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Evaluation of Future Trends Based on the Characteristics of Net Primary Production (NPP) Changes over 21 Years in the Yangtze River Basin in China

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Abstract: As the third largest river basin in the world, the Yangtze River basin in China has vegetation ecosystems in its plain, mountain, and alpine regions. Studying the change characteristics of the vegetation's net primary productivity (NPP) and its relationship with natural factors and human activities can aid with understanding, to a certain extent, the response of the ecosystem to global climate change. Based on a total of 21 years of MOD17A3 data products from 2000 to 2020, this paper analyzed the spatial variation characteristics and future trends of the NPP in this region by using the coefficient of variation (CV), trend analysis (β), and Hurst index (H) methods. Meanwhile, correlation analysis was used to explore the influence of natural factors and human activities on the NPP. The results show the following: (1) the total amount of the NPP in the Yangtze River Basin was relatively high, and the overall change trend is rising, while the inter-annual fluctuation is evident. The total amount of NPP ranges from 0.786 PgC (2000) to 1.024 PgC (2020), and the annual average was 0.932 PgC. This increase was mainly caused by the increase in the average NPP of forest land, cultivated land, and construction land. (2) The mean value of the NPP in the different regions of the Yangtze River Basin ranged from 0 (construction land) to 1902.89 gC/m^2·a. The mean value of the NPP in the Yangtze River Basin was high in the south and low in the north, as well as high in the middle and low in the east and west. The main high-value areas were located in the Hengduan Mountains and the Yunnan-Guizhou Plateau. The coefficient of variation (CV) was 0.0009–0.9980, and the mean CV was only 0.1126. Regarding the future development trend, 77.90% and 22.10% of the regions showed an increase, 22.10% showed a decrease, and 75.25% showed an anti-sustainable state. (3) The effect of human activities on the NPP was generally negative, and the loss of NPP due to land use change in 2020 was around 9.85 TgC when compared with the same in 2000. (4) The rainfall and temperature in the Yangtze River basin both showed a non-significant increase, and the correlation coefficient between the NPP and rainfall was between −0.874 and 0.910. Furthermore, the correlation coefficient of the temperature ranged from −0.928 to 0.929, with a positive correlation overall and a negative correlation locally, and the NPP changes were more susceptible to the influence of temperature than rainfall.

Keywords: Yangtze river basin; NPP variable characteristics; future trend; climate factors; land use change

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1. Introduction

Since the Industrial Revolution, the global climate has been gradually warming, with the global temperature increasing by approximately 1.5 °C compared to the pre-Industrial Revolution period [1,2]. This warming trend is primarily attributed to CO_2 emissions [3,4], prompting scientists worldwide to explore the use of plant carbon sinks as a means of reducing atmospheric CO_2 levels [5]. Net Primary Productivity (NPP), the organic matter produced by plants through photosynthesis, less the organic matter consumed by plant respiration, has emerged as a crucial metric for evaluating ecosystem productivity, with significant implications for sustainable development and ecological research. NPP enables assessments of productivity discrepancies among diverse ecosystems, comprehension of energy flow and carbon cycling processes within ecological systems, and prediction and monitoring of ecosystem responses to environmental fluctuations. Moreover, regional variations in NPP serve as vital parameters for describing the physiological and ecological conditions of vegetation, as well as crucial indicators for monitoring the dynamic carbon cycling within a region and its contribution to global carbon sequestration capacity. Therefore, the accurate estimation of regional vegetation NPP, as well as analysis of its changing patterns and future trends, are of paramount importance in regional ecosystem management and policy formulation.

The estimation of NPP has undergone three stages: actual measurement, statistical modeling, and mechanism modeling. However, the use of multi-source remote sensing data and models has become the prevailing method due to its low cost and relatively high accuracy. The estimation models can be divided into three categories: climate-related models, light energy utilization models (such as CASA, and GLOPEM), and other ecosystem process models [6]. The MODIS NPP product MOD17A3 is based on MODIS remote sensing parameters and utilizes the BIOME-BGC model and NPP data simulated by a light energy utilization model [7]. This dataset has been validated and applied in global and regional studies, including the Amazon rainforest [8], Great Barrier Reef [9], the Sahara region [10], and China [11,12], demonstrating its efficacy in reflecting the distribution and variations of regional NPP.

The Yangtze River Basin is the largest basin in China, spanning three geographical tiers and encompassing the eastern, central, and western regions of the country. It accounts for 18.8% of China's land area and 41% of its forested area, making it a pivotal ecological functional zone. With its diverse and intricate ecosystems, the Yangtze River Basin has become increasingly threatened by human activities, such as urbanization, industrialization, and agricultural expansion, resulting in mounting pressure on its natural environment [13]. However, the Chinese government's implementation of natural environmental protection policies, such as "Yangtze River Conservation", has mitigated the impact of these activities to some extent. Consequently, an in-depth investigation of the characteristics, mechanisms, and influencing factors of NPP in the Yangtze River Basin is critical to understanding the health of this ecosystem. It can also provide a scientific basis for the formulation of policies related to its ecological protection and sustainable development while serving as a scientific reference for similar regions worldwide.

Previous research has been insufficient in quantitatively studying the impacts of human activities, such as land use changes, on NPP. Furthermore, there has been limited research on the future trends of NPP, especially in the regional context of the Yangtze River Basin. The NPP variability is influenced by two aspects. One is natural factors, such as precipitation, temperature, sunshine [14], altitude, and soil properties [15,16], and the other is human activities, such as land cover change and human daily activities, which can interfere with the natural ecosystem [17]. Due to the spatial heterogeneity of NPP and its influencing factors, a quantitative analysis of the spatial and temporal dynamic characteristics and influencing factors of NPP at a regional scale cannot adequately explain the response mechanism of NPP to climate change and anthropogenic activities in different natural environments (e.g., elevation, slope, latitude, etc.). Moreover, this approach cannot provide effective data support for regional differentiated policy formulation to more accurately reflect the characteristics of NPP changes and future trends in different regions of the Yangtze River Basin.

This study utilizes the MODIS dataset to estimate NPP in the Yangtze River Basin from 2000 to 2021, with the following main research questions: (1) analyzing the stability of NPP over the past period by calculating the coefficient of variation; (2) analyzing the spatiotemporal characteristics of the Yangtze River Basin over the past 21 years (2000–2020) using Theil-Sen Median trend analysis and the Mann-Kendall test to determine if changes are significant; (3) quantitatively analyzing the response of NPP to natural factors, such as precipitation, temperature, and elevation, as well as human activities, such as land use changes; and (4) using the Hurst (H) index to analyze future trends of NPP in different regions of the Yangtze River Basin.

2. Materials and Methods

2.1. Study Area

The Yangtze River Basin is located between 24°30′–35°45′ N and 90°33′–122°25′ E, with a total length of about 6300 km and a main stream area of 1,800,000 km^2, thus making it the largest river in Asia and China and the third largest in the world. The Yangtze River Basin accounts for around 35.1% of China's total water flow, and the river flows in a west-to-east direction. The straight-line distance from east to west is over 3000 km, and the drainage basin width from north to south is generally around 1000 km on average—except for the source area and the Yangtze Delta, where it is smaller. The main stream originates in the Tanggula Mountains in the eastern part of the Tibetan Plateau and flows through 11 provinces, autonomous regions, and municipalities directly administered by the Central Government—Tibet, Qinghai, Yunnan, Sichuan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai—before it finally merges with the East China Sea (See Figure 1).

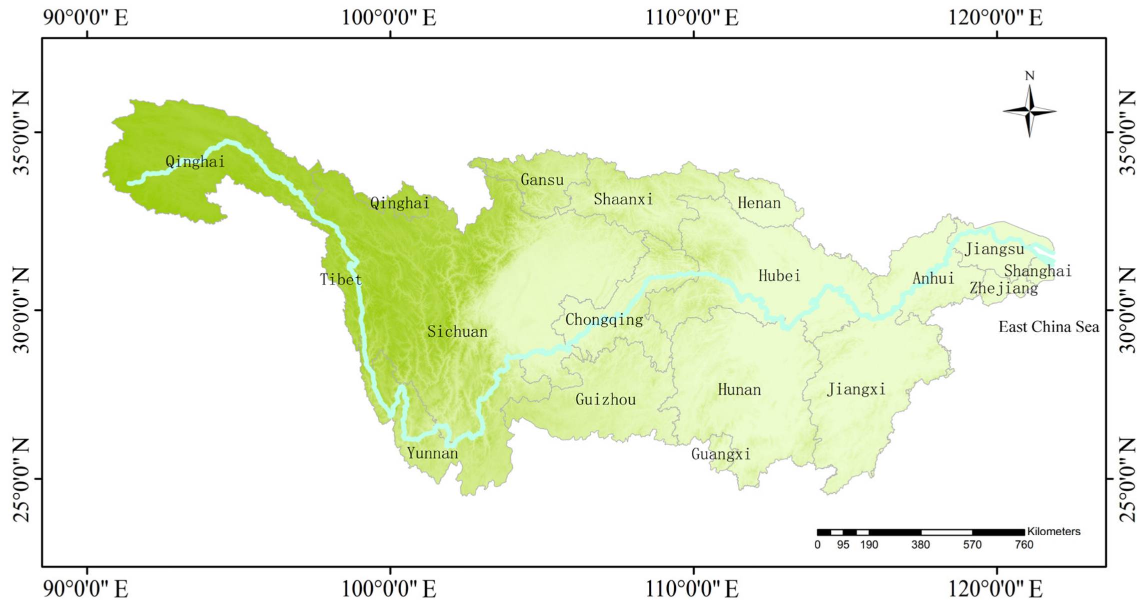

Figure 1. Scope of the Yangtze River Basin.

2.2. Date

2.2.1. NPP Data

The NPP data adopted in this study are a 2000–2020 MOD17A3 (NTSG https://lpdaac.usgs.gov/ (accessed on 2 January 2022)) product with a spatial resolution of 1 km. Furthermore, the resolution was adjusted to 500 m with the ARCgis10.6 resampling command. Mosaic, format conversion, and the reprojection of MODIS data were carried out using (MODIS Reprojection Tool) MRT. Unit conversion and cropping were carried out in ArcGIS10.6, and invalid values were eliminated. The NPP quality control data (NPP_QC) showed that the average reliability of the NPP inversion results that were of medium- and high-grade quality in the study area was 90.27%. Considering the large area of the Yangtze River Basin, as well as its complex terrain and cloudy climate, the data quality was found to be generally acceptable [18].

2.2.2. Natural Factors

Vegetation CO_2 uptake is achieved through plant photosynthesis, and the sunshine duration, which is one of the three main factors of meteorological plant photosynthesis (sunshine duration, temperature, and rainfall), was relatively constant. Thus, the temperature and humidity became the main factors influencing plant photosynthesis and, therefore, NPP [19]. As such, we included temperature and rainfall as some of the natural factors in our analysis. The duration of sunshine is relatively fixed, and the grade changes little; thus, the same region does not have a great influence on the change in NPP, while the temperature and rainfall show evident inter-year changes, which affect the photosynthesis of plants and became the main factors affecting the change in the NPP. Therefore, we included temperature and rainfall as some of the natural factors in the analysis. The meteorological data in this study were collected from the data center of the China Meteorological Administration (https://data.cma.cn/ (accessed on 2 January 2023)). Kriging interpolation was carried out on the rainfall data, and elevation correction was carried out on the air temperature data after interpolation. Finally, raster data with a resolution of 500 m were obtained.

The elevation difference of the Yangtze River Basin is approximately 6000 m, passing through the first, second, and third steps of China's topography, and the spatial differentiation of its topography is evident [20]. By controlling the water, heat, and soil conditions, the topography and geomorphology can affect other environmental variables, which then affect the regional vegetation pattern and cause variation in the mean changes in the NPP of different topography and geomorphology plants. Therefore, topographic factors (altitude, slope) are also included in the analysis as one of the influencing factors. The topographic data come from the DEM data of China's geospatial data cloud (https://www.gscloud.cn/ (accessed on 13 January 2023)), the accuracy of which are 30 m, and the data are resampled to 500 m. Then, a slope analysis was conducted on an ARCgis10.6, and the DEM and slope were graded via reclassification.

2.2.3. Human Activities

The most direct manifestation of the impact of human activities on the natural environment is the change in land use type [21]; thus, land use change was used in this study to reflect human activities. The land use data came from the Land-Use and Land-Cover Change (LUCC) data of the Chinese Academy of Sciences (http://www.resdc.cn/date.aspx (accessed on 13 January 2023)), which were then reclassified into cultivated land, grassland, water area, forest land, construction land, and unused land.

All data were defined with the same projection reference (WGS_1984_UTM_Zone_49N), range, and resolution (readopted to 500 m × 500 m); thus, the database was established.

2.3. Methods

2.3.1. NPP Coefficient of Variation (CV)

Coefficient of variation (CV) is often used to measure the relative stability (fluctuation) of geospatial data in a long time series [22], and it has also been used to evaluate whether the NPP in the Yangtze River Basin has been stable in the last 21 years. The calculation formula for this is the following:

$$\mathrm{Cv} = \frac{1}{NPP}\sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(NPP_{\mathrm{i}} - \overline{NPP})}{\mathrm{n}-1}} \quad (1)$$

where; C_V is the coefficient of variation; NPP_i is the annual value of i; n is the time series length (in this study, n = 21); and is the mean value of *NPP* in the Yangtze River Basin from 2000 to 2020. The larger the C_V value is, the larger the *NPP* fluctuation is within the time series; otherwise, the fluctuation is smaller.

2.3.2. Theil–Sen Median Trend Analysis and the Mann–Kendall Test

Theil–Sen median trend analysis and the Mann–Kendall test are important methods through which to judge the trend of long time series data [23]. As this method does not require data to obey a certain distribution, this methods is robust against outliers that might be introduced by data errors. The calculation formula for trend analysis is as follows:

$$\beta = median(\frac{NPP_{\mathrm{j}} - NPP_{\mathrm{i}}}{j - i}), 2000 \leq i < j \leq 2020 \quad (2)$$

where; β is the change trend, and $NPP_{\mathrm{i/j}}$ is the *NPP* value in years *i/j*. When $\beta > 0$, the *NPP* of the region showed an upward trend. When $\beta < 0$, the *NPP* of the region showed a downward trend.

The Mann–Kendall test was used to judge whether the variation trend of the *NPP* in this region was significant. The calculation formula is as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}}, S > 0 \\ 0, S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}}, S < 0 \end{cases} \quad (3)$$

$$S = \sum_{\mathrm{j=1}}^{\mathrm{n-1}} \sum_{\mathrm{i=j+1}}^{\mathrm{n}} \mathrm{sgn}(NPP\mathrm{j} - NPP\mathrm{i}) \quad (4)$$

$$\mathrm{sgn}(NPP\mathrm{j} - NPP\mathrm{i}) = \begin{cases} 1,\ NPP\mathrm{j} - NPP\mathrm{i} > 0 \\ 0,\ NPP\mathrm{j} - NPP\mathrm{i} = 0 \\ -1,\ NPP\mathrm{j} - NPP\mathrm{i} < 0 \end{cases} \quad (5)$$

$$\mathrm{var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (6)$$

where sgn is the sign function, and Z is the standardized statistic of the normal variance. Furthermore, the trend test was based on the null hypothesis $\mathrm{H_a}$: $\beta = 0$. The null hypothesis was rejected when $|\mathrm{Z_{MC}}| > \mathrm{Z_{1-a}}/2$: where; $\mathrm{Z_{1-a}}/2$ is the standard normal variance; α is the significance test level; and $\alpha < 0.05$ passes the significance test when $|\mathrm{Z_{MC}}| \geq 1.64$, indicating a significant change in the change region.

2.3.3. Analysis of Future Trends

The Hurst (H) index was used to quantify the long-term dependence of the NPP time series information [24]. The basic principle is as follows. Consider a NPP time series $\{NPP(\tau)\}$, and for any positive integer, define the mean series:

$$\overline{NPP}(\tau) = \frac{1}{\tau}\sum_{t=1}^{\tau} NPP(\tau)\ \tau = 1,\ 2,\ 3, \ldots,\ N \quad (7)$$

$X(t)$ is the cumulative deviation:

$$X(t,\tau) = \sum_{t=1}^{t}\left[NPP(t) - \overline{NPP(\tau)}\right]\ 1 \ \leq\ t\ \leq\ \tau \quad (8)$$

The polarity $R(\tau)$ is defined as:

$$R(\tau) = \max X(\mathrm{t}(\tau) - \min X(\mathrm{t}, \tau)\ \tau = 1,\ 2,\ \ldots\ (1\ \leq\ t\ \leq\ \tau) \quad (9)$$

The standard deviation $S(\tau)$ is defined as:

$$S(\tau) = \left[\frac{1}{\tau}\sum_{t=1}^{\tau}\left(NPP(t) - NPP(\tau)\right)^2\right]^{\frac{1}{2}} \tau = 1,\ 2,\ \ldots \quad (10)$$

If $R/S \propto \tau^H$ exists, it means that there is a Hurst phenomenon in the NPP time series. H is the Hurst index, and its value is obtained with the least squares fitting method. The value of H was in the range of 0–1, and it included three cases: (1) if H > 0.5, then the time series process represents sustainability, and the closer H is to 1, the stronger the degree of sustainability; (2) if H = 0.5, then the time series is random; and (3) if H < 0.5, then the time series process represents anti-sustainability (note that the future changes may differ from the present and may even develop in the opposite direction), and the closer H is to 0, the stronger the degree of anti-sustainability (See Figure 2).

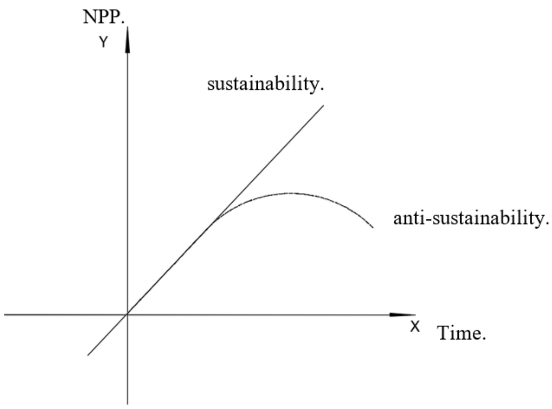

Figure 2. The trends of sustainability and anti-sustainability.

2.3.4. Factor Correlation Analysis and Test

Correlation analysis refers to the analysis of two or more random variables, and it measures the degree of correlation between these variables [25]. The correlation coefficient r lay between [−1, 1], and when r < 0, the variables were negatively correlated with each other. When r > 0, the variables were positively correlated. Moreover, ∣r∣→1 indicates that the correlation is greater, and when r = 0, it means that the variables are not correlated with each other. The calculation formula for this is as follows:

$$r = \frac{\sum_{i=1}^{n}(Xi - \overline{X})(Yi - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(Xi - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Yi - \overline{Y})^2}} \quad (11)$$

where r is the correlation coefficient, and $\overline{X}$ and $\overline{Y}$ are the means, and r is the correlation coefficient

3. Results

The annual NPP in the Yangtze River Basin from 2000 to 2020 ranges from 0.786 PgC to 1.024 PgC (1PgC = 1015 g). The average value for the past 21 years is 0.932 PgC, with the maximum value occurring in 2015 at 1.024 PgC. The annual average NPP was between 431.31 gC/(m^2·a) to 561.69 gC/(m^2·a), with a multi-year average of 511.75 gC/(m^2·a). The overall NPP showed an upward trend, but large fluctuations occurred in 2005, 2013, 2014, and 2015, and especially in 2014 and 2015. From Figure 2, we can see that the NPP changes during this period can be divided into four stages: an increasing stage from 2000 to 2003; a fluctuating increase from 2004 to 2012; a large amplitude oscillation from 2013 to 2015; and a fluctuating increase from 2016 to 2020 (See Figure 3).

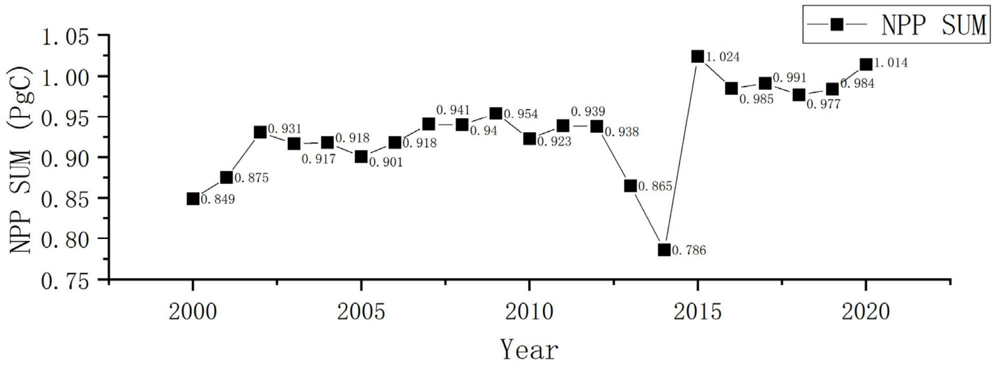

Figure 3. Trends in the NPP of the Yangtze River Basin, 2000–2020.

3.1. Spatial and Temporal Characteristics of NPP

3.1.1. NPP Spatial Means and the Coefficients of Variation

From 2000 to 2020, the average NPP of various land uses in the Yangtze River Basin ranged from 0 to 1902.89 gC/(m^2·a) per unit area 0 gC/(m^2·a), and this mainly relates to construction land with significant spatial differences. As shown in Figure 4, the overall pattern was high in the south and low in the north, high in the central region, and low in the east and west. The areas with a below average NPP were mainly located in the Qinghai–Tibet Plateau and the eastern mouth of the Yangtze River, followed by the middle and lower reaches of the Yangtze River plain and the Chengdu Basin. The areas with relatively high average NPP were mainly distributed in the Hengduan Mountains, Yunnan-Guizhou Plateau, and Wushan Mountains, with the Hengduan Mountains being the most prominent.

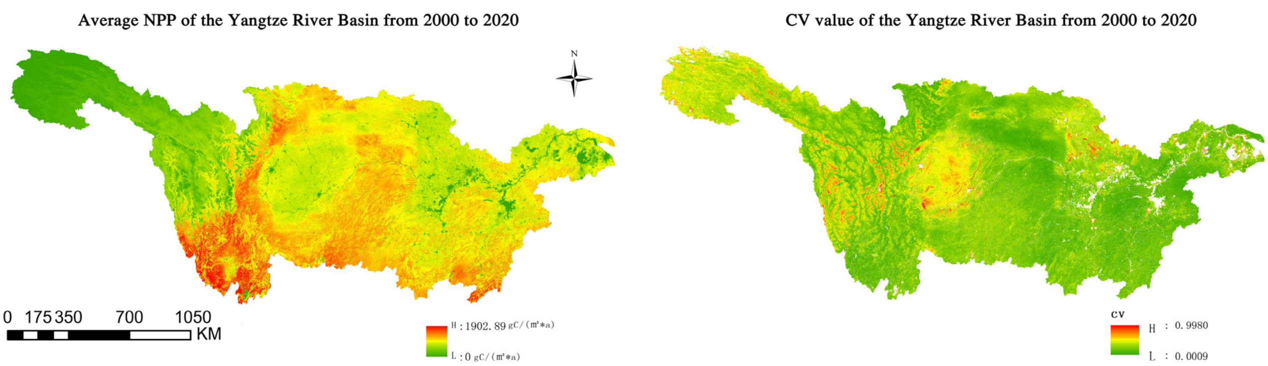

Figure 4. The average NPP and the Cv Value of the Yangtze River Basin, 2000–2020.

From 2000 to 2020, the Cv of the NPP in the Yangtze River Basin ranged from 0.0009 to 0.9980, indicating significant spatial differences in the distribution of the Cv in this region. As shown in Figure 2, there are clear concentrated areas, with the regions that have large variation coefficients being mainly distributed in the western Qinghai–Tibet Plateau, Chengdu Basin, Hengduan Mountains, Wushan Mountains, and the middle and lower reaches of the Yangtze River. These regions can be roughly divided into two categories: one is the areas with higher average altitude, such as the western Qinghai–Tibet Plateau, Hengduan Mountains, and Wushan Mountains; the other is the areas with rapid urbanization during this period, such as the Chengdu Basin and the middle and lower reaches of the Yangtze River. Other regions have relatively low Cv values. The mean Cv value was 0.1126, indicating that the NPP in this region was relatively stable during this period and was less affected by natural and human factors.

3.1.2. Theil–Sen Median Trend Analysis and Mann–Kendall Test

The β value of the NPP in the Yangtze River Basin ranged from −45.2667 to 42.4875 (as shown in Figure 5), with 77.90% of the basin area showing an increasing trend (β > 0) and 22.10% showing a decreasing trend (β < 0). This indicated an overall increasing trend in this region. The average value of β was 3.14, indicating a relatively weak overall upward trend, which is consistent with the previous analysis. As shown in Figure 2, the areas with a more evident increasing trend were located in the Sichuan Basin, the southern Qinling Mountains, and the northern Yunnan-Guizhou Plateau. The Qinghai–Tibet Plateau and the middle and lower reaches of the Yangtze River plain showed a weak alternating pattern of slight decrease and slight increase, while the western Yunnan-Guizhou Plateau and Hengduan Mountains showing a decreasing trend.

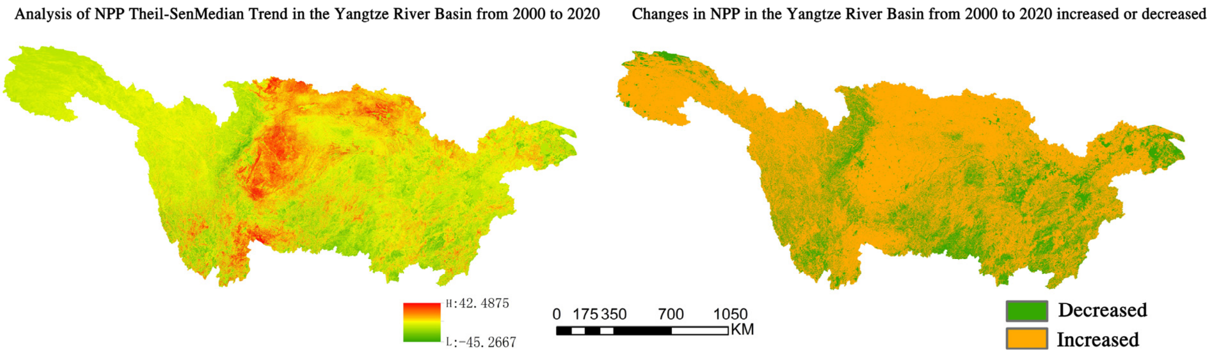

Figure 5. The NPP Theil–Sen median trend of the Yangtze River Basin, 2000–2020.

By overlaying the results of the Theil–Sen median trend analysis and Mann–Kendall test, we can obtain four scenarios (as shown in Figure 6): significantly increased (SI), significantly decreased (SD), non-significantly increased (Non-SI), and non-significantly decreased (Non-SD). The results show that SI accounted for 8.23% of the study area, and it was mainly concentrated in the Qinghai–Tibet Plateau and the western edge of the Sichuan Basin, indicating that the ecological environment in these areas has been continuously improving. SD accounted for 8.85% of the study area and was mainly distributed in the Hengduan Mountains, certain areas of the Yunnan-Guizhou Plateau, and along the Yangtze River downstream, which are areas with frequent human activities and rapid urbanization. Non-SD accounted for 10.7% of the study area and was mainly distributed in Guizhou, Hunan, Jiangxi, and Hubei, where rural tourism has developed rapidly in recent years and where there is slight human interference. Non-SI accounted for 73.20% of the study area and was widely distributed in the study area, and the increase in NPP in these areas was due to the natural growth of plants.

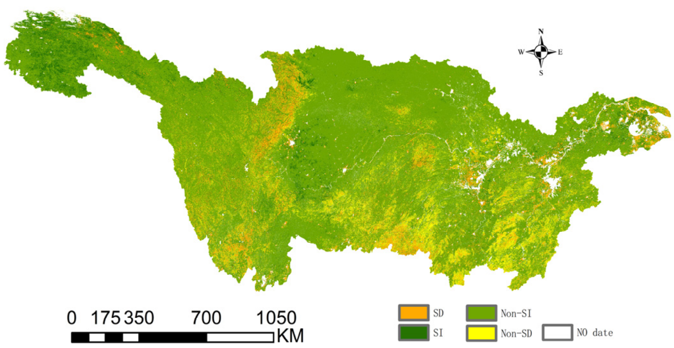

Figure 6. Significance test for trends in the Yangtze River Basin.

3.2. The Impact of Natural Factors on NPP Fluctuations

3.2.1. The Response of the NPP to Climate

Through analysis, it was found that the annual average temperature in the Yangtze River Basin between 2000 and 2020 ranged from 10.93 °C to 11.92 °C, with a multi-year average temperature of 11.45 °C, thus showing a non-significant upward trend. The annual rainfall ranged from 964.11 mm to 1208.23 mm, with a multi-year average rainfall of 1105.86 mm, which also showed a non-significant upward trend and was essentially consistent with the trend of NPP changes.

From Figure 7, it can be seen that the variation in the NPP from 2000 to 2020 was affected by both rainfall and temperature. When the temperature and rainfall are suitable for plant growth, the efficiency of photosynthesis can be improved, resulting in more carbon accumulation. For example, in 2015, the average temperature was 11.48 °C, and the rainfall was 1111.63 mm, resulting in a NPP of 1.024 Pg—the highest value in many years. However, in 2014, although the average rainfall and temperature were both in the middle range, with a rainfall of 1160.1 mm and an average temperature of 11.56 °C, the average highest temperature that year was 23.15 °C, which was significantly different from the multi-year average highest temperature of 22.44 °C (according to the T-test in SPSS23 ($p < 0.05$)). The abnormally high temperature resulted in a NPP of only 0.786 PgC, which was the lowest in many years. In 2000, when the average temperature was only 10.93 °C and the rainfall was 11.31 mm, the NPP was 0.849 PgC, which was also the second lowest in many years. According to the T-test conducted in SPSS23 ($p < 0.05$), there was a significant difference between the NPP and the multi-year average highest temperature of 11.45 °C due to the abnormally low temperature throughout the year, which led to a decrease in the NPP.

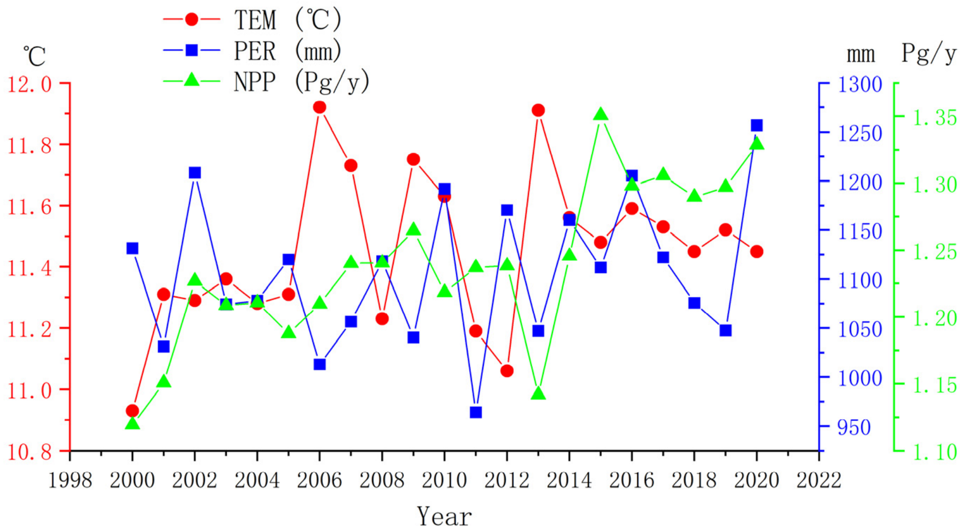

Figure 7. The NPP, rainfall, and temperature variations.

To further analyze the response of the NPP to climate, this study conducted a correlation analysis and a significance T-test to analyze the correlation between the NPP and rainfall and temperature. The correlation coefficient between the NPP and rainfall in the Yangtze River Basin from 2000 to 2020 ranged from −0.874 to 0.910, with positive correlation accounting for 51.47% of the area and negative correlation accounting for 48.53%. The significance ($p < 0.05$) T-test accounted for 51.50% of the total area, with significant positive correlation accounting for around 45.86% of the total area, and these areas were mainly concentrated in the Sichuan Basin, the middle and lower reaches of the Yangtze River, and other areas with relatively low altitudes. The significant negative correlation accounted for around 5.64% of the total area and was mainly concentrated in the southern Qinling Mountains and the Hengduan Mountains (Figure 8). When we compared the correlation coefficient between the NPP and annual rainfall with the altitude of the region, we found that there were positive and negative separation zones at altitudes of 700 m–1000 m and 4200–4700 m, respectively. The areas below a 700 m altitude, such as the middle and lower reaches of the Yangtze River and the Sichuan Basin, showed positive correlations. The eastern hilly areas—such as Wuyi Mountain and Southeast Nanling, which are at altitudes of 700 m–1000 m—showed alternating positive and negative correlations. The areas at altitudes of 1000 m–4200 m, such as the Qinghai–Tibet Plateau, Yunnan-Guizhou Plateau, and southern Qinling Mountains, showed negative correlations, while the areas at altitudes of 4200 m–4700 m showed positive correlations. When the altitude exceeded 4700 m, it showed negative correlations again, indicating that there is a certain zonal differentiation pattern at different altitudes in the Yangtze River Basin for the positive and negative correlations between the NPP and rainfall.

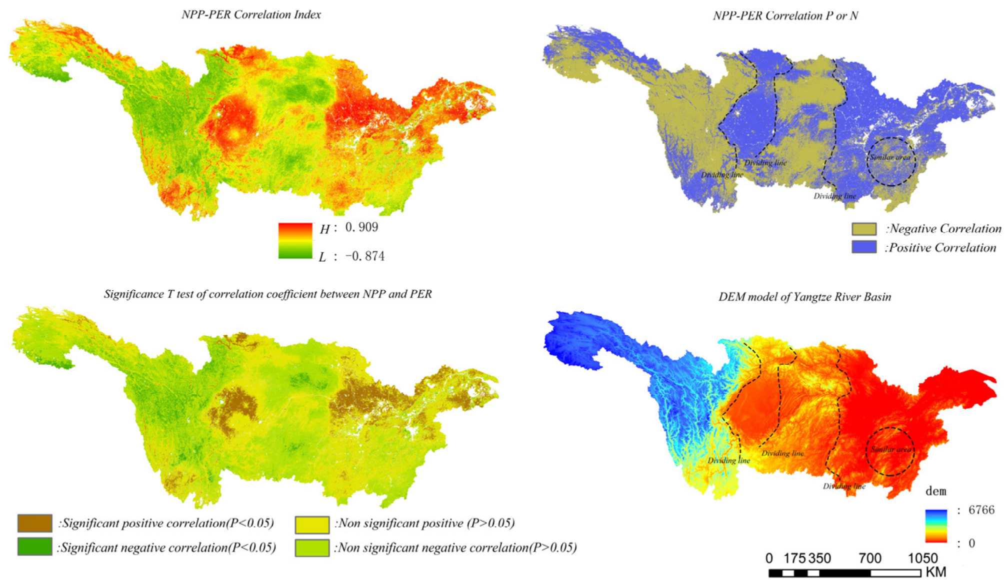

Figure 8. Analysis of the vegetation NPP and PER correlations.

The correlation coefficient between the NPP and temperature in the Yangtze River Basin from 2000 to 2020 ranged from −0.928 to 0.929, with positive correlation accounting for 55.43% of the basin area and negative correlation accounting for 44.57%. The positive correlation was mainly distributed in high-altitude areas, such as the Qinghai–Tibet Plateau, Yunnan-Guizhou Plateau, and southern Qinling Mountains (Figure 9). By comparing the positive correlation between rainfall and plant NPP, it was found that around 70% of the areas (when NPP was positively correlated with rainfall) were negatively correlated with temperature in most cases, and vice versa. This indicates that the occurrence of any extreme weather (high temperature or heavy rainfall) will affect the total amount of the NPP in the Yangtze River Basin. The proportion of significant ($p < 0.05$) *t*-tests accounted for 93.67% of the total area, with significant positive correlations accounting for around 50.68% of the total area, and these were mainly concentrated in high-altitude areas, such as the Qinghai–Tibet Plateau, Hengduan Mountains, and southern Qinling Mountains. These areas have lower temperatures throughout the year and are, therefore, more sensitive to changes in temperature. The significant negative correlations accounted for around 43.00% of the total area and were mainly concentrated in low-altitude areas, such as the Sichuan Basin and the middle and lower reaches of the Yangtze River (where the temperature is usually high, and excessively high temperatures will reduce the photosynthetic efficiency of vegetation).

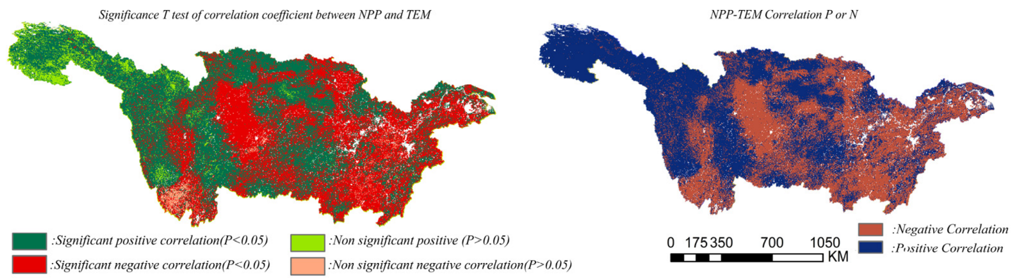

Figure 9. Analysis of the vegetation NPP and TEM correlations.

3.2.2. The Impact of Topography and Landforms on NPP

This article aims to explore the impact of elevation (ELE) changes on the NPP. A cross-sectional map of the terrain and a distribution map of the NPP were drawn along the Yangtze River (see Figure 10). The vertical zonation of geography results in significant differences in the mean NPP at different altitude levels. From Figure 10, it can be seen that the distribution of the NPP at different altitudes is significantly different, and there is a clear separation zone between the 3500 m and 4000 m altitudes. Below a 3500 m altitude, the NPP increases with increasing altitude, but when it exceeds 4000 m, the NPP decreases with increasing altitude.

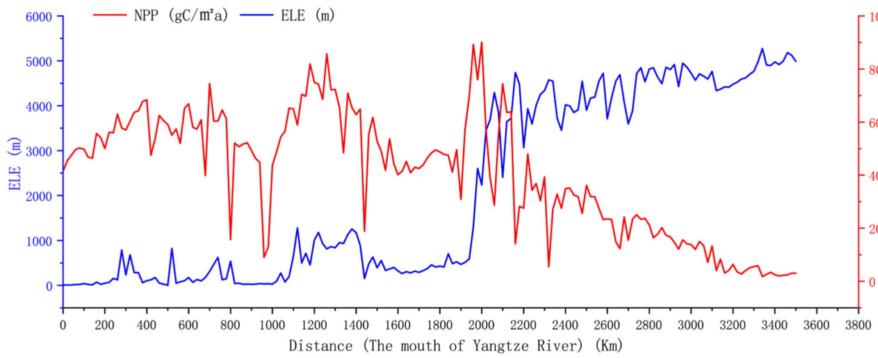

Figure 10. The variation in the NPP with topography.

Different slopes can form local microclimates and also affect surface runoff, drainage, and soil conservation. Different aspects can also affect plant illumination, further affecting plant growth [26]. Through DEM data analysis, it was found that the terrain in the study area was undulating (as shown Table 1), with a maximum slope of 67.7°. In this study, based on the actual situation of the Yangtze River Basin and the relevant literature, we first divided the slope of the Yangtze River Basin into nine levels. Slopes below 15° accounted for around 86.3% of the total area. Overall, the NPP in this region increased with increasing slopes.

Table 1. Comparison and statistical table of the NPP and slope changes.

Slope	<2	2–7	7–15	15–25	25–35	35–45	45–55	55–65	>65
NPP ($C/m^2{\cdot}a$)	421.57	525.72	560.67	578.74	602.93	601.36	596.14	612.54	613.87

3.3. The Impact of Land Change on the NPP

The impact of land use change on the NPP has two sides: on the one hand, the conversion of high-productivity land use types to low-productivity land use types, such as the conversion of forest land to construction land, resulted in NPP loss; on the other hand, the conversion of low-productivity land use types to high-productivity land use types, such as the conversion of farmland to forest land, led to an increase in the NPP.

We classified the land use data downloaded from the Chinese Academy of Sciences Resource and Environment Data Cloud Platform into six categories (farmland, woodland, grassland, water, construction land, and un-utilized land). We analyzed the land use changes in 2000, 2010, and 2020, and we visualized the NPP gains and losses caused by land use changes. The results show that, during the study period, the land use in the Yangtze River Basin was mainly composed of forest land, cropland, and grassland. However, there have been significant changes in land use types, with a total area of 355,389.25 km^2, which accounts for 19.52% of the total area of the region. The largest change occurred in the extent of cropland, which decreased by 23,295 km^2 and was mainly converted to forest land, construction land, and grassland, indicating significant achievements in the region's land reclamation and afforestation efforts. The amount of forest land converted in and out was relatively large, with a total decrease of around 4533.25 km^2, and it was mainly converted to cropland or degraded to grassland. Grassland decreased by 22,357.5 km^2, with most of it converted to cropland and forest land. The area of construction land increased from 22,552 km^2 to 55,485.75 km^2, a 1.46-fold increase. This change occurred mainly from the occupation of cropland, which accounts for 80% of the total source, followed by forest land (10.32% of the total source), while other land use types changed relatively little (as shown Figure 11).

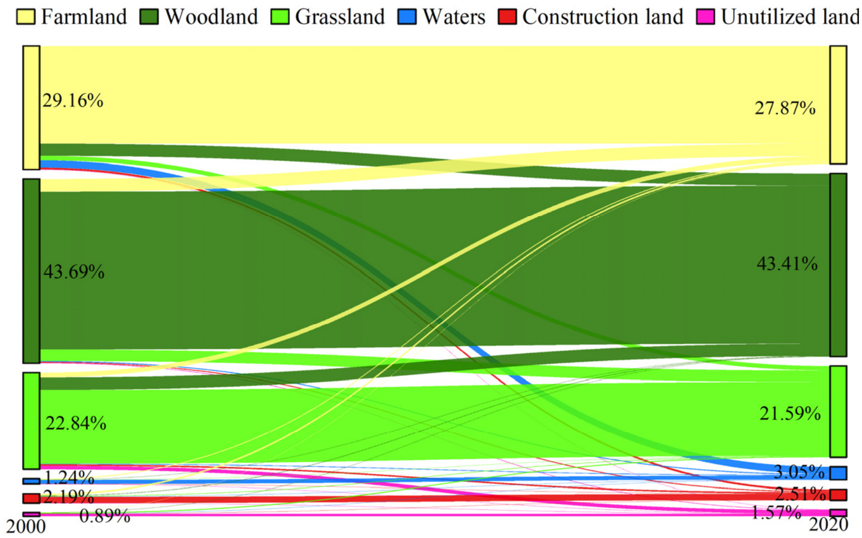

Figure 11. The land use change flow in the period from 2000 to 2020.

In terms of the NPP loss and gain caused by land use change, the NPP in 2020 increased when compared to that in 2000, but the land use change resulted in a decrease of 9.85 TgC in the NPP. Among them, the conversion of forest land to grassland led to a decrease of 15.45 TgC (1 T = 1012) in the NPP, followed by the conversion of cropland to construction land, which resulted in a decrease of 6.61 TgC in the NPP. Other changes, such as the conversion of forest land to cropland (−4.55 TgC), and the conversion of cropland to grassland (−4.31 TgC), also led to a decrease in the NPP. At the same time, certain land use changes also led to an increase in the NPP, such as the conversion of grassland to forest land, which resulted in an increase of 16.72 TgC in the NPP, which is greater than the decrease caused by the conversion of forest land to grassland. The conversion of grassland to cropland resulted in an increase of 4.69 TgC in the NPP, and the conversion of cropland to forest land resulted in an increase of 4.39 TgC in the NPP. Overall, the NPP changes caused by land use changes between non-construction land categories in the study area remained essentially stable, while the conversion of non-construction land to construction land resulted in a net decrease of 6.64 TgC in the NPP (accounting for 67.41% of the total decrease) (as shown Figure 12).

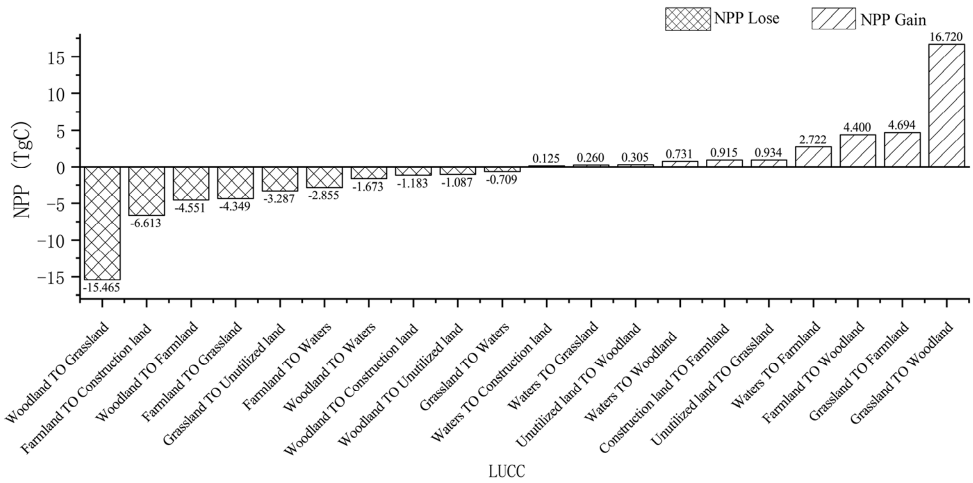

Figure 12. The NPP loss and gain caused by land use change.

After analyzing the average NPP values of different land use types in different years, it was found that the increase in the total NPP in the Yangtze River Basin was due to the increase in the average NPP values of various land use types. From Figure 13, it can be seen that, the NPP average value of construction land increased the most, from 290.84 g C/(m^2·a) to 394.38 g C/(m^2·a) (an increase of 35.60%); this was followed by cropland, with the NPP average value increasing from 488.23 g C/(m^2·a) to 607.67 g C/(m^2·a); and, next was forest land, with the NPP average value increasing from 576.53 gC/(m^2·a) to 672.61 g C/(m^2·a) (an increase of around 16.66%). The average values of other land use types, such as grassland and water areas, did not change a great deal, while the unused land showed fluctuations, but its proportion in the Yangtze River Basin was small; thus, its impact on the total NPP was limited.

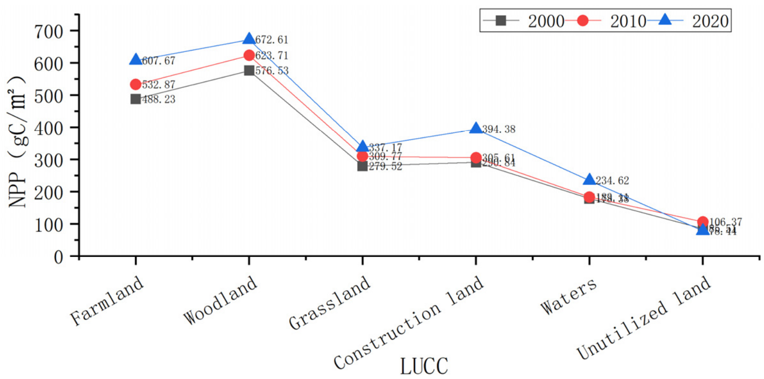

Figure 13. The annual average NPP changes in land use.

3.4. Future Trends in NPP Changes in the Yangtze River Basin

Through using the NPP data from the Yangtze River Basin from 2000 to 2020, the H value of the NPP in this region was calculated to range from 0.002 to 0.592, with a mean of 0.299, indicating a certain degree of reverse persistence in the overall future trend of this region. According to the analysis results, the reverse persistence area accounted for 99.96% of the total area, with strong reverse persistence accounting for 24.71% and weak reverse persistence accounting for 75.25%. In addition, the random areas accounted for around 0.005%, and the weak persistence areas accounted for 0.029%. In terms of the spatial distribution of the H index, the areas with strong reverse persistence were mainly divided into two categories: one is the Qinghai–Tibet Plateau, which has a high altitude and fragile ecology in the upper reaches of the Yangtze River; the other is the southern part of Hubei Province, the northern part of Hunan Province, the southern part of Anhui Province, the northern part of Jiangxi Province, Jiangsu Province, Zhejiang Province, and Shanghai City, which is where economic development is relatively fast. The weak reverse persistence areas were mainly distributed in the middle reaches of the Yangtze River, with the Sichuan Basin and Yunnan-Guizhou Plateau as the main areas. These areas have high vegetation cover throughout the year and a good ecological environment.

The results of trend analysis were overlaid with the Hurst index, resulting in 11 outcome types: a significant decrease in future anti-sustainable state (SD-Anti-S); a significant decrease in future sustainable state (SD-S); a significant increase in future anti-sustainable state (SI-Anti-S); a significant increase in future randomness state (SI-R); a significant increase in future sustainable state (SI-S); a non-significant decrease in future anti-sustainable state (Non-SD-Anti-S); a non-significant decrease in future randomness state (Non-SD-R); a non-significant decrease in future sustainable state (Non-SD-S); a non-significant increase in future anti-sustainable state (Non-SI-Anti-S); a non-significant increase in future randomness state (Non-SI-R); and a non-significant increase in future sustainable state (Non-SI-S).

From Table 2, it can be seen that the main trends in the future of this region are SD-Anti-S, SI-Anti-S, Non-SD-Anti-S, and Non-SI-Anti-S, accounting for 8.22%, 8.85%, 10.72%, and 72.17%, respectively. From a regional perspective, Non-SI-Anti-S is widely distributed in the Yangtze River Basin, which, to a certain extent, indicates that the future changes in the NPP of the Yangtze River Basin may decrease. In the Hengduan Mountains, Yunnan-Guizhou Plateau, and Wuling Mountains, Non-SD-Anti-S and SD-Anti-S alternate, indicating that, although the current vegetation in these areas is good, NPP has decreased due to local climate and human factors (Figure 14). These areas should be a focus of attention for the government in the future as they also have the potential for NPP growth in the Yangtze River Basin. SI-S was concentrated in the Qinghai–Tibet Plateau and the headwaters of the Yangtze River, indicating that the policies and related projects of the Chinese government for the protection of the headwaters of the Yangtze River are continuing to play a role. At the same time, our study noted that the SI-S areas within this region only accounted for 0.004% of the total area.

Table 2. Future trends of the NPP.

Result	SD-Anti-S	SD-S-R	SI-Anti-S	SD-R	SI-S	Non-SD-Anti-S	Non-SD-R	Non-SD-S	Non-SI-Anti-S	Non-SI-R	Non-SI-S
Proportion	8.22390%	0.00260%	8.84720%	0.00010%	0.00410%	10.72360%	0.00005%	0.00250%	72.17410%	0.00020%	0.02170%

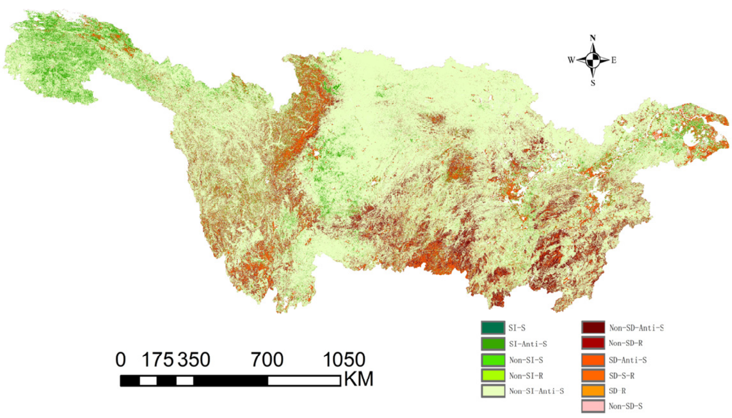

Figure 14. The future change trend and significance test of the NPP in the Yangtze River Basin.

4. Discussion

4.1. The Increase in the Average NPP Values of Land Use Types Is the Main Reason for the Increase in Total NPP in the Yangtze River Basin

Based on the MODIS 17A13 product NPP data, it was found that the plant NPP in the Yangtze River Basin showed an upward trend from 2000 to 2020, with 77.90% of the area in the Yangtze River Basin showing an increase in NPP. This study's conclusion is consistent with the research results of Wang J.Y. and others [27,28].

The main reasons for the increase in the NPP in the Yangtze River Basin may come from the following aspects. (1) The increase is mainly due to the long-term implementation of policies, such as returning farmland to forests, afforestation, and nature reserve construction by the Chinese government, which has allowed most forests to grow naturally. As the trees gradually grow, their carbon sequestration capacity increases. Luo, Q.L., and others have come to the same conclusion in their studies on the impact of policy implementation on the local ecosystem service systems in the Yangtze River Economic Belt [29]. (2) Cities in the Yangtze River Basin have increased their green areas for improving the living environment, leading to an increase in the average NPP of construction land. (3) In the past 20 years, China's investment in agriculture has led to a continuous application of agricultural technology in production, resulting in increased agricultural production. The official data on agricultural production in China confirms this conclusion (China's agricultural GDP was CNY 1.39 trillion in 2000 and CNY 7.17 trillion in 2020). Lin B.Q. and others have reached similar conclusions in their analysis of certain elements and technological progress in Chinese agriculture [30]. It is worth noting that over 70% of the NPP in the Yangtze River Basin is increasing, but it is currently in an unsustainable state for the future. However, the NPP will not always show a continuous increase. When the NPP reaches a certain value, it will fluctuate. It also reflects the greater environmental protection pressure in the region in the future. The Chinese government should continue to strengthen its investment in the region and should maintain the continuity of environmental protection policies.

4.2. The Spatial Distribution of NPP Is Affected by Changes in Latitude and Altitude

The NPP in the Yangtze River Basin gradually decreases from north to south, and this is mainly due to the climate change caused by changes in latitude. The Yangtze River Basin is mainly of a subtropical and temperate climate. As latitude decreases, the angle of solar radiation increases, providing better sunlight conditions for plants. As latitude increases, the angle of solar radiation decreases. The NPP is highest in the Hengduan Mountains due to good water and heat conditions, high vegetation coverage, and the area being mainly forest land, resulting in high photosynthetic efficiency in these areas [31,32]. From east to west, the overall pattern shows an increase and then a decrease, and this is mainly due to changes in terrain. In low-altitude areas, as altitude increases, rainfall gradually increases, and temperature gradually decreases, providing a suitable ecological environment for plant growth in this altitude range. At the same time, the low-altitude areas are mainly cultivated land and construction land, which are greatly affected by human interference. With increasing altitude, forest land increases, human interference decreases, and plant productivity increases. However, when the altitude exceeds a certain threshold, the natural environment gradually becomes harsher, and it is mainly characterized by low temperature and low rainfall. These areas are usually no longer suitable for plant growth, and vegetation productivity decreases due to sparse vegetation. This view is confirmed in the study by Cheng S.S. and others on the impact of terrain on human activities and on the NPP in the Yangtze River Basin [33].

4.3. Rainfall and Temperature Jointly Affect Changes in NPP

Climate factors are one of the important factors affecting vegetation, playing an important role in the spatiotemporal dynamic pattern and distribution of forest productivity. Suitable temperature and rainfall can promote plant growth, but excessive (or insufficient) temperature and rainfall can inhibit the photosynthesis of vegetation and can reduce the accumulation of NPP. For example, high temperatures can enhance vegetation respiration, leading to excessive carbon consumption and plant stomata closure, thereby reducing the photosynthesis of the vegetation [34,35]. The positive correlation between the NPP and temperature and precipitation in the Yangtze River Basin was greater than the negative correlation, indicating that the NPP in the Yangtze River Basin is, in the main, positively correlated with temperature and precipitation, which is consistent with the research results of GAO Y.H. and others [36,37]. In addition, the average absolute value of the correlation coefficient between the NPP and temperature in the Yangtze River Basin and the regions that passed the significance test are both greater than that of precipitation, indicating that temperature is the main temperature factor affecting vegetation growth in the Yangtze River Basin. Studies have shown that droughts under climate warming may lead to a decrease in the NPP, especially in high-temperature areas, which can explain why there is a negative correlation between certain areas in the Yangtze River Basin and temperature and rainfall [38,39].

4.4. Human Activities Are the Main Cause of Local NPP Reduction

Land use change is the most direct manifestation of human activity interferences with the natural environment. Overall, human activities have a negative impact on the NPP in the Yangtze River Basin, which is consistent with the research by Xie C.H. and others on the correlation between human activities and NPP [40]. The main trend of the land use change in the study area was the transfer from land use types with higher NPP to those with lower NPP, resulting in a loss of NPP. This loss is the main reason for the NPP loss caused by human activities. Even in cases where land use types remain unchanged, even slight human activities can also cause fluctuations in the total NPP in the region. These regions are mainly located in the Wuling Mountains and Yunnan-Guizhou Plateau, which share a common characteristic of being economically underdeveloped, but they have recently experienced rapid development in rural tourism and nature-based recreation. The construction of tourism infrastructure and the influx of a large number of people into the natural environment have caused fluctuations in the NPP [41,42]. Of course, certain human activities have also led to an increase in the NPP, such as tree planting in cities, agricultural production, and ecological restoration.

4.5. Limitations and Future Work

Although this article has conducted basic research on the changing characteristics, influencing factors, and future trends of the Yangtze River Basin, it still has certain limitations. First, the explanatory power of each factor on NPP changes in terms of interaction has not yet been quantitatively analyzed. Second, the selection of influencing indicators could be more comprehensive, such as adding wind speed, extreme weather, and other climate impacts, increasing nighttime lighting for human activities, and other factors that may affect NPP changes, such as carbon dioxide concentration and soil fertility. These could provide a more comprehensive analysis of the reasons for NPP changes in the Yangtze River Basin. Finally, this study only analyzed the future trends of NPP changes, without predicting the total amount of future NPP or simulating its spatial distribution, which is an important direction for future research. Furthermore, building upon current research, it is imperative to establish a robust foundation for future governmental directives pertaining to ecological conservation, particularly in regions where growth is currently observed but anti-sustainability in future.

5. Conclusions

5.1. The Vegetation Productivity Level in the Yangtze River Basin Is Generally High, with an Overall Upward Trend in the NPP and Significant Interannual Fluctuations

The total NPP ranges from 0.786 PgC to 1.024 PgC, with a multi-year average of 0.932 PgC. The annual average NPP ranges from 431.31 gC/(m^2·a) to 561.69 gC/(m^2·a), with a multi-year average of 511.75 gC/(m^2·a). The NPP has gone through four stages: an upward stage, a fluctuating upward stage, a sharp decline, and a fluctuating upward stage again.

5.2. The Average NPP in Different Regions of the Yangtze River Basin Ranges from 0 to 1902.89 gC/(m^2·a), with Significant Spatial Differences

The overall pattern shows a high-south and low-north trend, with high values in the central region and low values in the east and west (which are caused by changes in latitude and altitude). The main high-value areas are located in the Hengduan Mountains and the Yunnan-Guizhou Plateau. The coefficient of variation (CV) ranges from 0.0009 to 0.9980, indicating significant spatial variability, with a mean CV of 0.1126 (which is relatively stable overall). In terms of future development trends, regions with increasing and decreasing NPP account for 77.90% and 22.10% of the area, respectively. At the same time, 75.25% of the regions show a reverse persistent state, and only 0.0041% of the regions show a significant and sustained increase in the future.

5.3. The Correlation Coefficient between the NPP and Precipitation in the Yangtze River Basin Ranged from −0.874 to 0.910, with a Ratio of Positive and Negative Correlations of 51.47% and 48.53%, Respectively

The correlation between the precipitation and NPP is related to altitude, and it showed a certain inter-belt distribution pattern with changes in altitude. The correlation coefficient between the NPP and temperature ranged from −0.928 to 0.929, with a ratio of positive and negative correlations of 55.43% and 44.57%, respectively. Regions with low annual temperatures were more sensitive to temperature changes. The correlation between temperature and the NPP was also related to precipitation, with around 70% of the regions showing a negative correlation with temperature while being positively correlated with precipitation, and vice versa.

5.4. Human Activities Have a Negative Impact on the NPP

The area of land use change in 2020 compared to 2000 was 355,389.25 km^2, with the largest decrease being in cultivated land, which decreased by about 23,295 km^2. The largest increase was in construction land, which increased by about 32,933.75 km^2. Land use change resulted in a loss of NPP of about 9.85 TgC. The overall increase in NPP was due to an increase in the average NPP of the land use types, with the largest contribution coming from an increase in the average NPP of construction land from 290.84 gC/(m^2·a) to 394.38 gC/m^2·a. This was followed by an increase in the average NPP of forest land from 576.53 gC/(m^2·a) to 672.61 gC/(m^2·a), and then an increase in the average NPP of cultivated land from 488.23 gC/(m^2·a) to 607.67 gC/(m^2·a).

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