The assessment of the previous round of GTGP could provide a reference for the next round. Although some studies have analyzed vegetation change in recent years [25,39,40], there are few studies to quantify the relative contribution of climate variations and anthropogenic activities (especially ecological restoration programs) to the forest ecosystem in YRB. Therefore, we selected NPP as an indicator of forest status to explore the driving mechanism of forest variation. The objectives of this research were: (1) to evaluate the spatial pattern and dynamic of forest NPP in the YRB; (2) to evaluate the relative contribution of climate variations and anthropogenic activities (especially the ecological restoration programs) to the forest variation; (3) to identify the dominant factor of the dynamics of forest ecosystems in the YRB.

2. Materials and Methods
2.1. Study Area

The Yangtze River basin (24°30' N–35°45' N, 90°33' E–122°25' E) has a catchment area of 1.8 × 10^6 km^2 that originates from the Tibetan Plateau [25]. It covers 17 provinces and 2 municipalities. As shown in Figure 1, it consists of eleven subregions, namely (1) Jinsha River basin (JSRB); (2) Mintuo River basin (MTRB); (3) Jialing River basin (JLRB); (4) Hanjiang River basin (HJRB); (5) Wujiang River basin (WJRB); (6) Dongting Lake basin (DTLB); (7) Poyang Lake basin (PYLB); (8) Mainstream area of the upper reaches of the Yangtze River (MAURYR); (9) Mainstream area of the middle reaches of the Yangtze River (MAMRYR); (10) Mainstream area of the lower reaches of the Yangtze River (MALRYR); (11) Taihu Lake basin (THLB). The mean annual temperature is about 14.5 °C and the mean annual precipitation is about 1100 mm in the YRB [41]. The forest is the dominant vegetation type in this basin due to the good hydrothermal conditions. The forest types in the YRB include evergreen coniferous forest (EC), evergreen broad-leaved forest (EB), deciduous broad-leaved forest (DB), shrubs (S) and sparse woods (SW).

2.2. Data Sources

The actual NPP dataset was derived from the moderate-resolution imaging spectroradiometer (MODIS) NPP product (MOD17A3) during 2000–2015 (http://www.ntsg.umt.edu/ (accessed on 13 May 2020)). The spatial resolution of this dataset is 1 km. Previous researches indicated that the MODIS NPP agrees well with the field observed NPP [42]. The digital elevation model (DEM) data with a spatial resolution of 90 m was downloaded from the Geospatial Data Cloud (http://www.gscloud.cn/ (accessed on 13 May 2020)). The vegetation map in 2000 with a resolution of 1 km was obtained from “Cold and Arid Regions Science Data Center at Lanzhou” (http://westdc.westgis.ac.cn (accessed on 13 May 2020)). The meteorological dataset (including mean annual temperature and precipitation) and the land-use dataset with a spatial resolution of 1 km during 2000–2015 were collected from the Center for Resources and Environment of the Chinese Academy of Sciences (http://www.resdc.cn/ (accessed on 13 May 2020)). The land-use dataset includes six primary classes of land use types (cropland, forest, grassland, water, urban, and barren) were included. The vegetation map in 2000 was used to determine the area of different forest types, and the two phases of land use data were used to assess the area changes of various land use types from 2000 to 2015.
Figure 1. The overview of the study area: (a) geographical location of the Yangtze River basin and its subregions; (b) forest type; (c) digital elevation model.

2.3. Methodology

2.3.1. Definition and Calculation of ANPP, PNPP and HNPP

In this research, three kinds of NPP were defined to quantify the relative contributions of climate variations and anthropogenic activities to forest variations. The MOD17A3 product was selected as the ANPP, which is the actual condition of forest NPP. The PNPP simulated by the Thornthwaite Memorial model is the forest NPP only driven by climate factors. In addition, the HNPP is defined as the difference between PNPP and ANPP, which reflects the influences of anthropogenic activities on forest NPP. The methodological framework can be expressed as follows [30].

\[
HNPP = PNPP - ANPP
\]  

(1)

The Thornthwaite memorial model is based on the Miami model with good accuracy. It used precipitation and temperature data as inputs to calculate PNPP on a pixel scale. The equations are as follows [32]:

\[
PNPP = 3000 \left[ 1 - e^{-0.0009695(v-20)} \right]
\]  

(2)

\[
v = \frac{1.05r}{\sqrt{1 + \left( 1 + \frac{1.05r}{L} \right)^2}}
\]  

(3)

\[L = 3000 + 25t + 0.05t^3\]

(4)

where PNPP represents the annual potential NPP (g cm\(^{-2}\)); \(v\) represents the annual mean actual evapotranspiration (mm); \(L\) represents annual mean potential evapotranspiration (mm); \(r\) represents the mean annual precipitation (MAP) (mm); \(t\) represents the mean annual temperature (MAT) (°C).
2.3.2. Trend Analysis

Linear regression analysis was selected to detect the changing trend of all variables (i.e., ANPP, PNPP, HNPP, MAP and MAT) from 2000 to 2015 at the pixel level [32]. The slope coefficient of the pixel-level trend was calculated based on the following formula [34]:

\[
\text{Slope} = \frac{n \times \sum_{i=1}^{n} (i \times Var_i) - (\sum_{i=1}^{n} i)(\sum_{i=1}^{n} Var_i)}{n \times (\sum_{i=1}^{n} i^2) - (\sum_{i=1}^{n} i)^2}
\]

(5)

where \(n\) represents the total number of years during the study period, and \(i\) represents the serial number of the year. \(Var_i\) represents the research variable of the \(i\)-th year.

Based on the F-test, the variation of forest NPP was divided into six categories shown as Table 1 to represent the degree of forest restoration or degradation [32].

Table 1. Six levels were defined to reflect the degree of forest dynamic.

| Forest Status       | Slope  | \(p\)-Value   | Degree of Forest Dynamic         |
|---------------------|--------|---------------|----------------------------------|
| Forest restoration  | \(>0\) | \(p > 0.05\)  | Slight forest restoration        |
|                     | \(>0\) | \(0.01 < p < 0.05\) | Moderate forest restoration       |
|                     | \(>0\) | \(p < 0.01\)  | Obvious forest restoration        |
| Forest degradation  | \(<0\) | \(p > 0.05\)  | Slight forest degradation        |
|                     | \(<0\) | \(0.01 < p < 0.05\) | Moderate forest degradation       |
|                     | \(<0\) | \(p < 0.01\)  | Serious forest degradation        |

To determine the NPP loss and NPP increment from 2000 to 2015, we use the following formula to estimate the NPP change for each pixel [43]:

\[
\Delta \text{NPP} = (n - 1) \times \text{Slope}
\]

(6)

where \(n\) represents the number of years during the study, which is 16 in this study.

2.3.3. Scenario Establishment

Based on slope coefficients of the above three kinds of NPP, eight scenarios were established to quantify the contribution of climate variations and anthropogenic activities to forest growth (Table 2) [32,44].

Table 2. Eight scenarios were established to identify driving forces for forest dynamics.

| Forest Status       | Scenario | \(S_{\text{ANPP}}\) | \(S_{\text{PNPP}}\) | \(S_{\text{HNPP}}\) | Dominant Driving Force                          |
|---------------------|----------|---------------------|---------------------|---------------------|------------------------------------------------|
| Forest restoration  | 1        | \(>0\)              | \(>0\)              | \(>0\)              | Climate-dominated forest restoration (CDR)       |
|                     | 2        | \(>0\)              | \(<0\)              | \(<0\)              | Human-dominated forest restoration (HDR)         |
|                     | 3        | \(>0\)              | \(>0\)              | \(<0\)              | Both dominated forest restoration (BDR)          |
|                     | 4        | \(>0\)              | \(<0\)              | \(>0\)              | Neither Affected the forest restoration (R-Error) |
| Forest degradation  | 5        | \(<0\)              | \(<0\)              | \(<0\)              | Climate-dominated forest degradation (CDD)        |
|                     | 6        | \(<0\)              | \(>0\)              | \(>0\)              | Human-dominated forest degradation (HDD)         |
|                     | 7        | \(<0\)              | \(<0\)              | \(>0\)              | Both dominated the forest degradation (BDD)       |
|                     | 8        | \(<0\)              | \(<0\)              | \(>0\)              | Neither Affected the forest degradation (D-Error) |

Notes: \(S_{\text{ANPP}}\), \(S_{\text{PNPP}}\), and \(S_{\text{HNPP}}\) denote the slope coefficients of ANPP, PNPP, and HNPP in each pixel, respectively.

For forest restoration \((S_{\text{ANPP}} > 0)\), if \(S_{\text{PNPP}} > 0\) and \(S_{\text{HNPP}} > 0\) (Scenario 1), then climate change promoted an increase in forest NPP, and human activities induced a decrease in forest NPP. Thus, forest restoration is dominated by climate change (CDR). If \(S_{\text{PNPP}} < 0\) and \(S_{\text{HNPP}} < 0\) (Scenario 2), then climate change resulted in a decrease in forest NPP, and human activities facilitated an increase in forest NPP. Therefore, forest restoration is dominated.
by human activities (HDR). If $S_{PNPP} > 0$ and $S_{HNPP} < 0$ (Scenario 3), then both climate change and human activities facilitated an increase in forest NPP. In this scenario, the forest NPP restoration is dominated by both climatic and human factors (BDR). If $S_{PNPP} < 0$ and $S_{HNPP} > 0$ (Scenario 4), then climate change and human activities both facilitated a decrease in forest NPP while the ANPP still experienced an increasing trend, which can be considered as the error in the scenario of forest restoration (R-Error).

For forest degradation ($S_{ANPP} < 0$), if $S_{PNPP} < 0$ and $S_{HNPP} < 0$ (Scenario 5), then climate change caused a decrease in forest NPP, and human activities facilitated an increase in forest NPP. In this scenario, forest degradation is dominated by climate change (CDD). If $S_{PNPP} > 0$ and $S_{HNPP} > 0$ (Scenario 6), then climate change promoted an increase in forest NPP, and human activities caused a decrease in forest NPP. In this scenario, forest degradation is dominated by human activities (HDD). If $S_{PNPP} < 0$ and $S_{HNPP} < 0$ (Scenario 7), then the forest degradation is dominated by both climatic and human factors (BDD). If $S_{PNPP} > 0$ and $S_{HNPP} < 0$ (Scenario 8), then climate change and human activities both facilitated an increase in forest NPP while the ANPP still experienced a decreasing trend, which can be considered the error in the scenario of forest degradation (D-Error).

2.3.4. Correlation Analysis

The Pearson correlation coefficient was used to study the responses of ANPP to climate factors (i.e., MAP and MAT) using the following equation [31]:

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

(7)

where $n$ represents the serial number of the year, $x_i$ and $y_i$ represent ANPP and climate factors of the $i$-th year, respectively.

3. Results

3.1. Spatial Distribution of Forest NPP from 2000 to 2015

The spatial distributions of forest ANPP, PNPP, and HNPP in the YRB showed obvious heterogeneity from 2000 to 2015 (Figure 2). The average forest ANPP, PNPP, and HNPP were 598.07 gC m$^{-2}$ yr$^{-1}$, 1508.57 gC m$^{-2}$ yr$^{-1}$, and 907.65 gC m$^{-2}$ yr$^{-1}$, respectively. The highest ANPP was observed in the JSRB, with a mean value of 693.43 gC m$^{-2}$ yr$^{-1}$.

The PNPP values ranged from 500 gC m$^{-2}$ yr$^{-1}$ to 700 gC m$^{-2}$ yr$^{-1}$ in most regions of the YRB. In the HJRB, the ANPP value was the smallest, with an average value of 425.47 gC m$^{-2}$ yr$^{-1}$ from 2000 to 2015 (Figure 2a). As can be seen from Figure 2b, the forest PNPP gradually increased from northwest to southeast. The highest forest PNPP value occurred in the PYLB. Better hydrothermal conditions in these areas may produce PNPP with a value greater than 1800 gC m$^{-2}$ yr$^{-1}$. On the contrary, the lowest PNPP value mainly occurred in the JSRB, with an average value of 1263.57 gC m$^{-2}$ yr$^{-1}$. Generally, as shown in Figure 2c, the pattern of forest HNPP was consistent with that of PNPP. The regions with high forest HNPP values were mainly observed in the PYLB and DTLB, which implied that the negative anthropogenic activities were intensifying during 2000–2015, which led to the decline of ANPP values in these regions.
3.2. The Trends in Forest ANPP, PNPP and HNPP in the YRB

The trends of forest ANPP, PNPP, HNPP in the YRB showed apparent spatial heterogeneity during 2000–2015 (Figure 3). The area of forest ANPP showing an increasing trend reached $49.73 \times 10^4$ km$^2$, occupying 57.25% of the total forest area, especially in most parts of the JSRB, JLRB, and the northern part of the HJRB. The area of forest ANPP showing a downward trend was $37.14 \times 10^4$ km$^2$, accounting for 42.75% of the total forest area. These areas were mainly located in WJRB, PYLB and DTLB (Figure 3a). Concerning PNPP (Figure 3b), the area with an upward trend in forest PNPP reached $42.66 \times 10^4$ km$^2$, occupying 49.11% of the total forest area, mainly located in the MTRB, JLRB, PYLB, MALRYR and the western parts of HJRB and DTLB. The increase in PNPP indicated that climate variations may benefit forest growth in these regions. Meanwhile, 50.89% of the forest area showed a downward trend in forest PNPP, reaching $44.21 \times 10^4$ km$^2$. These regions were mainly observed in the JSRB, WJRB, MAURYR, the eastern part of the HJRB, and the central part of the DTLB. In these regions, climate variations were found to be harmful to forest growth. The trends of HNPP could reflect the impact of anthropogenic activities on forest variation. As shown in Figure 3c, approximately 47.64% of the forest area experienced an increasing trend in HNPP, which was mainly distributed in the PYLB, MALRYR, the western part of DTLB, JLRB, and the eastern part of the MTRB and the Yangtze River Delta. The increase in HNPP suggested that anthropogenic activities were not conducive to forest restoration in these regions. The regions where HNPP showed downward trends occupied 52.36% of the total forest area, which mainly occurred in the JSRB, HJRB, WJRB, MAURYR, and central part of DTLB. In these regions, anthropogenic activities could be beneficial to forest growth from 2000 to 2015.
3.3. Forest ANPP Dynamics at the Tributary Level in the YRB

Considering the proportion of forest is relatively low in MAURYR, MAMRYR, MAL-RYR and THLB, we mainly analyzed the forest ANPP dynamics in the rest seven main tributaries of the YRB. Figure 4 illustrates the spatial distribution of change trends of forest ecosystems in the YRB from 2000 to 2015. The area of forest restoration reached $49.73 \times 10^4$ km$^2$, occupying 57.25% of the total forest area. Slight restoration regions were mainly concentrated in the JSRB, MTRB, JLRB, the most regions of HJRB, and northeastern part of PYLB, which covered an area of 45.05% of the total forest area. Moderate restoration regions accounted for approximately 6.64% of the total forest area, mostly concentrated in the northeast of the JLRB, northwestern of HJRB, and scattered in many locations of the JSRB. Obvious restoration regions occupied about 5.56% of the total forest area, mainly occurred in the JSRB, northwestern of MTRB, northeastern of JLRB, and central part of HJRB. By contrast, 42.75% of the total forest area showed degradation, reaching $37.14 \times 10^4$ km$^2$. In specific, slight degradation regions were mostly distributed in the WJRB, PYLB and DTLB, which occupied 40.10% of the total forest area. The moderate degradation regions were mostly scattered in the southwestern part of the DTLB, the central part of the WJRB and the PYLB, accounting for 1.95% of the total forest area. Severe degradation regions only accounted for 0.70% of the study area. These regions were mainly observed in the southwestern part of the DTLB, the southern part of the JSRB, and the central part of the WJRB.

The area and ANPP dynamics of forest ecosystems at a tributary level were analyzed (Table 3). The results indicated that the restored area of the forest ecosystem was greater than the degraded area in the YRB ($49.73 \times 10^4$ km$^2$ vs. $37.14 \times 10^4$ km$^2$). For the forest restoration, the total area of the forest restoration in these seven tributaries was in the order of JSRB ($11.50 \times 10^4$ km$^2$) > JLRB ($7.21 \times 10^4$ km$^2$) > HJRB ($5.96 \times 10^4$ km$^2$) > DTLB ($5.53 \times 10^4$ km$^2$) > PYLB ($4.61 \times 10^4$ km$^2$) > MTRB ($4.19 \times 10^4$ km$^2$) > WJRB ($1.71 \times 10^4$ km$^2$). The forest total ANPP increased by approximately 26.71 TgC due to the forest restoration from 2000 to 2015. The total ANPP increase in the JSRB was the largest, reaching 10.40 TgC, followed by the JLRB (4.70 TgC). Among these tributaries, the total
ANPP increment in the WJRB was the lowest (0.55 TgC). For the remaining tributaries, the total ANPP of forest restoration in the HJRB, MTRB, PYLB and DTLB increased by 3.89 TgC, 2.31 TgC, 1.44 TgC and 1.27 TgC, respectively.

![Degradation class](image)

**Figure 4.** Forest restoration and degradation dynamics in the YRB from 2000 to 2015.

**Table 3.** The forest dynamics in terms of area and total ANPP in different tributaries from 2000 to 2015 (1 TgC = 10^{12} gC).

| Region   | Forest Restoration Region | Forest Degradation Region |
|----------|---------------------------|---------------------------|
|          | Area/10^4 km^2 | Total ANPP/TgC | Area/10^4 km^2 | Total ANPP/TgC |
| JSRB     | 11.50         | 10.40         | 2.87          | −1.41         |
| MTRB     | 4.19          | 2.31          | 1.56          | −0.71         |
| JLRB     | 7.21          | 4.70          | 0.84          | −0.19         |
| HJRB     | 5.96          | 3.89          | 1.75          | −0.61         |
| WJRB     | 1.74          | 0.55          | 3.72          | −1.79         |
| DTLB     | 5.53          | 1.27          | 14.83         | −7.49         |
| PYLB     | 4.61          | 1.44          | 7.18          | −3.52         |

In terms of forest degradation, the area of degraded forests in the DTLB was the largest, reaching 14.83 × 10^4 km^2, followed by PYLB (7.18 × 10^4 km^2), WJRB (3.72 × 10^4 km^2), JSRB (2.87 × 10^4 km^2), HJRB (1.75 × 10^4 km^2), and MTRB (1.56 × 10^4 km^2), and the least forest degradation observed in JLRB (0.84 × 10^4 km^2). It is noteworthy that approximately 59.26% of forest degradation was distributed in the PYLB and DTLB. Concerning the reduction of ANPP, the total forest ANPP in the YRB declined 16.29 TgC due to forest degradation from 2000 to 2015. Specifically, the largest forest total ANPP reduction occurred in the DTLB (7.49 TgC), followed by the PYLB (3.52 TgC). The total ANPP reduction in the WJRB was 1.79 TgC, which was the third-largest ANPP reduction, followed by the JSRB (1.41 TgC), MTRB (0.71 TgC), and HJRB (0.61 TgC). The JLRB had the lowest ANPP reduction (0.19 TgC). Total ANPP reduction in the PYLB and DTLB occupied approximately as much as 67.59% of the total forest ANPP reduction.

The changes of ANPP in different forest types were different (Table 4). The largest total ANPP increase was the evergreen coniferous forest (13.98 TgC) and was followed by the evergreen broad-leaved forest (5.79 TgC). Deciduous broad-leaved forests had the third-highest total ANPP increase (3.92 TgC), followed by Shrubs (2.46 TgC). The total ANPP increase in the sparse woods was the lowest (0.56 TgC), which was due to the minimum restoration area of sparse woods. Meanwhile, the evergreen coniferous forest had the
highest total ANPP reduction, with an average value of 6.65 TgC, followed by evergreen broad-leaved forest and Shrubs, with approximately the same value of 4.54 TgC. The total ANPP reduction of deciduous broad-leaved forest and sparse woods was relatively low.

Table 4. The forest dynamics in terms of area and total ANPP of different forest types from 2000 to 2015. (1 TgC = 10^{12} gC).

| Forest Type                  | Forest Restoration Region | Forest Degradation Region |
|------------------------------|----------------------------|---------------------------|
|                              | Area/10^4 km² | Total ANPP/Tg C | Area/10^4 km² | Total ANPP/Tg C |
| Evergreen coniferous forest  | 26.48         | 13.98           | 16.10         | −6.65           |
| Evergreen broad-leaved forest| 10.33         | 5.79            | 8.95          | −4.54           |
| Deciduous broad-leaved forest| 4.87          | 3.92            | 1.07          | −0.42           |
| Shrubs                       | 6.90          | 2.46            | 9.86          | −4.54           |
| Sparse woods                 | 0.93          | 0.56            | 0.38          | −0.14           |

3.4. Contributions of Climate Variation and Anthropogenic Activities to Forest ANPP Variation

3.4.1. Contribution of Climate Variation and Anthropogenic Activities to Forest Restoration at the Tributary Level

As can be seen from Figure 5a, the spatial pattern of forest restoration dominated by specific factors during 2000–2015 was analyzed. The climate-dominated restoration (CDR) regions were mainly concentrated in the JLRB, north part of the MTRB, PYLB, and lower reach region of the YRB. The human-dominated restoration (HDR) region was mainly located in the JSRB, the southern part of the HJRB, the middle reaches of the Yangtze River, and the northern part of the DTLB. The forest restoration dominated by climate variation and anthropogenic activities (BDR) was mostly located in the northern part of the HJRB and JLRB, as well as scattered in the JSRB and MTRB. Moreover, the area percentage of CDR, HDR and BDR regions in the different tributaries was analyzed. The CDR region and the HDR region occupied 32.88% and 48.39% of forest restoration respectively. The BDR region only occupied 16.55% of the restoration area and the remaining 2.18% could be attributed to modeling errors.

Figure 5. Spatial distribution of dominated driving factors of forest restoration (a) and degradation (b) in the YRB.

The area proportion of dominated driving factors of forest dynamics showed obvious heterogeneity in the seven tributaries of the YRB. For forest restoration (Figure 6(a-1)), the area percentages of ANPP increase caused by climate variations were greater than that induced by anthropogenic activities in the PYLB (86.50% vs. 5.68%), JLRB (63.94% vs. 11.29%), and MTRB (41.44% vs. 29.97%). The anthropogenic activities had a greater contribution to forest restoration than climate variations in the WJRB (90.92% vs. 3.76%), JSRB (87.10% vs. 4.05%), DTLB (61.22% vs. 24.20%), and HJRB (44.34% vs. 16.86%). In addition, the contributions of the combined effects of climate variations and anthropogenic activities to forest restoration in these seven tributaries were relatively small except for the JLRB (24.36%), MTRB (27.46%) and HJRB (37.13%).
As shown in Figure 6(b-1), the dominant driving force of forest restoration of five different forest types was found to be different. The anthropogenic activities dominated larger area percentages of ANPP increase than climate variations in the evergreen coniferous forest (46.47% vs. 41.48%), evergreen broad-leaved forest (50.03% vs. 37.83%), shrubs (50.03% vs. 37.83%), and sparse woods (66.15% vs. 17.65%). Meanwhile, the ANPP increase of deciduous broad-leaved forests was mainly dominated by both climatic factors and anthropogenic activities (45.33%), followed by climate variations (29.60%), with anthropogenic activities being the least (23.88%).

3.4.2. Contribution of Climate Variations and Anthropogenic Activities to Forest Degradation at the Tributary Level

The relative contributions of climate variations and anthropogenic activities to forest degradation were also analyzed based on four degradation scenarios defined in Table 2 (Figures 5 and 6). The climate-dominated forest degradation (CDD) regions were mainly located in the southern part of the JSRB, WJRB, Three Gorges Reservoir Area, and the central part of HJRB and DTLB. The anthropogenic activities that dominated forest degradation (HDD) were mainly observed in the PYLB and southwestern and northeastern parts of the DTLB. The percentage of forest degradation dominated by both factors (BDD) was relatively low, which was mostly scattered in the WJRB, DTLB, and southern part of the PYLB.

In the seven tributaries of the YRB, the contributions of climate variations, anthropogenic activities, and the combined effects of the two factors in forest degradation were different. For forest ANPP degradation (Figure 6(a-2)), the climate variations dominated a larger area percentage of ANPP decrease than anthropogenic activities in the JSRB (74.81% vs. 13.23%), HJRB (82.50% vs. 5.79%), and WJRB (59.89% vs. 20.56%). Meanwhile, anthropogenic activities had a greater contribution to forest degradation than climate variations in the MTRB (45.35% vs. 40.05%), DTLB (44.53% vs. 32.58%), especially, JLRB (75.88% vs. 11.21%), and PYLB (80.08% vs. 7.73%). In addition, the combined effects of climate variations and anthropogenic activities in the seven tributaries had a relatively small contribution to the decline of forest ANPP.
As shown in Figure 6(b-2), the dominant factor of ANPP decrease in different forest types was different. Climate variations have larger area percentages of ANPP than anthropogenic activities in the deciduous broad-leaved forest (78.69% vs. 7.77%) and sparse woods (45.25% vs. 42.96%). Meanwhile, the area percentages of ANPP decrease caused by anthropogenic activities were greater than that induced by climate variations in the evergreen coniferous forest (47.74% vs. 36.05%), evergreen broad-leaved forest (42.03% vs. 36.51%), and shrubs (48.79% vs. 35.93%).

3.4.3. Contribution of Climate Variations and Anthropogenic Activities to Forest ANPP Dynamics in the Whole YRB

The contribution of climate variations and anthropogenic activities and their combined effect on forest dynamics in the YRB were analyzed (Figure 7). The total ANPP increased by 26.71 TgC due to forest restoration from 2000 to 2015. Climate variations resulted in an ANPP increment of 8.32 TgC, which occupied 37.54% of the area of forest restoration. Anthropogenic activities increased 13.25 TgC in ANPP, covering 47.77% of the area of forest restoration. Both factors induced an increase of 5.14 TgC in ANPP, accounting for 14.69% of the area of forest restoration. Forest degradation resulted in a decline of 16.29 TgC in ANPP. Climate variations and anthropogenic activities induced an ANPP loss of 5.12 and 7.90 TgC, which accounted for about 38.22% and 46.33% of the area of forest degradation, respectively. The combined effect of two factors resulted in an ANPP reduction of 3.28 TgC, accounting for 15.45% of the area of forest degradation. In general, the total forest ANPP increased by 10.42 TgC in the YRB from 2000 to 2015. The main reason for the increase was that the area of restored forests was larger than that of degraded forests (49.73 × 10^4 km^2 vs. 37.14 × 10^4 km^2) during 2000–2015.

![Figure 7](image_url). The contribution of specific driving factors to total ANPP in the YRB.

3.5. The Relationship between Forest ANPP and Climate Factors in the Whole YRB

In this study, the temperature generally increased while the trend of precipitation showed apparent spatial heterogeneity in the YRB (Figure 8). The MAP and MAT increased by 3.11 mm/yr and 0.018 °C/yr from 2000 to 2015, respectively. To better understand
the influence of climatic factors on the forest ANPP variation, the correlation coefficients between forest ANPP and climate factors (i.e., precipitation and temperature) in pixel were analyzed (Figure 9). The mean value of the correlation coefficient between forest ANPP and MAP or MAT were 0.11 and 0.21, respectively. There was a positive correlation between forest ANPP and precipitation in 62.81% of the study area and a significant positive correlation in 12.27% of the study area. A negative correlation between forest ANPP and MAP occurred in 37.19% of the study area and only 4.53% was significant. In terms of temperature, 77.86% of the study area experienced a positive correlation between forest ANPP and MAT, and 14.90% of the study area passed the significance test. Meanwhile, the areas where forest ANPP and MAT were negatively correlated accounted for 22.14% of the study area, and only 0.71% passed the significance test ($p < 0.05$).

Figure 8. Spatial pattern of the trends of (a) MAP and (b) MAT in the YRB from 2000 to 2015.

Figure 9. Spatial pattern of correlation coefficients between (a) ANPP and MAP and (b) ANPP and MAT in the YRB from 2000 to 2015.

4. Discussion

4.1. The Impact of Climate Variations on Forest ANPP Dynamic in the YRB

Climate variations mainly influence forest ecosystem restoration or degradation through changes in precipitation and temperature, which could affect photosynthesis and plant respiration and, thereby control vegetation growth [45]. In this study, the area of forest restoration and degradation dominated by climate variations accounted for 37.54% and 38.22% of the forest region in the YRB, respectively. This indicated that climate variations were an important driving force of forest dynamics in the YRB. In this study, the temperature generally increased while precipitation variations showed apparent spatial heterogeneity in the YRB, which was in line with the research of Qu, et al. [46]. In the PYLB, forest restoration was mainly dominated by climate variations. The increase of temperature and precipitation occurred in this tributary, which lead to an increment of PNPP. Climate warming could lengthen growing seasons and enhance the photosynthesis of vegetation,
which is conducive to vegetation growth [12]. A similar situation occurred in the JLRB and MTRB. This was in line with previous researches. For instance, Fan et al. [47] indicated that the NDVI showed an increasing trend in 94.9% of the Poyang Lake basin, which was mainly due to the rising temperature. Climate variations mainly resulted in forest degradation in the JSRB, WJRB, HJRB, DTLB, and the MAURYR. In these regions, the temperature increased while the precipitation decreased dramatically, which exerted an adverse effect on vegetation growth. Warming without sufficient precipitation will increase evaporation and drought risk, which may lead to reduced photosynthesis efficiency, suppression of plant activity, and reduced organic matter production [48]. This was consistent with previous researches. For instance, Tong et al. [12] indicated that the above-ground biomass decreased due to drought in southwestern China by using the LPJ-GUESS model. Lai et al. [49] reported that drought events generally induced approximately 30% of the NPP reduction in most of the sub-regions in China. Wang et al. [50] indicated that intensifying drought stress would limit increases of forest NPP in southern China.

The correlation analysis showed that the area that forest ANPP was positively related with temperature was greater than that with precipitation (77.86% vs. 62.81%). The mean value of the correlation coefficient between NPP and precipitation was about twice that of temperature (0.21 vs. 0.11). This result indicated that the temperature was the dominant climatic factor of the forest dynamics in the YRB during the study period, which was consistent with some previous studies [25,34,44]. However, some other studies have concluded that precipitation was the main climate factor driving vegetation change [31,45,51]. The main reason for the difference is the different geographical locations of the study area. In the arid and semi-arid areas, the precipitation is the limiting factor of vegetation growth, and the change in precipitation could affect soil moisture and photosynthesis rate, thereby affecting vegetation productivity; however, in humid regions such as the YRB, the precipitation is sufficient, which reduces the sensitivity of vegetation growth to the change of precipitation, while the rising temperature will increase the photosynthetic rate, which is beneficial to vegetation growth.

4.2. The Impact of Anthropogenic Activities on Forest ANPP Dynamic in the YRB

Anthropogenic activities also play a crucial role in forest ecosystem dynamics. Ecological restoration programs can effectively improve ecosystem productivity. In this study, the area of forest restoration dominated by anthropogenic activities was greater than that by climate variations, which should be ascribed to a variety of major ecological restoration programs launched in the YRB in recent decades. As mentioned before, the GTGP was objective to convert cropland in hilly areas into forests and grassland [52]. As shown in Table 5, the cropland area in the YRB has dramatically decreased during the study period, which indicated that GTGP has made considerable achievements. The NFCP aimed to protect natural forests through logging bans [18]. Zhang et al. [25] reported that the forest area decreased by 1291 km$^2$ from 1990 to 2000, which was about twice that from 2000 to 2015 in this study (Table 5). This indicated that forest destruction has been controlled to a certain extent due to the implementation of NFCP. In the JSRB, the climate variations were not beneficial to vegetation growth while the forest ANPP still showed an upward trend, which should be attributed to the ecological restoration programs implemented. This indicated that restoration programs could effectively mitigate the adverse effect of climate variations and improve the regional ecological environment. This result was consistent with the study of Yin et al. [53], who reported that the contribution of anthropogenic activities to ANPP change was about twice of climate variations in the Hengduan Mountain region. This study indicated that in the MAURYR (i.e., Three Gorges Reservoir Area), the ecological restoration projects have dramatically mitigated the adverse effects of the Three Gorges Project and induced forest restoration in this region, which was in line with the study of Xu et al. [54]. In the northern part of HJRB and JLRB, the implementation of ecological restoration programs coupled with climate variations increased forest ANPP. This was consistent with Zhou et al. [55] who pointed out that the increase in NPP was
mainly ascribed to ecological projects in the Bailong River basin. Numerous researches have proved the great benefit of ecological projects. In general, human activities dominated 47.77% of the forest restoration region and induced an increment of 13.25 TgC in NPP, which indicated that ecological restoration programs dominated forest restoration in the YRB during the study period. This was consistent with previous studies. For instance, Chen et al. [56] selected NDVI as an indicator to explore the driving mechanism of forest change during 2000–2015 and indicated that ecological programs were the dominant driving factor of forest change in the Yangtze River basin. Tong et al. [12] found that major ecological programs could exert positive influences on vegetation growth to mitigate the adverse effect of climate variations. Ouyang et al. [17] pointed out that the carbon sequestration increased by 23.4% from 2000 to 2010 due to the implementation of multiple ecological conservation programs in China. Chen et al. [16] indicated that China occupied 25% of the global increment in LAI with only 6.6% of global vegetation area from 2000 to 2017, which was due to multiple major ecological programs implemented.

Table 5. The extent of change in land areas under different types of land cover in the YRB: 2000–2015. (Area, unit: km$^2$).

| Region | Croplands | Forests | Grasslands | Waters | Urban | Barren |
|--------|-----------|---------|------------|--------|-------|--------|
| JSRB   | –553      | 114     | –276       | 299    | 524   | –107   |
| MTRB   | –1178     | –186    | 198        | 127    | 988   | 53     |
| JLRB   | –1324     | 152     | 102        | 78     | 922   | 71     |
| HJRB   | –1235     | –154    | 78         | 465    | 839   | 7      |
| WJRB   | –403      | 384     | –649       | 39     | 633   | –3     |
| DTLB   | –1545     | –218    | –578       | 320    | 2026  | –4     |
| PYLB   | –663      | –616    | 22         | 205    | 1309  | –257   |
| YRB    | –15,004   | –637    | –1358      | 2422   | 14,917| –227   |

However, anthropogenic activities could result in forest degradation as well. In this study, the degradation area that resulted from anthropogenic activities occupied approximately 46.33% of the area of forest degradation during the study period. These regions were mainly distributed in the southwest part of DTLB and PYLB. These regions have undergone rapid economic development and urbanization in recent years [57,58]. Moreover, these two tributaries are characterized by lower elevations, flat terrain, which means more intensive human disturbance to the forest ecosystem. Among the seven main tributaries of the YRB, the largest forest loss and urban area increase both occurred in the DTLB and PYLB (Table 5). Rapid urbanization could dramatically change the land use and cover and compress the space of vegetation growth, consequently leading to a reduction of vegetation NPP. For instance, Li et al. [20] pointed out that the national total loss of NPP induced by urbanization accounted for 1.695 TgC in China from the late 1980s to 2015. It is noteworthy that the NFCP is only implemented in the upper and middle reaches of the YRB, while the DTLB and PYLB are not included [18]. This implied that deforestation might not be effectively controlled in these regions. Consequently, the extent of the NFCP should be expanded to cover these two basins to mitigate forest ecosystem degradation. We noticed that among the five forest types, the shrub is the only forest type in which the area of degradation was larger than that of restoration (9.86 km$^2$ vs. 6.90 km$^2$). Moreover, the ANPP loss of this forest type was nearly twice of ANPP increment (4.54 TgC vs. 2.46 TgC). Compared with the other four forest types, the shrub is more sensitive to human disturbance. Therefore, it is recommended that the government pay more attention to the protection of shrubs and establish a reasonable protection system to reduce the damage to the shrub ecosystem by natural and human factors.

4.3. Limitation and Uncertainty

This study used NPP based scenario method to quantify the relative contribution of climate variations and anthropogenic activities to forest dynamics, it still has some limita-
tions. Firstly, except for climate and human factors, some other factors could influence the forest ecosystems such as forest fire, disease, pests, soil erosion, CO₂ fertilization effect, and nitrogen deposition [13,46]. Secondly, the Thornthwaite Memorial model utilized to calculate the PNPP only used the main meteorological factors (precipitation and temperature) as inputs, other meteorological factors such as solar radiation and relative humidity were not taken into account, which may affect the accuracy of PNPP. Thirdly, this research only evaluated the integrated contribution of climate variations and anthropogenic activities to forest dynamics, while the relative contribution of specific anthropogenic activities is hard to evaluate because of the limitation of the method used in this study. Despite these limitations, the results of the current study revealed the overall trend of forest ANPP and determined the relative contribution of climate variations and anthropogenic activities to forest dynamics in the YRB, which can provide a valuable reference for forest ecosystem restoration and management in the future. Moreover, it can be useful to reach a more effective implementation of SDG 15.3 (Land Degradation Neutrality Initiative) in the YRB.

5. Conclusions

In this study, the NPP was selected as an indicator to monitor the forest variation and distinguish quantitatively the relative contribution of climate variations and anthropogenic activities to forest restoration and degradation in the YRB from 2000 to 2015. The main conclusions are summarized as follows:

(1) In general, the total forest ANPP increased by 10.42 TgC in the YRB, and forest restoration occurred in 57.25% of the study area from 2000 to 2015. The forest degradation was mainly observed in WJRB, DTLB and PYLB.

(2) Climate variations and anthropogenic activities were both important driving forces of forest dynamics. On the whole, anthropogenic activities exerted greater influence than climate variations on both forest restoration and degradation during the study period. Anthropogenic activities dominated the forest restoration in the JSRB, HJRB, WJRB, MAURYR and DTLB and the forest degradation in the MTRB, JLRB, DTLB and PYLB. In contrast, climate variations were the dominant driving force of forest restoration in the MTRB, JLRB and PYLB, and forest degradation in the JSRB, HJRB and WJRB.

(3) Among the five forest types, shrubs experienced the most severe degradation during the study period, which should arouse great attention. More attention should be paid to the protection of shrubs and a reasonable protection system should be established to reduce the damage to the shrub ecosystem by natural and human factors.

(4) Ecological restoration programs implemented have effectively mitigated the adverse effect of climate variations and dominated forest restoration, while rapid urbanization in the mid-lower region has resulted in forest degradation in YRB.

(5) The forest degradation in DTLB and PYLB may be ascribed to the absence of NFCP. Therefore, we recommend that the extent of the NFCP should expand to cover the DTLB and PYLB to alleviate forest degradation in these two basins.

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Abbreviations

ANPP  Actual Net Primary Productivity
BDD  Both dominated the forest degradation
BDR  Both dominated forest restoration
CDD  Climate-dominated forest degradation
CDR  Climate-dominated forest restoration
DTLB  Dongting Lake basin
GTGP  Grain to Green Program
HDD  Human-dominated forest degradation
HDR  Human-dominated forest restoration
HJRB  Hanjiang River basin
HNPP  Human-induced Net Primary Productivity
JLRB  Jialing River basin
JSRB  Jinsha River basin
MAP  Mean annual precipitation
MAT  Mean annual temperature
MODIS  Moderate-resolution Imaging spectroradiometer
MTRB  Mintuo River basin
MAURYR  Mainstream area of the upper reaches of the Yangtze River
MAMRYR  Mainstream area of the middle reaches of the Yangtze River
MALRYR  Mainstream area of the lower reaches of the Yangtze River
NFCP  Natural Forest Conservation Program
NPP  Net Primary Productivity
PNPP  Potential Net Primary Productivity
PYLB  Poyang Lake basin
SDGs  Sustainable Development Goals
THLB  Taihu Lake basin
WJRB  Wujiang River basin
YRB  Yangtze River Basin

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