Journal of Animal & Plant Sciences, 34(3): 2024, Page: 747-755
ISSN (print): 1018-7081; ISSN (online): 2309-8694
https://doi.org/10.36899/JAPS.2024.3.0761

DISTRIBUTION AND VARIATION OF NET PRIMARY PRODUCTIVITY IN FORESTLAND AND GRASSLAND OF CHINA

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ABSTRACT

Net primary productivity (NPP) can characterize the state and service functions of terrestrial ecosystems and reflect the responses of plants to climate fluctuations and human disturbances. Many studies have analysed changes in NPP and its influencing factors in some parts of China, but few studies have made in-depth comparisons between different regions, decades, and land cover types across China. Based on uniform NPP products and land cover data, the distribution, difference and variation of NPP in forestland and grassland in China were investigated with GIS spatial analysis and least-squares regression methods, and results indicated that average NPP increased gradually from northwest to southeast, and the regions with average NPP of 1-200 gC m^{-2} yr^{-1} occupied the largest proportion. During 1981–2018, the regions where decadal average NPP increased were larger than those where NPP decreased, and the areas with inter-decadal difference of 1-50 gC m^{-2} yr^{-1} were the largest. In different land cover types or regions, NPP generally exhibited a rapid rising trend in the 1990s and a slow or declining trend in the 2000s. Annual NPP increased at a rate of 13.2 gC m^{-2} $decade^{-1}$ in the entire study area during 1981–2018, and the NPP in forestland and grassland increased at a speed of 15.6 and 11.1 gC m^{-2} $decade^{-1}$, respectively. Spatially, NPP increased at a rate of 1-100 gC m^{-2} $decade^{-1}$ in most areas, and the increasing trend was statistically significant in Qinghai-Tibetan Plateau, most of Northwest China and eastern Northeast China. The area with a significant increase in NPP over the past 38 years accounted for 21.0% of the total study area. Our results highlight the consistent and upward variation of NPP in general, but there are some distinctions among different land cover types and different regions of China, and higher quality datasets and more reliable methods should be fully explored in further studies.

Keywords: Net primary productivity, spatial distribution, linear trend, forestland and grassland, China.

Published first online March 27, 2024 Published final May 31, 2024

INTRODUCTION

During the 20th century, the Earth's climate has experienced major changes characterized primarily by global warming (IPCC, 2021). Climate change is of great concern because of its significant impacts on global economy, natural ecosystems, and human health (Zhang *et al*., 2020). Net primary productivity (NPP) is the amount of organic matter produced by green plants through photosynthesis after deducting autotrophic respiration (organic matter consumed by plants to maintain their own survival and growth). It can indicate the ecosystem service capability and reflect the response of plants to a variety of biological and abiotic factors, including climate change, soil erosion and production practices (Liu *et al*., 2017; Ye *et al*., 2019; Yang *et al*., 2021), among which climate has strong and profound direct and indirect effects on vegetation productivity in ecosystems worldwide (Chu *et al*., 2016; Ye *et al*., 2019).

Located in the southeast of Eurasia, China is a world-renowned East Asian monsoon climate zone (Shi and Cui, 2021). The advance and retreat time of winter/summer monsoon and the amount of precipitation have significant effects on vegetation NPP. Some studies have investigated the distribution and dynamics of NPP, for example, Guo *et al*. (2021) found that NPP in urban areas of Beijing–Tianjin–Hebei region was the lowest, and during 2005–2015, the NPP losses were the greatest in the peripheral areas, rather than the most urbanized city center. Ge *et al*. (2021) investigated the contributions of anthropogenic activities and climate change to NPP in China and showed that NPP increased significantly at a pace of 3.13 gC m^{-2} yr^{-1} during 2001–2016, and the contribution of climate to the change of NPP increased from 1.57 gC m^{-2} yr^{-1} to 1.88 gC m^{-2} yr^{-1}.

However, to the best of our knowledge, most of the previous studies centered upon the changes and influencing factors of NPP in some areas of China (Cui *et al*., 2016; Ye *et al*., 2019; Guo *et al*., 2021; Yang *et al*., 2021), and few studies have used uniform data to look at NPP across China and make in-depth comparisons. Meanwhile, as the most important natural vegetation in China, forests and grasslands have made remarkable achievements along with China's ecological civilization construction in recent decades (Chen *et al*., 2019; Niu *et al*., 2022; Liu *et al*., 2022). But there are few studies specifically focusing on NPP of China's forestland and grassland (Liu *et al*., 2021; Shi *et al*., 2022). Therefore, the purpose of this paper is to investigate the changes and spatiotemporal differences of NPP in forestland and grassland across China. We assumed that the changes of NPP showed a consistent and increasing trend in the whole forestland and grassland of China, but there were obvious differences among different regions, different land cover types and different decades.

MATERIALS AND METHODS

Net primary productivity data: Net primary productivity (NPP) products from improved MuSyQ-NPP model (Cui *et al*., 2016) at 0.05-deg (approximately 5 km) resolution in TIFF format from 1981 to 2018 were used. With a time resolution of 8 days and geographic latitude/longitude projected information, these data obtained from National Earth System Science Data Center (http://www.geodata.cn). In MuSyQ-NPP model, daily NPP products were estimated using the fraction of photosynthetically active radiation absorbed by canopy (FPAR) through light use efficiency model and the leaf area index obtained from Global Land Surface Satellite (Cui *et al*., 2016; Yu *et al*., 2018), as well as ERA-Interim meteorological data.

Land cover data: Land cover data with 100 m spatial resolution in 1990, 2000, 2010 and 2020 were used to extract forestland and grassland in China during 1981–2018. Based on remote sensing images such as Landsat TM/ETM and Landsat 8 and geographic knowledge, these data were retrieved and updated through human-computer interaction methods (Liu *et al*., 2003; 2014), including forestland, cropland, grassland, construction land, water area and unused land, a total of 6 types and 25 subtypes. In this paper, the areas that have always been forestland or grassland in the above four periods are selected as study area (Fig. 1), and the area of selected forestland and grassland was 178.65×10^4 and 210.06×10^4 square kilometers, respectively.

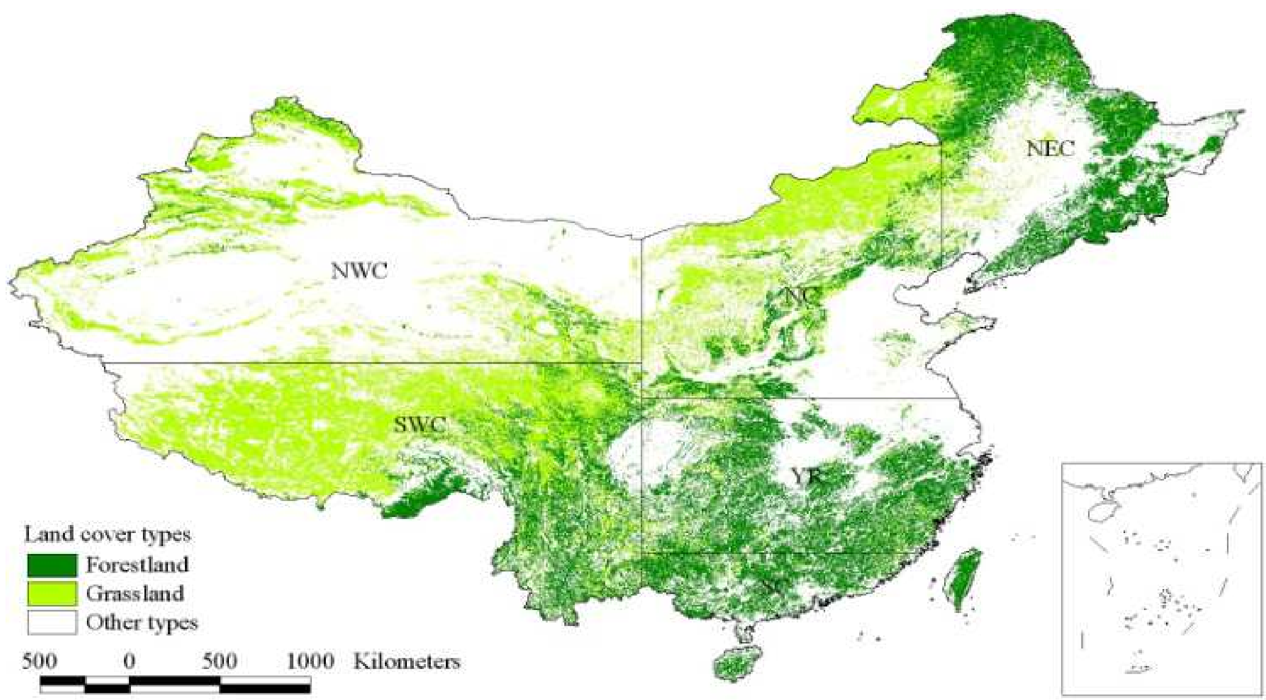


Figure 1. The study area (including forestland and grassland) and the spatial distribution of six regions of China

Processing and calculation of NPP data: The NPP products were firstly converted from TIFF to Grid format in ArcGIS 10.3 software (ESRI, 2015), and then the grid-based annual NPP was obtained by daily NPP accumulation. According to the spatial distribution of selected forestland and grassland in China (Fig. 1), the annual NPP values in forestland and grassland, and annual NPP values in each land cover type (forestland or grassland) were extracted with mask processing in ArcGIS 10.3. For analyzing the temporal variation or difference of NPP in the whole study area and each land cover type, a simple arithmetic average method based on grid number was used to calculate the average values of NPP in the corresponding area. Annual NPP in four periods, i.e. from 1981 to 1990 (1980s), from 1991 to 2000 (1990s), from 2001 to 2010 (2000s) and from 2011 to 2018 (2010s), were calculated by arithmetic average method, and the differences between the two periods were also calculated.

China was divided into six regions according to its physical geographical characteristics and climatic distribution (Cui *et al*., 2018; Shi and Cui, 2021), i.e. Northwest China (NWC), North China (NC), Northeast China (NEC), Southwest China (SWC), Mid-lower Yangtze River valley (YR) and South China (SC), which was shown in Figure 1. In order to analyze the difference of NPP in different regions of China, a simple arithmetic average method was used to calculate the regional-averaged values of six regions in China based on the number of grids.

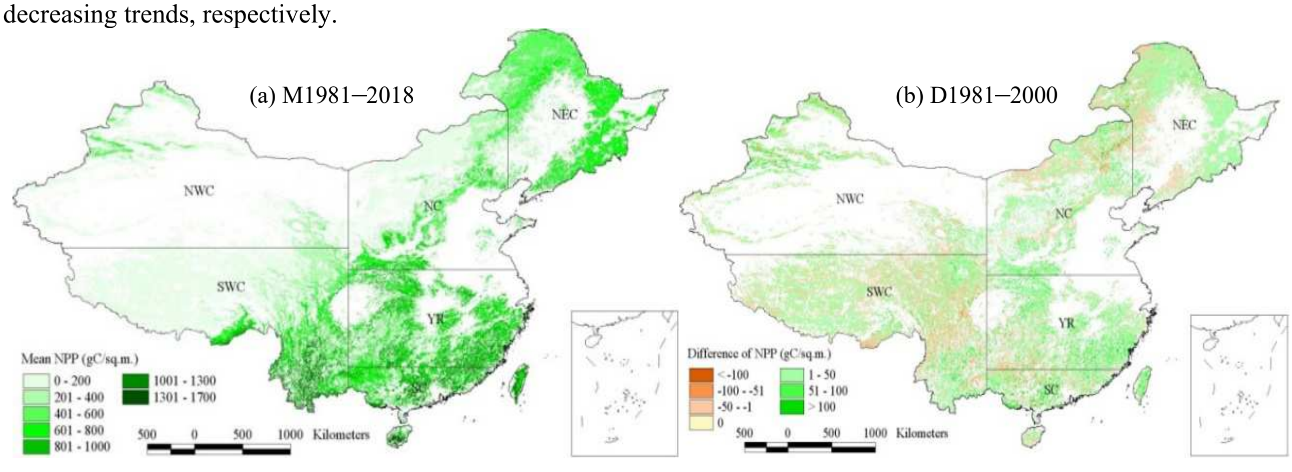
Analysis of distribution and variation of NPP: Based on annual NPP values in selected forestland and grassland of China from 1981 to 2018, the spatio-temporal distribution and variation of average NPP, including the spatial distribution of multi-year NPP averages, the inter-decadal difference, inter-annual variation and linear regression trend of forestland and grassland in China as a whole were analyzed. Different from the past, this paper also analyzed the temporal and spatial pattern, change and inter-decadal difference of NPP in two land cover types and six regions of China respectively.

Linear trends based on least-square fitting were commonly applied to explore possible changes of long-term data (Cui *et al*., 2018; Cui and Shi, 2021). The variation trend of NPP was calculated by using the least-squares regression method for each pixel, the whole study area, different types of land cover and six regions of China, and statistical significance was evaluated with a two-tailed t test. Here linear regression coefficient (slope) reflected the trend and magnitude of change. For NPP, the positive and negative values indicated increasing and decreasing trends, respectively.

RESULTS

Spatial distribution of average annual NPP: NPP in forestland and grassland in China increased gradually from northwest to southeast (Fig. 2a). Among them, the annual averaged NPP was higher in southern China, and NPP in most areas was above 600 gC m^{-2} yr^{-1}. The hydrothermal conditions in these areas are better, the proportion of forest vegetation is larger, and the vegetation coverage is higher. The annual averaged NPP in most areas of northwestern China was less than 400 gC m^{-2} yr^{-1}. The vegetation types in these areas are mainly desert and grassland, and vegetation growth is restricted by precipitation. The averaged NPP values in North China (NC) and Northeast China (NEC) were mainly between 200-800 gC m^{-2} yr^{-1}.

In forestland and grassland of China, areas with average NPP of 1-200 gC m^{-2} yr^{-1} accounted for the largest proportion (36.18%), followed by those with average NPP of 201-600 (31.75%) and 601-1000 (27.51%) gC m^{-2} yr^{-1}, and areas with NPP values of 1001-1700 gC m^{-2} yr^{-1} were the smallest (3.77%). However, the distribution of NPP was different in different land cover types and regions (Table 1). For forestland, areas with an average annual NPP of 601-1000 gC m^{-2} yr^{-1} accounted for the largest corporation, and those with averaged NPP of 1-200 gC m^{-2} yr^{-1} were the least. For grassland, the areas with average annual NPP values of 1-200 gC m^{-2} yr^{-1} were the most, and those with annual NPP of 1001-1700 gC m^{-2} yr^{-1} were the least. In six regions, the distribution of NPP was also different. In NEC and Mid-lower Yangtze River valley (YR), annual NPP of 201-1000 gC m^{-2} yr^{-1} occupied the majority, while in Northwest China (NWC), NC and Southwest China (SWC), NPP of 1-600 gC m^{-2} yr^{-1} was in most study areas, due to the large proportion of grassland. In South China (SC), annual NPP of 601-1000 gC m^{-2} yr^{-1} accounted for the largest area, followed by those with NPP of 1001-1700 gC m^{-2} yr^{-1}.



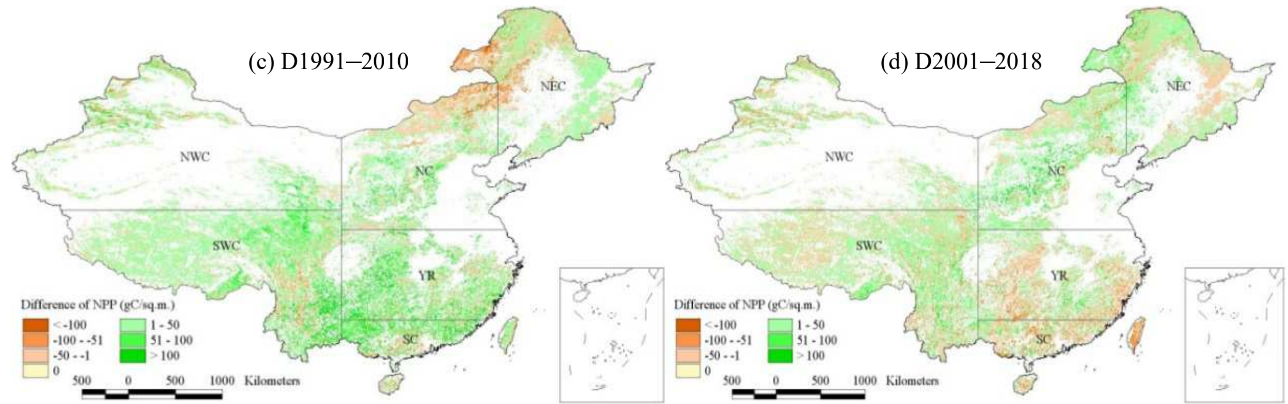


Figure 2. Spatial distribution of average annual NPP (a) and the decadal differences (b, c, d) in forestland and grassland in China

(D1981–2000: the average annual NPP in the 1990s minus that in the 1980s; D1991–2010: the average annual NPP in the 2000s minus that in the 1990s; D2001–2018: the average annual NPP in the 2010s minus that in the 2000s)

Table 1. The area percentage of different NPP intervals in forestland and grassland in China (Units: %).

Land cover types or regions		Average annual NPP intervals (gC m^{-2} yr^{-1})			
		1-200	201-600	601-1000	1001-1700
Land cover types	Forestland (FL)	5.35	36.00	51.24	7.29
	Grassland (GL)	62.41	26.95	7.34	0.77
Regions	Northwest China (NWC)	68.62	26.75	0.80	0.01
	North China (NC)	40.29	43.51	15.24	0.01
	Northeast China (NEC)	3.95	58.66	37.29	0.01
	Southwest China (SWC)	60.76	19.48	14.48	4.95
	Mid-lower Yangtze River valley (YR)	0.81	27.55	67.88	3.67
	South China (SC)	0.97	11.85	61.80	25.17

Decadal difference of average annual NPP: During 1981–2000, the change (increase or decrease) of NPP was generally small, mostly between -50 and 50 gC m^{-2} yr^{-1} (Fig. 2b). Among them, NPP increased mainly in northern and eastern NEC, southwestern NC, northern NWC, northern and southeastern YR and Taiwan. During 1991–2010, NPP increased in eastern NEC, western NC, most areas of YR and SWC, and northern SC, while NPP decreased in western NEC and northern NC, moreover, the increase or decrease of NPP was larger, ranging from -100 to 100 gC m^{-2} yr^{-1} in most areas (Fig. 2c). Between 2001 and 2018, the areas where NPP increased were larger than those NPP decreased, and the values were also greater, between -50 and 100 gC m^{-2} yr^{-1} in most regions (Fig. 2d). The NPP increase occurred mainly in western and northern NEC, most NC and some parts of eastern SWC. Meanwhile, NPP decreased in most areas of YR and SC, southern SWC and some areas of Qinghai-Tibet Plateau.

The statistical analysis showed that in the four decades, the areas where NPP increased were larger than those NPP decreased, and the areas of NPP increased by 1-50 gC m^{-2} yr^{-1} were the largest (Fig. 3). Compared with those in 1980s, 1990s and 2000s, the areas where NPP increased in the 1990s, 1990s and 2010s were 66.2%, 68.9% and 56.1% of the study area, and the areas where NPP decreased were 30.3%, 28.8% and 40.6%, respectively. In all three periods of 1980s–1990s, 1990s–2000s and 2000s–2010s, the areas where NPP increased by 1-50 gC m^{-2} yr^{-1} were the largest, which was 56.2%, 49.4% and 46.3% of the entire study area, respectively. This was followed by a NPP decrease of 1-50 gC m^{-2} yr^{-1}, which was 28.0%, 23.0% and 33.6%, respectively. In the last two decades of the last century, the areas where NPP increased had increased, while in this century, the areas where NPP decreased had increased.

Inter-annual variation of regional-averaged NPP: Prominent change of regional-averaged NPP was observed in forestland and grassland of China (Fig. 4). The NPP increased significantly in the entire study area at a rate of 13.2 gC m^{-2} $decade^{-1}$ during 1981–2018. It did not change significantly during 1981–1990 but increased rapidly during 1991–2018 at a speed of 13.2 gC m^{-2} $decade^{-1}$ (r = 0.84, P < 0.001). During 1981–2018, NPP in forestland and grassland increased significantly at rates of 15.6 and 11.1 gC m^{-2} $decade^{-1}$, respectively, but the inter-annual characteristics were different. Forestland NPP increased slightly during 1981–1990 but increased rapidly during 1991–2005 at a rate of 32.0 gC m^{-2} $decade^{-1}$ (r = 0.79, P < 0.001). From 2006 to 2018, forestland NPP decreased slightly. Grassland NPP changed non-significantly during 1981–1990 but increased rapidly during 1991–2018 with a speed of 12.4 gC m^{-2} $decade^{-1}$ (r = 0.86, P < 0.001).

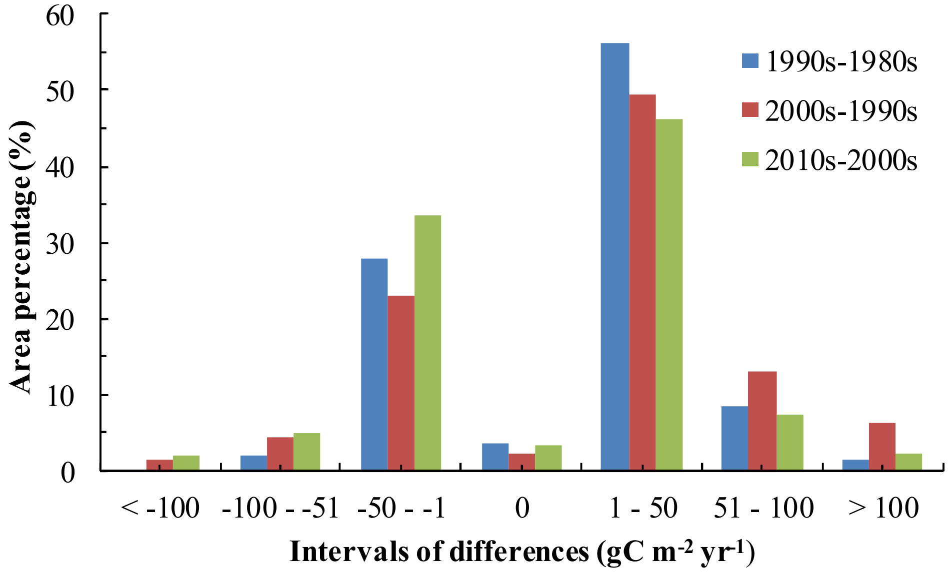


Figure 3. The proportion of decadal differences of averaged NPP in forestland and grassland in China from 1980s to 2010s
(1980s: 1981–1990; 1990s: 1991–2000; 2000s: 2001–2010; 2010s: 2011–2018)

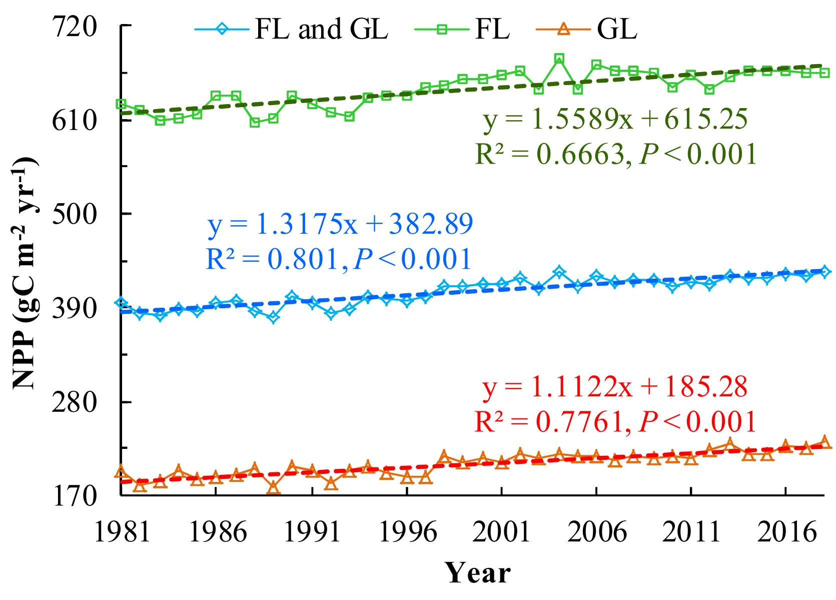


Figure 4. Inter-annual variation of NPP in forestland and grassland in China
(The thick, square dotted lines are linear trends estimated by least-squares regression)

Spatial trend and regional difference in NPP: During 1981–2018, NPP increased with a speed of 1-100 gC m^{-2} $decade^{-1}$ in most areas of forestland and grassland in China (Fig. 5a), and in Qinghai-Tibetan Plateau, the eastern and northern NEC, western NC and most areas of NWC, the increasing trend was statistically significant (Fig. 5b). In the northwestern NEC, northern NC, and some areas of SWC, Hainan and Taiwan, NPP decreased at a speed of 1-50 gC m^{-2} $decade^{-1}$, and the trend was statistically significant in northern NC and some areas of western NEC. In terms of regional average, NPP increased significantly in the five regions except NEC from 1981 to 2018, with the trend values of 11.6, 14.7, 12.0, 24.4 and 19.5 gC m^{-2} $decade^{-1}$ in NWC, NC, SWC, YR and SC, respectively (Fig. 5c1-c6). In NC, NWC and SWC, NPP continued to increase during 1981–2018, while in YR and SC, NPP increased before 2004, and then decreased.

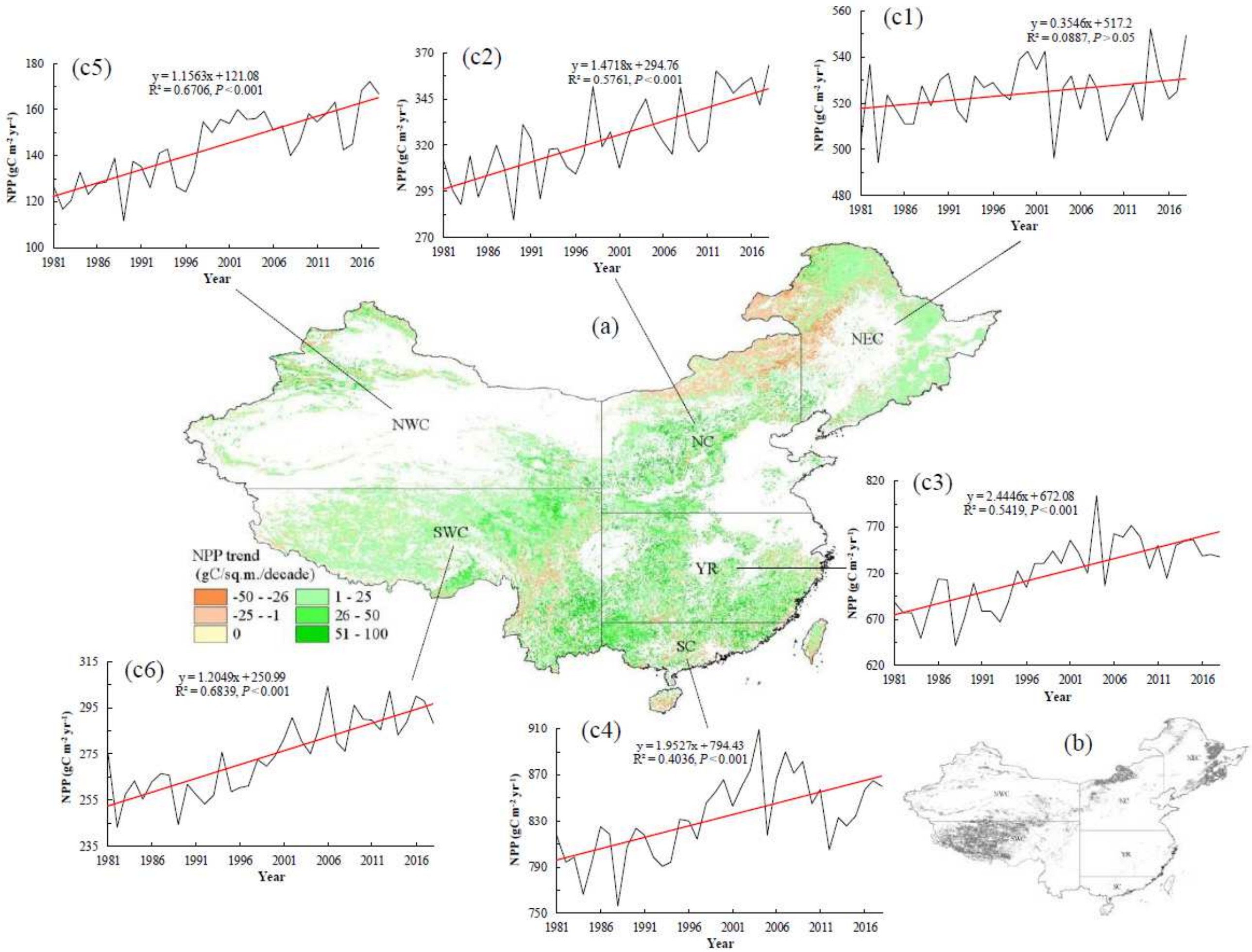


Figure 5. Spatial trend of NPP (a), regions passing the significance test at the 0.05 level (b) and the inter-annual variation of NPP in different regions (c1-c6) in forestland and grassland in China during 1981–2018

The variations of NPP were different in different periods. NPP increased in the entire study area at a rate of 6.5, 31.8 and 15.9 gC m^{-2} $decade^{-1}$ respectively, in the 1980s, 1990s and 2010s, and decreased in the 2000s at a speed of 0.4 gC m^{-2} $decade^{-1}$. The trends were significant in the 1990s ($P < 0.001$) and 2010s ($P < 0.01$). In different land cover types or regions, NPP generally showed a rapid increasing trend in the 1990s, but a slow or declining trend in the 2000s (Table 2). In the 1990s, NPP increased significantly in forestland, grassland and in most regions, especially in forestland, the YR and SC, NPP increased at a rate of 45.8, 82.0 and 70.6 gC m^{-2} $decade^{-1}$, respectively, and the trends were all significant at the 0.001 level. In the other three periods (1980s, 2000s and 2010s), NPP trends in different land cover types and regions were not statistically significant.

There were 75.2% of the entire study area where NPP increased, and 21.0% of the total study area where NPP increased significantly in forestland and grassland of China. The proportion of area with NPP reduction and significant reduction was 18.3% and 2.7% respectively. In forestland, the areas where NPP increased were much larger than those where NPP decreased (77.8% vs. 19.2% of forestland area), and there were 10.8% of the forestland area with significant increase of NPP (Table 3). In 72.9% of grassland area, NPP increased, of which 29.8% of grassland area NPP increased significantly. The proportion of area with NPP reduction and significant reduction was 17.6% and 4.2% of the grassland area respectively.

Table 2. Trends and significances of decadal NPP in forestland and grassland in China during 1981–2018.

Land cover types or regions		NPP trends (gC m^{-2} decade^{-1})			
		1980s	1990s	2000s	2010s
Land cover types	FL	7.222	45.823***	-1.428	16.018
	GL	5.802	19.865*	0.503	15.869
Regions	NWC	8.963	23.620*	-9.142	20.518
	NC	11.134	23.537	3.668	25.443
	NEC	14.265	16.452	-18.66	24.143
	SWC	-3.24	18.099*	7.799	6.325
	YR	11.766	82.000***	1.455	0.528
	SC	7.717	70.552***	9.583	47.817

***Trend is significant at the 0.001 level; *Trend is significant at the 0.05 level.

Table 3. The area percentage of different trends and significances for NPP in forestland and grassland in China (Units: %).

Land cover types or regions		Negative trend		Positive trend	
		Total	Sig	Total	Sig
Land cover types	FL	19.22	1.01	77.79	10.79
	GL	17.56	4.18	72.94	29.77
Regions	NWC	13.03	3.17	75.22	28.58
	NC	28.57	8.28	65.13	9.11
	NEC	29.19	2.11	66.52	26.22
	SWC	11.03	1.69	80.44	33.91
	YR	12.84	0.13	85.06	0.61
	SC	23.54	0.73	74.38	0.51

Sig: Trend is significant at the 0.05 level.

In six regions of China, NPP increased in more areas than NPP decreased (Table 3). The areas where NPP increased were ranged from 65.1% to 85.1% of the entire study area, while those where NPP decreased were between 11.0% and 29.2%. The areas of NPP decreased significantly were also smaller than those where NPP increased significantly. In NC, the areas of NPP decreased significantly were the largest (8.3%), while those with significant increase of NPP were the largest (33.9%) in SWC. In YR and SC, the proportion of areas with significant increase or decrease of NPP was smaller.

DISCUSSION

Net primary production (NPP) has important values for evaluating the carrying capacity of terrestrial ecosystems and understanding the carbon cycle (Liang *et al*., 2015; Liu *et al*., 2017). Average annual NPP in forestland and grassland in China presented obvious regional differences and increased gradually from northwest to southeast (Fig. 2a), which was basically in agreement with previous studies (Liang *et al*., 2015; Liu *et al*., 2017). For instance, Liang *et al*. (2015) indicated that average NPP in China showed a gradient increasing from the northwest to the southeast, which was mainly due to the spatial variability of annual rainfall. Shi *et al*. (2022) showed that NPP in China presented a spatial pattern of lower in the northwest and higher in the southeast from 2001 to 2020. Tu *et al*. (2023) indicated that the average NPP in China was lower in the north and higher in the south, increasing gradually from northwest to southeast.

In the entire study area, NPP increased with a speed of 13.2 gC m^{-2} decade^{-1} during 1981–2018 (Fig. 4), however, the change of NPP was different in different land cover types and different regions of China. In forestland and grassland, NPP increased at a rate of 15.6 and 11.1 gC m^{-2} decade^{-1}, respectively (Fig. 4). Spatially, although NPP increased at a speed of 1-100 gC m^{-2} decade^{-1} in most areas, it decreased at a speed of 1-50 gC m^{-2} decade^{-1} in the northwestern NEC, northern NC, and some areas of SWC, Hainan and Taiwan (Fig. 5a). Previous studies also showed that NPP in China was generally on the rise in recent years, but the regional differences were obvious. For example, Liu *et al*. (2017) showed the increase of NPP was mainly concentrated in the northwest and central parts of Inner Mongolia, Qinghai-Tibet Plateau and southeast coastal areas of China. Shi *et al*. (2022) found that the areas with significant increase of NPP were much larger than those where NPP decreased significantly in China during 2001–2020.

Although the spatial pattern and trend of NPP were consistent with the findings of previous studies, there are some limitations or uncertainties in the datasets and methods used. In this study, land cover data of four periods were used to extract unchanged forestland and grassland as research objects. Considering the influence of human activities, each pixel may not reflect the actual land cover type within a 100 m × 100 m area (Cui *et al*., 2023). Secondly, although the applicability and reliability of MuSyQ-NPP model for estimating global NPP has been demonstrated (Cui *et al*., 2016; Yu *et al*., 2018), its application in China still has certain uncertainties and limitations, which have some impacts on the current research results. Finally, the spatio-temporal diversity and complexity of plant biochemical processes also bring some uncertainties to land cover classification and NPP estimation based on remote sensing or process models (Wang *et al*., 2017). Given the above uncertainties and limitations, it is necessary to explore higher quality datasets and more reliable methods to study spatiotemporal variations and differences in NPP (Cui *et al*., 2023).

Conclusion: The average annual NPP of forestland and grassland in China showed a gradient increasing from the northwest to the southeast. From 1981 to 2018, NPP in forestland and grassland showed an increasing trend, and generally exhibited a rapid rising trend in the 1990s and a slow or declining trend in the 2000s. Spatially, NPP increased in most areas, and in Qinghai-Tibetan Plateau, most Northwest China and eastern Northeast China, the increasing trend was significant. In six regions of China, the areas where NPP increased were larger than those of NPP decreased. Our results highlight the consistent distribution and change of NPP in general, but there are some differences between different land cover types and different regions of China. Considering the limitations or uncertainties in the present study, higher quality datasets and more reliable methods should be fully explored in further studies.

Authors' contributions: Jun Shi: Conceptualization, Methodology, and Writing-original draft. Linli Cui: Writing-review & editing, Supervision and Funding acquisition.

Acknowledgments: This study was supported by the Climate Change Project of China Meteorological Administration (No. QBZ202412), Natural Science Foundation of Shanghai (No. 23ZR1456900) and National Key Research and Development Program of China (No. 2023YFC3805304-1). We are grateful to National Earth System Science Data Center (http://www.geodata.cn).

Conflict of interest disclosure: The authors declare no conflict of interest.

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