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Inventory of China's Net Biome Productivity since the 21st Century

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Abstract: Net biome productivity (NBP), which takes into account abiotic respiration and metabolic processes such as fire, pests, and harvesting of agricultural and forestry products, may be more scientific than net ecosystem productivity (NEP) in measuring ecosystem carbon sink levels. As one of the largest countries in global carbon emissions, in China, however, the spatial pattern and evolution of its NBP are still unclear. To this end, we estimated the magnitude of NBP in 31 Chinese provinces (except Hong Kong, Macau, and Taiwan) from 2000 to 2018, and clarified its temporal and spatial evolution. The results show that: (1) the total amount of NBP in China was about 0.21 Pg C/yr^1. Among them, Yunnan Province had the highest NBP (0.09 Pg C/yr^1), accounting for about 43% of China's total. (2) NBP increased from a rate of 0.19 Tg C/yr^1 during the study period. (3) At present, NBP in China's terrestrial ecosystems is mainly distributed in southwest and south China, while northwest and central China are weak carbon sinks or carbon sources. (4) The relative contribution rates of carbon emission fluxes due to emissions from anthropogenic disturbances (harvest of agricultural and forestry products) and natural disturbances (fires, pests, etc.) were 70% and 9.87%, respectively. This study emphasizes the importance of using NBP to re-estimate the net carbon sink of China's terrestrial ecosystem, which is beneficial to providing data support for the realization of China's carbon neutrality goal and global carbon cycle research.

Keywords: terrestrial ecosystem; net biome productivity; inventory; net primary productivity

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1. Introduction

The main sources of carbon in terrestrial ecosystems are ground and underground biomass, soil, and dead organic matter [1–5]. The terrestrial ecosystem is a significant carbon sink [6,7] and plays an important role in the global carbon cycle, and the carbon uptake accounts for 8–11% of the global carbon sink [8–10]. It also plays an important role in mitigating global climate change [3,11]. In undisturbed natural ecosystems, usually, the magnitude of net ecosystem productivity (NEP) is used as a measure of the net carbon sink level of terrestrial ecosystems [2,12]. If NEP is positive, it means that the ecosystem is a carbon sink; Otherwise, it is a carbon source [13]. However, on a regional and larger spatial scale, previous studies have shown that terrestrial ecosystems are affected by activated carbon and animal predation (FE_{RCCI}), agriculture, forestry, and grass product harvesting (FE_{AD}); also the effects of deforestation, fire, and river carbon leakage (FE_{ND}) [12–14]. Therefore, using the magnitude of NEP to measure the size of the terrestrial ecosystem carbon sink will lead to a larger magnitude of the terrestrial ecosystem carbon sink than it already is [9]. Relevant scholars advocate the use of net biome productivity (NBP) as an indicator to measure the carbon sink level of terrestrial ecosystems [15–17]. This indicator subtracts the photosynthetic products consumed by abiotic respiratory metabolisms such as fire, pests and diseases, animal eating, deforestation, and harvesting of agricultural and forestry products from NEP [9,12,14,18].

At present, because of the key role of terrestrial carbon sinks in regulating climate warming, a large number of studies have analyzed the factors that affect the ecosystem carbon cycle in different ways. For example, the agricultural carbon emissions in the 20th century were estimated through the agricultural products harvested in China [19]. Estimation of the carbon emissions of terrestrial ecosystems caused by the utilization of forest products used data from the China Forestry Statistical Yearbook [6]. Based on Grassland Statistical Yearbook data and remote sensing data, the effects of grazing intensity and terrain on carbon exchange capacity of desert grassland were studied [20]. In recent years, the quantitative evaluation of the carbon sink capacity of terrestrial ecosystems has become an important basis for regional climate control and carbon pool management; it has been highly valued by governments at all levels and international organizations [21,22]. These studies have made a great contribution to clarifying the magnitude and spatial distribution of the net biome productivity of regional and even Chinese terrestrial ecosystems. However, from various research results, there are still large differences in the research results of the net biome productivity of terrestrial ecosystems, whether at the national or regional scale. At present, studies have suggested that the NBP in China is 0.20–0.970 Pg C yr^{-1} [9,23–29]. As a result, there is still no consensus on the carbon sink level, specific spatial distribution pattern, and evolution characteristics of terrestrial ecosystems in China. Therefore, clarifying the net biome productivity of China's terrestrial ecosystems, especially the magnitude, spatial pattern, and evolution characteristics of net biome productivity, can provide technical and theoretical support for the formulation of carbon management policies in various regions.

This paper integrates multi-source comprehensive data of ecosystems and quantitatively evaluates the response mechanism of China's NBP to natural and human factor processes from 2000 to 2018, based on the eddy correlation method. The purpose of this study is to quantify the level of carbon sinks in terrestrial ecosystems in China, analyze the space temporal evolution of NBP, and identify the driving factors of NBP space–time changes.

2. Materials and Methods

2.1. Data Sources

NPP data were obtained from the NASA/EOS LPDAAC Data Distribution Center (https://earthdata.nasa.gov/, accessed on 30 January 2022) MOD17A3 and MOD13A3 Moderate Resolution Imaging Spectroradiometer (MODIS) datasets with a spatial resolution of 1 km. The period time is 2000–2018, and this product is widely used to study the carbon cycle [9,30]. The national basic geographic data come from geospatial data sources (http://www.gscloud.cn/, accessed on 30 April 2022). Precipitation (MAP) and air temperature (MAT) data (2000–2018) were obtained from China Earth System Science Data Center (http://www.geodata.cn/data/datadetails.html?dataguid, accessed on 30 April 2022). The resolution is 1 km × 1 km [31]. From 2000 to 2018, the data on the output of agricultural products per unit area, forest products (logs, bamboo, fuelwood), annual pest and disease area, and fire area by the province in China are from the *2000–2018 China Statistical Yearbook* (http://www.stats.gov.cn/tjsj/ndsj/, accessed on 30 April 2022). The runoff data of major rivers and the annual sediment discharge data of major stations are from the *China River Sediment Bulletin*. All raw data were adjusted to the same spatial resolution (1 km × 1 km) using the data assimilation method. In gis10.3, the spatial data are counted according to the administrative boundary with the zonal statistical tool, and finally, the emission flux statistics of activated carbon and animal intake, human-induced disturbance, and natural disturbance are interpolated to the spatial extent.

2.2. Research Methods

2.2.1. Net Ecosystem Productivity (NEP)

Net ecosystem productivity (NEP) has been widely studied by scientists from all over the world as an important indicator for measuring ecosystem carbon sinks. At present, there are many methods for NEP calculation. For example, Yu et al. conducted a quadratic regression analysis in China by considering the effect of the interaction between MAT and MAP on carbon flux. The interaction between MAT and MAP was found to have a statistically significant effect on NEP ($t = -3.76$, $p < 0.01$) [32], and an empirical model between MAT and MAP and NEP was established. This plays a crucial supporting role in understanding China's NEP changes. Therefore, in our study, based on the empirical model established by Yu et al., the precipitation (MAP) and air temperature (MAT) data of the China National Earth System Science Data Center from 2000 to 2018 were used with a resolution of 1 km × 1 km. The magnitude of NEP in the Chinese region from 2000 to 2018 was calculated.

$$\text{NEP} = 48.98\text{MAT} + 0.79\text{MAP} - 0.05\text{MAT} \times \text{MAP} - 313.85 \quad (1)$$

MAT means annual mean temperature ($°C/yr^1$), and MAP means annual mean precipitation (mm/yr^1).

2.2.2. Net Biome Productivity (NBP)

Net biome productivity (NBP) is considered a potential carbon sink for terrestrial ecosystems under current climatic conditions in China [9,14,17]. The flux of emissions from reactive carbon and creature ingestion, the flux of emissions from anthropogenic disturbances, and the flux of emissions from natural disturbances are subtracted from NEP [9,12–24,33]. Therefore, the calculation formula of NBP is as follows:

$$\text{NBP} = \text{NEP} - \text{FE}_{\text{RCCI}} - \text{FE}_{\text{AD}} - \text{FE}_{\text{ND}} \quad (2)$$

FE_{RCCI} is the fluxes of emissions from reactive carbon and animal ingestion ($Tg\ C/yr^1$); FE_{AD} is the flux of emissions from human factor disturbances ($Tg\ C/yr^1$); and FE_{ND} is the flux of emissions from natural disturbances ($Tg\ C/yr^1$).

2.2.3. Emission Flux of Activated Carbon and Biological Respiration

Reactive carbon FE_{RC} and creature ingestion FE_{CI} form the flux of emissions from reactive carbon and creature ingestion (FE_{RCCI}) [9,14,28,34,35]. Therefore, the FE_{RCCI} estimates for 31 provinces and cities in China are as follows:

$$\text{FE}_{\text{RCCI}} = \text{FE}_{\text{RC}} + \text{FE}_{\text{CI}} \quad (3)$$

Activated Carbon Compounds FE_{RC} primarily considers non-methane volatile organic compounds (NMVOC), carbon monoxide (CO), and CH_4 emissions.

$$\text{FE}_{\text{RC}} = \text{FE}_{\text{CH4}} + \text{FE}_{\text{NMVOC}} + \text{FE}_{\text{CO}} \quad (4)$$

FE_{CH4} is the carbon emission flux of the terrestrial ecosystem caused by CH_4 emissions ($Tg\ C\ yr^{-1}$); FE_{NMVOC} is the carbon emission flux of the terrestrial ecosystem caused by NMVOC emissions ($Tg\ C/yr^1$); and FE_{CO} is the carbon emission flux of the terrestrial ecosystem caused by CO emissions ($Tg\ C/yr^1$).

Creature ingestion FE_{CI} mainly considers forests as the carbon emissions caused by diseases, pests, and rats in forests [36–39].

$$\text{FE}_{\text{CI}} = \text{FE}_{\text{diseasea}} + \text{FE}_{\text{pests}} + \text{FE}_{\text{rats}} \quad (5)$$

$FE_{diseasea}$ is the carbon depletion flux of terrestrial ecosystems caused by forest disease ($Tg\ C/yr^1$); FE_{pests} is the carbon depletion flux of terrestrial ecosystems caused by forest pests' emissions (Tg C/yr^1); and FE_{rats} is the carbon depletion flux of terrestrial ecosystems caused by forest rats (Tg C/yr^1).

2.2.4. Ecosystem Carbon Emission Flux Caused by Human Disturbance

The carbon flux caused by human disturbance refers to the removal of carbon from the terrestrial ecosystem by humans through the collection of agricultural products and the utilization of forest and grass products [14,40]. Accurately assessing the level of ecosystem carbon sinks consumed by harvesting agroforestry and grass products is of great significance for quantifying ecosystem net biome productivity [18]. At present, the most feasible method to assess the carbon flux consumed by harvesting agricultural, forestry, and grass products is to estimate the magnitude of total carbon emission based on the regional macroeconomic activity level and the corresponding carbon emission coefficient. [9,12,14,18,33]. The formula is as follows:

$$FE_{AD} = CCU_C + CCU_F + CCU_G \tag{6}$$

FE_{AD} is the flux of emissions from human factor disturbances (Tg C/yr^1); CCU_C is the carbon emission of agricultural products harvested (Tg C/yr^1); CCU_F is the carbon emission of forestry harvesting (Tg C/yr^1); and CCU_G is the carbon emission of grass product harvesting (Tg C/yr^1).

2.2.5. Natural Disturbance Emissions Carbon Flux

The flux of emissions from natural disturbances FE_{ND} mainly considers the carbon emission of the ecosystem by forest fire FE_p and water erosion (FL_{Gwa}) [33,41–43]. Therefore, the FE_{ND} estimates for 31 provinces and cities in China are as follows:

$$FE_{ND} = FE_P + FL_{GWa} \tag{7}$$

The FE_{ND} is the flux of emissions from natural disturbances (Tg C/yr^1); FE_P is the forest fire carbon emission flux (Tg C/yr^1); and FL_{Gwa} is the water erosion caused by carbon emission flux (Tg C/yr^1).

3. Results

3.1. Spatial and Temporal Evolution of Net Ecosystem Productivity

Based on the empirical model of NEP, temperature, and precipitation, the annual average NEP in China from 2000 to 2018 was calculated to be 1.06 Pg C/yr^1 (equivalent to 3.886 Pg CO_2/yr^1). From the perspective of spatial distribution, China's NEP as a whole is high in the southeast and low in the northwest, with a decreasing trend from southeast to northwest. As shown in Figure 1a, high values are mainly concentrated in the southwest and south China regions of China. For example, the total amount of Yunnan is 0.13 Pg C/yr^1, and the flux is 339.25 T C/yr^1; the total amount of Guangxi is 0.08 Pg C/yr^1, and the flux is 338.25 T C/yr^1; the total amount of Guangdong is 0.06 Pg C/yr^1, and the flux is 338.16 T C/yr^1. The low-value areas are mainly distributed in Tibet, Xinjiang, and Qinghai in western and northwestern China, with total amounts of −0.009 Pg C/yr^1, −0.008 Pg C/yr^1, and 0.003 Pg C/yr^1, respectively.

Through the analysis of the evolution trend of NEP, it is found that as shown in Figure 1b, China's NEP showed an overall increasing trend from 2000 to 2018 (Slope = 1.48). The regions with the largest increase in NEP are southern Tibet, southern Sichuan, Yunnan, Shaanxi, Anhui, and Jiangsu, as well as Heilongjiang, Jilin, and Liaoning in the northeast. However, NEP decreased significantly in northern Xinjiang, eastern Sichuan, Guizhou, Hunan, and Jiangxi, while NEP did not change significantly in most areas of northwestern Xinjiang, southeastern Tibet, and southern Qinghai.

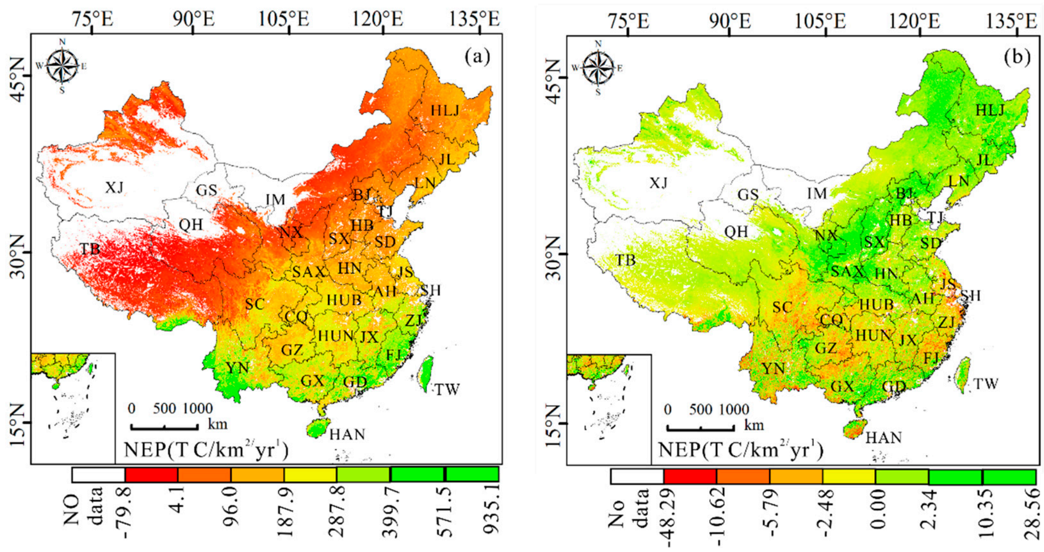

Figure 1. The spatial distribution and evolution trend of China's average NEP from 2000 to 2018 (Lack of data from Hong Kong, Macau, and Taiwan Province): (**a**) spatial distribution of annual average NEP, (**b**) changing trend.

3.2. Carbon Emission by Natural and Human Factors Interference

The total FE_{RCCI} of carbon emissions caused by activated carbon and biological uptake in China's terrestrial ecosystems is 0.08 Pg C/yr^1. The total anthropogenic disturbance carbon emission (FE_{AD}) caused by harvesting of agricultural, forestry, and grass products was 0.74 Pg C/yr^1. The total amount of natural disturbance carbon emissions (FE_{ND}) caused by forest fires and river carbon leakage was 0.03 Pg C/yr^1. Among them, the spatial distribution of FE_{RCCI} is shown in Figure 2a, and the areas with high flux values are mainly distributed in southwest, north, central, and eastern China, such as Anhui, Jiangsu, and Henan. Low values are mainly distributed in northwest China, such as Xinjiang, Tibet, Qinghai, Inner Mongolia, and so on. The overall spatial distribution of FE_{AD} is high in the east and low in the west, as shown in Figure 2c; the areas with the highest intensity appear in Shandong, Anhui, Jiangsu, Henan, and Hubei regions, especially in Henan, Jiangsu and Shandong regions where the FE_{AD} intensity exceeds 180 T C/km^2/yr^1. However, the FE_{AD} intensity of Inner Mongolia, Qinghai, Xinjiang, and Tibet in northwest China is lower than 39 T C/km^2/yr^1. Interestingly, the carbon emission FE_{ND} caused by forest fires, rivers, etc. occurred in southwest and south China, with higher incidence and lower incidence in north, central and eastern China, as shown in Figure 2e.

From the time scale, FE_{RCCI} showed a trend of increasing volatility from 2000 to 2018. As shown in Figure 2b, the highest value was 0.82 Pg C/yr^1 in 2008, and the growth rate was small. The total increase in 19 years was 3 Tg C, and the effect on the reduction in NBP was not significant. FE_{AD} showed a rapid growth trend, as shown in Figure 2d, with a total increase of 0.25 Pg C during the study period. Carbon emissions from forest fires and river seepage showed a decreasing trend, as shown in Figure 2f, with a decreasing rate of 0.04 Tg C/yr^1.

3.3. Net Biome Productivity Spatial Distribution

Based on the integration of multi-source data, the NBP flux of China's terrestrial ecosystem was calculated, as shown in Figure 3a. The calculation shows that the total NBP of China's terrestrial ecosystem from 2000 to 2018 was 0.21 Pg C/yr^1, and the flux was −2.4 T C/km^2/yr^1. Spatially, it shows a decreasing trend from southeast to northwest. The areas with high NBP values are mainly concentrated in southwestern China. For example, the total amount of Yunnan Province is 0.09 Pg C/yr^1, accounting for 42.8% of the NBP of the terrestrial ecosystem, and the flux is 234.86 T C/km^2/yr^1. The total amount in Guangxi was 0.06 Pg C/yr^1, accounting for 28.5% of the NBP of the terrestrial ecosystem, and the flux was 253.69 T C/km^2/yr^1. In addition, NBP in Heilongjiang, China reached 0.03 Pg C/yr^1, accounting for 14.3% of the total NBP, with a flux of 66.29 T C/km^2/yr^1. The low-value areas are mainly concentrated in the northwest region of China. For example, the total amount of Tibet is −0.048 Pg C/yr^1, and the flux is −39.92 T C/km^2/yr^1.

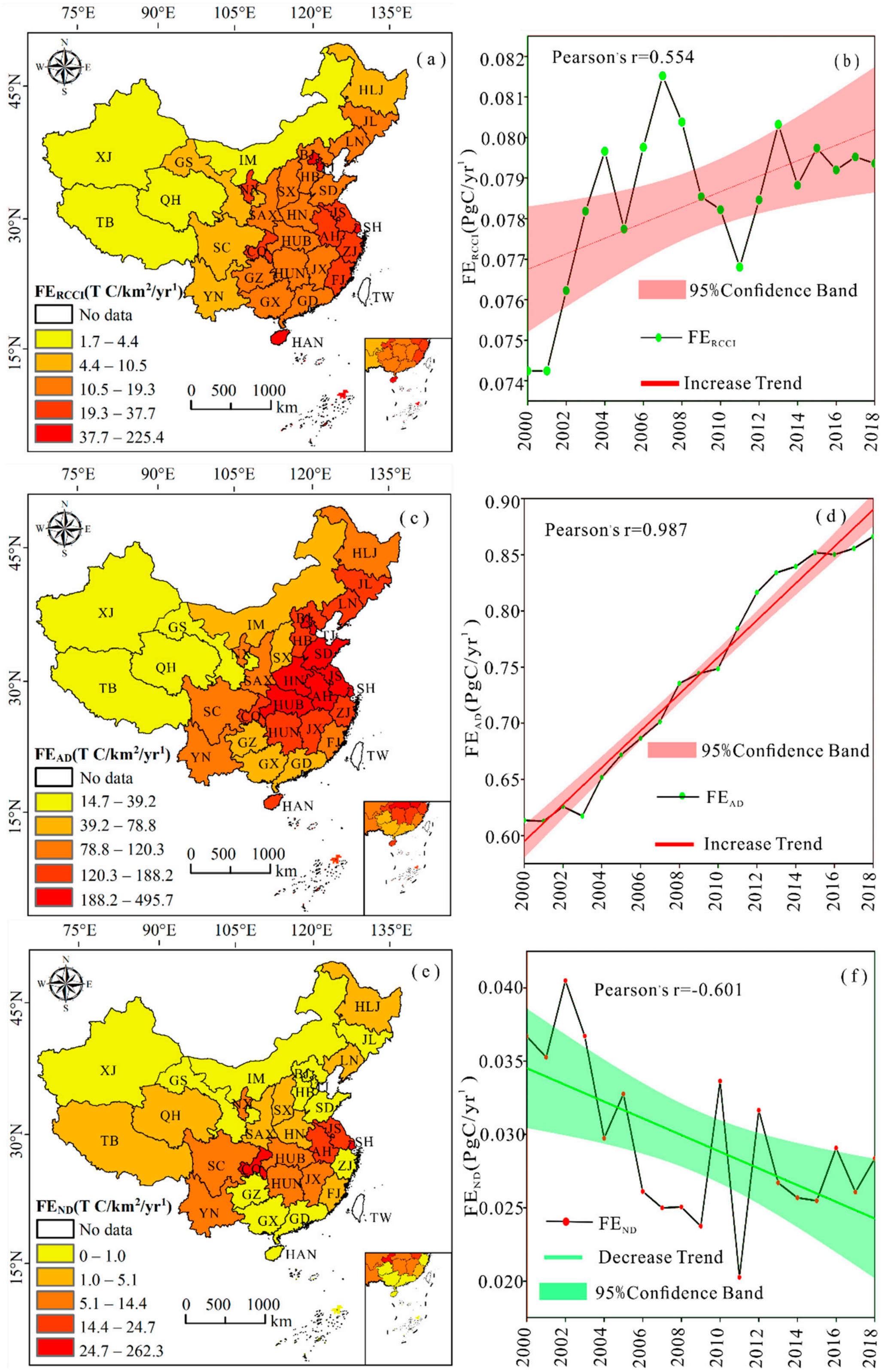

Figure 2. Spatial distribution and temporal evolution characteristics of natural and man-made carbon

emissions (Lack of data from Hong Kong, Macau, and Taiwan Province): (**a**) Average annual carbon release due to activated carbon and biological ingestion, (**b**) Average annual carbon release from the use of agroforestry and grass products, (**c**) Annual average carbon release caused by forest fire and geological carbon leakage, (**d**) Temporal evolution characteristics of carbon release caused by activated carbon and biological intake, (**e**) Temporal evolution characteristics of carbon release caused by utilization of agricultural, forestry and grass products, (**f**) Temporal evolution characteristics of carbon release caused by forest fire and geological carbon leakage.

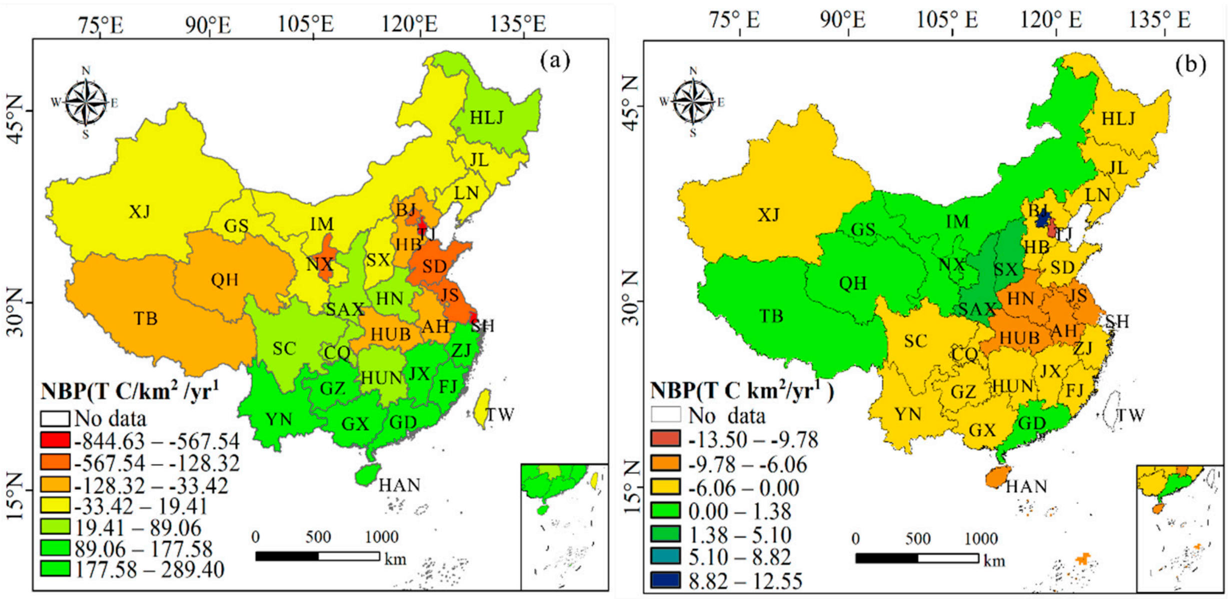

Figure 3. The spatial distribution and evolution trend of China's average NBP from 2000 to 2018 (Lack of data from Hong Kong, Macau, and Taiwan Province): (**a**) spatial distribution of annual average NBP, (**b**) changing trend.

The evolution trend of China's terrestrial ecosystem NBP was analyzed using the pixel-based trend analysis method. The spatial distribution of its changing trend is shown in Figure 1b. From 2000 to 2018, the areas where NBP of China's terrestrial ecosystems increased significantly were mainly distributed in bands in Inner Mongolia, Gansu, Qinghai, and Tibet, with an annual increase of about 1.38 T C/km^2. In addition, the increase in Beijing is the most obvious, with an annual increase of about 8.82–12.55 T C/km^2. However, in Figure 1b, we also find that NBP shows a slight downward trend in most of the southwestern regions.

In the past 19 years, the NEP has been 1.06 Pg C/yr^1. Supplemented Tables S1–S3, the utilization of agricultural, forestry, and grass products consumes 70% of NEP. In addition, natural disturbances such as animal husbandry, volatile organic compound emissions, fire, water erosion, and wind erosion consume 10% of NEP. Finally, the total amount of NBP is 0.212 Pg C/yr^1 and increases at the rate of 0.19 Tg C/yr^1. As shown in Figure 3b, the regions that contribute the most to the total amount of NBP are the southwest, south China, and some northeast regions such as Yunnan, Guangxi, and Heilongjiang. In addition, the contribution of Tibet, central China, and northwest China to the total amount of NBP is relatively low, Figure 4. During the study period, NBP declined slowly in southwest and south China. NBP in north China, such as Beijing and Hebei, and northwest China, such as Xinjiang, Qinghai, and Gansu, is increasing.

3.4. *The Increase in the FE_{AD} was the Main Driving Force behind the Decrease in the NEP*

Since 2000, the remarkable increase in FE_{AD} has contributed the most to the decrease in NEP (70%), especially in northeastern, northern, and central China, with a relative contribution rate of >30%. This increase in FE_{AD} is attributed to the large–scale agricultural production on the plains, which, while producing high yields, continuously fertilizes the land, changes the soil structure, and damages the integrity of the ecosystem, thus increasing the carbon emission of the land (Figure 5). We found that 81.58% of FE_{AD} (742 Tg C/yr^1) was carbon emission caused by the use of agricultural products. In addition, the contribution of the FE_{RCCI} to the change in the NEP is also very important, reaching 7.17%. In terms of the FE_{RCCI} (76 Tg C/yr^1), 50.25% of the carbon emission was from the FE_{CO}. This phenomenon was mainly concentrated in northeastern, central, southern, and southwestern China. Of course, the NEP is also affected by other factors. Among them, the relative contribution rate of the FE_{ND} was only 2.74%. Although it is less than those of the first two, the relative contribution rate of the FE_{ND} also has a very important impact on the NBP.

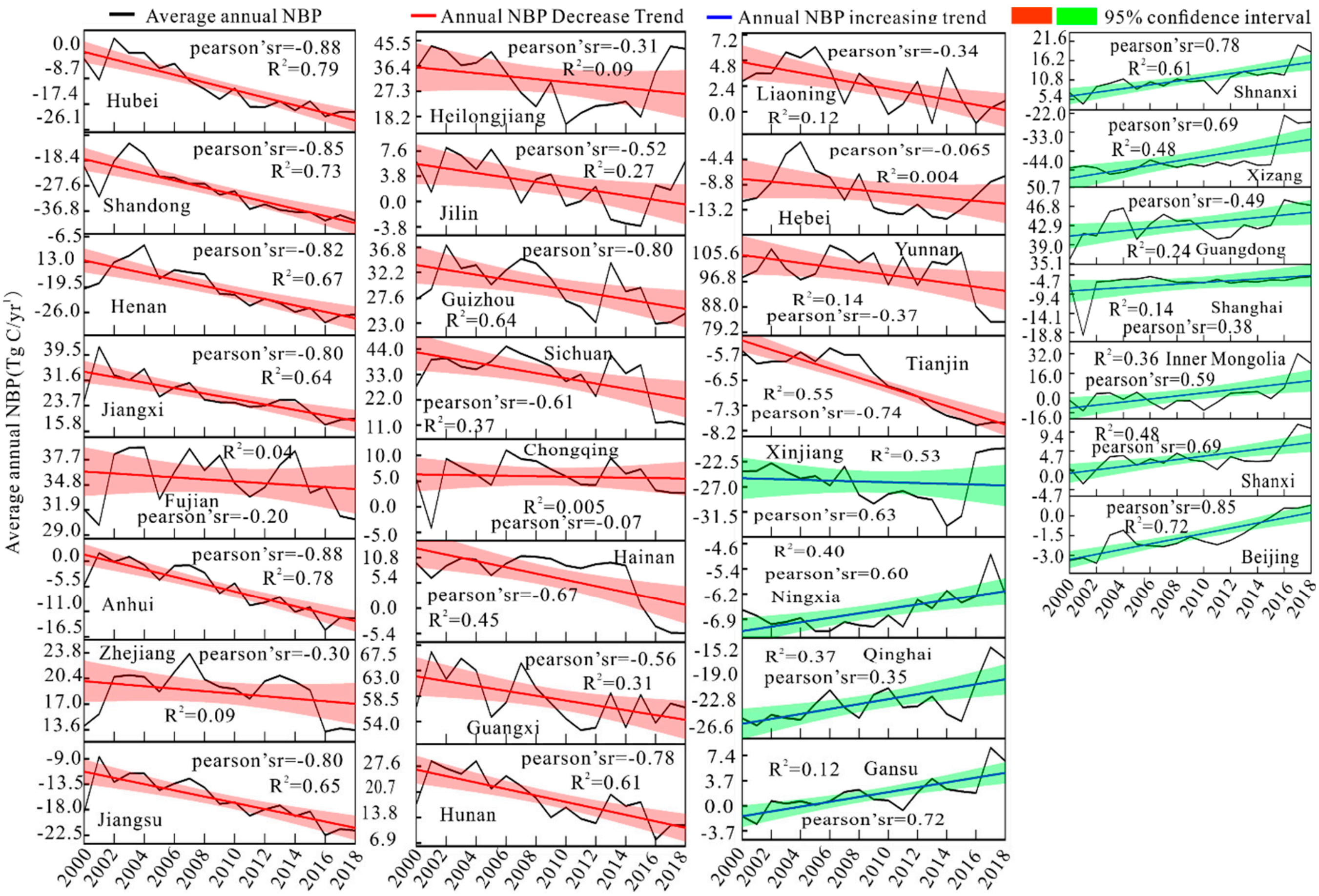

Figure 4. The evolution of the NBP anomalies in various regions of China from 2000 to 2018.

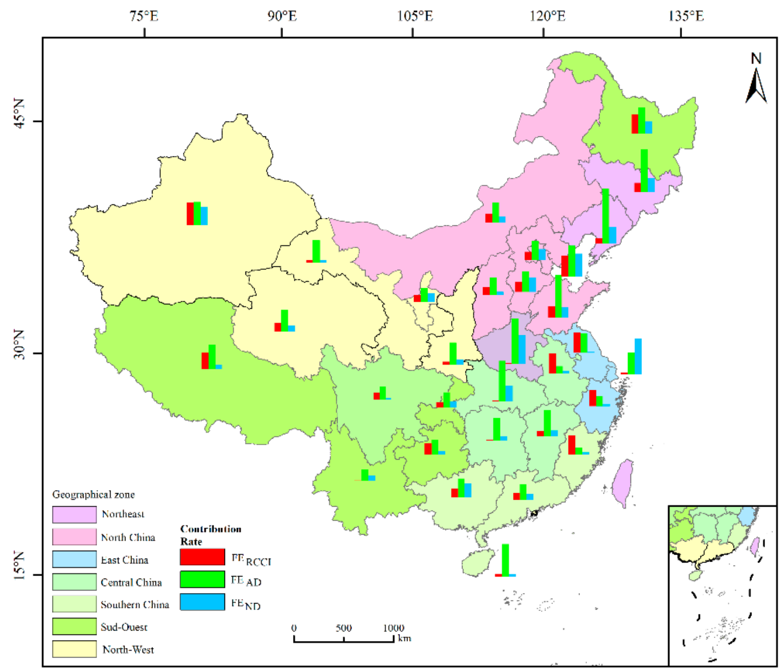

Figure 5. Spatial distribution of contribution rates of FE_{RCCI}, FE_{AD}, and FE_{ND} to NEP decline of the terrestrial ecosystem in China from 2000–2018 (Lack of data from Hong Kong, Macau, and Taiwan Province).

4. Discussion

4.1. Comparison with Other Research Results

To further illustrate the accuracy and reliability of the calculation results, we started with the various factors that affect the NBP and compared the calculation results in this paper with those of related studies. First, in terms of the carbon emission caused by the FE_{RCCI}, the CH_4, NMVOC, and CO emissions from rice fields, natural wetlands, lakes, and terrestrial plants were estimated (Table 1). Among them, we used the conversion rate of paddy net primary productivity (NPP) to paddy CH_4 to model CH_4 emissions from paddy fields in China (6.77 Tg C/yr^1). The results of this study are similar to those estimated by the empirical model [44,45], conversion coefficient of NPP and CH_4 [46], DNDC model [47,48], emission coefficient [49], and meta-analysis [50]. The CH_4 emissions from natural wetlands and lakes (including reservoirs and ponds) estimated based on sample surveys and statistical data are 1.48–1.76 Tg CH_4/yr^1 [51]. Our estimated CH_4 emissions from natural wetlands based on the same method are slightly lower (1.16 Tg CH_4/yr^1). In addition, CH_4 is easily generated in situ in land plants under aerobic conditions. In this study, the aerobic plant CH_4 emission model ($PLANT_{CH4}$) was used to estimate the CH_4 emissions of aerobic plants in China (10.66 Tg CH_4/yr^1), which is slightly lower than the previously reported value of 11.83 Tg CH_4/yr^1 [52]. Based on the natural volatile organic compounds ($NVOC_s$) global emission model [53], the annual NMVOC emissions from China's surface vegetation have been estimated to be 13.23–17.71 Tg C/yr^1 [37]. We used the same method to estimate the NMVOC emissions from the surface vegetation in China from 2000 to 2018 (15.15 Tg C/yr^1). This shows that the results of this study are reliable for the estimation of the NMVOC flux from China's surface vegetation. Based on the average value from global CO research [49], we roughly estimate that China's CO emissions are 38.53 Tg C/yr^1. In addition, forest diseases and insect pests are important components affecting the carbon emission of natural ecosystems [48,54]. Based on the method of estimating the carbon flux of forest diseases and insect pests [17,55], the carbon emission flux caused by forest diseases and insect pests in China's forests and grasslands from 2000 to 2018 was estimated using forest disease and insect pest data from the Forestry Statistical Yearbook. The carbon emissions from the ecosystem caused by diseases, pests, and rodents were 4.2 Tg C. This value is slightly lower than the value of 4.29 Tg C/yr^1 reported from 1990 to 2009 [55].

Table 1. Comparison of carbon emission levels of natural and human-made interference.

FE_{RCCI}	CH_4 Emission (Tg C/yr^1)	Study Period	References
CH_4 emission flux statistics from rice fields in China	3.90~8.52	2008	[50]
	6.77	2000–2018	This study
The CH_4 emissions from natural wetlands and lakes (including reservoirs and ponds)	1.48~1.76		[51]
	1.16	2000–2018	This study
CH_4 emissions of aerobic plants	11.83		[52]
	10.66	2000–2018	This study
NVOCs	13.23~17.71		[37,53]
	15.15	2000–2018	This study
CO	38.5	2001–2010	[33,56]
	38.53	2000–2018	This study
Creature ingestion	4.29	1990–2009	[55]
	4.2	2000–2018	This study
FE_{AD}	806	2001–2010	[55,57]
	742	2000–2018	This study
FE_P	1.61		[55]
	1.45	2000–2018	This study

Using the agricultural product output data from the *Agricultural Statistical Yearbook* and using the method [51], we calculated the carbon emission flux of China's agricultural product utilization (595.75 Tg C/yr^1), which is slightly lower than the previously reported value of 630.54 Tg C/yr^1 [56]. The carbon loss caused by timber harvesting in China's terrestrial ecosystem is increasing at a rate of 4.4 Tg C yr^{-1}, and the average annual carbon emission is 34.25 Tg C/yr^1 [55]. In this study, *Forestry Statistical Yearbook* data and the research method of [56] were used to estimate the carbon emission of forest product utilization in China from 2000 to 2018 (40.37 Tg C/yr^1), Our research results are slightly larger than the previously reported value. Concerning the carbon loss caused by livestock consuming feed products, we calculated the hay yield from 2000 to 2018 using remote sensing methods and correlation coefficients [8]. According to the related methods [56] of calculating the carbon emission of grass products, the carbon loss caused by livestock consumption of feed products in China was calculated to be 106.3 Tg C/yr^1, which is slightly less than the previously reported value of 114 Tg C/yr^1 [56]. In addition, the decrease in the grassland area is a direct cause of the decrease in the carbon emission of grass products.

We calculated China's forest carbon sinks using the stock volume method [58] and used the biomass consumption method [21] to estimate carbon emissions caused by forest fires in China (1.45 Tg C/yr^1), which is slightly lower than the previously reported value of 1.61 Tg C/yr^1 [55]. Regarding the carbon loss caused by the transport of sediments by rivers, based on the data from the 2000–2018 Sediment Bulletin, we estimated that the carbon loss caused by the transport of sediments by China's major rivers was 27.94 Tg C/yr^1, which is slightly lower than the previously reported value of 29.57 Tg C/yr^1 [56].

4.2. Analysis of Influencing Factors of Regional Net Biome Productivity

The NBP in China from 2000 to 2018 was 0.212 Pg C/yr^1, Table 2. This result is similar to the atmospheric inversion method [59], DEM model [3], resource inventory method [60], and meta-analysis [9]. From Figure 3, it can be found that the overall changes in China's NBP from 2000 to 2018 can be divided into three categories. One is the southwest and south China regions, where the total amount of NBP is relatively high, and the NBP increases slowly during the study period, which we call the slow-growing region. The second category is that the total amount of NBP in central China and east China is relatively low, showing a rapid downward trend during the study period, which we call the rapid decline area. The third category is north China and northwest China. The total amount is low, showing a rapid growth trend. We call it the rapid growth area.

Table 2. Main results of China NBP in previous research reports.

Model	Study Period	NBP (Pg C/yr[1])	Reference
Biomass and soil carbon inventories, Atmospheric inversions method.	1980–1990	0.19~0.26	[8]
Atmospheric inversion method	2001–2010	0.31~0.33	[59]
DEM	2001–2005	0.28	[3]
Resource inventory method	2004–2008	0.28	[60]
Meta-analyses		0.20~0.25	[9]
Eddy covariance measurements	2000–2018	0.212	This study

The reasons for the rapid decline, slow growth, and rapid growth of NBP in China are mainly related to the ecological and environmental protection policies of each region and the type of regional economy. For example, since 1980, large-scale projects of returning farmland to forests have been implemented in southwest and south China, where the total amount is relatively large, and in the rapidly growing north and northwest regions. The disturbance of human activities to the ecosystem is weakened, as shown in Figure 2c, and the carbon emission of FE_{AD} caused by the production and utilization of agricultural, forestry, and grass products is lower. In particular, grassland ecological restoration projects in northwestern regions such as Xinjiang, Tibet, Qinghai, and Inner Mongolia, and wetland protection projects in northeastern regions have increased the carbon sink function of ecosystems [8]. Studies have shown that during the ten years from 2001 to 2010, the increase in carbon sinks due to the implementation of ecological projects in China was 74 Tg C/yr[1] [44]. In addition, south China and southwest China are located in the middle and low latitudes of 15–30° N, located in the subtropical monsoon climate zone, and are greatly affected by the southeast and southwest monsoon. Precipitation is generally above 1000 mm, resulting in a large photosynthetic potential, resulting in a relatively high total NEP of net terrestrial ecosystem productivity [61]. On the contrary, in central China and east China, as China's population and economic concentration areas due to the development of local society and the economy, the impact of human activities on the surface cover has increased [62] and a large amount of carbon in the ecosystem is released into the atmosphere [63]. Especially in major agricultural provinces such as Henan, in the process of food production, disturbance to the land causes the carbon stored in the ecosystem to be released into the atmosphere again through food production. The annual carbon emission to the atmosphere is 57 Tg C/yr[1], accounting for the total amount of NEP 5.4%.

4.3. Science and Uncertainty in the Carbon Sink Assessment

The current methods for evaluating carbon sinks in terrestrial ecosystems include the resource inventory method, eddy correlation method, ecosystem process model simulation method, atmospheric reflection method, etc. Each method has its advantages and disadvantages, as shown in Table 3. To realize the long-term continuous positioning observation of the carbon sink flux of China's regional fine time-scale ecosystems, based on integrating multi-source data, this study estimated the carbon sink of China's regional terrestrial ecosystems based on the eddy correlation method. In addition, fully considering the carbon flux component of harvesting agricultural, forestry, and grass products. The carbon flux components of CH_4 and NMVOC such as logging, fire, farmland, wetland, and lake are shown in Figure 6. To some extent, it has overcome the deficiency of the eddy correlation method in estimating terrestrial ecosystem carbon sinks.

Table 3. Comparison of advantages and disadvantages of different research methods.

Method	Advantages	Disadvantages	References
Resource inventory method	The observation results of vegetation and soil carbon storage at the sample scale are more accurate.	(1) Long observation period and low spatial resolution. (2) The ecosystem coverage is incomplete. (3) Sampling and regional scale carbon sink conversion uncertainty are relatively large. (4) The lateral transfer of ecosystem carbon cannot be measured.	[26,32]
Eddy covariance measurements	Long-term continuous positioning observations of carbon flux in the ecosystem. Contributes to understanding the response and mechanism of the carbon cycle process to environmental changes.	(1) Unable to distinguish heterogeneity between soil carbon changes in the agricultural ecosystem and carbon flux components such as crop harvesting. (2) The influence of disturbance factors such as deforestation and fire on the ecosystem carbon sink is not considered, resulting in an overestimation of the ecosystem carbon sink at the regional scale.	[64,65]
Ecophysiological Process Models	Quantitatively distinguish the contributions of different driving factors to terrestrial carbon sink changes, which can predict future changes in terrestrial carbon sinks.	(1) There are great uncertainties in the structure and parameters of the model. (2) Does not consider the impact of ecosystem management on the carbon cycle.	[66,67]
Atmospheric inversion method	Real-time changes in carbon sources and sinks can be estimated on a global scale.	(1) The spatial resolution is low, and the carbon fluxes of different ecosystem types cannot be accurately distinguished. (2) Terrestrial-atmosphere carbon exchange other than CO_2 is not considered.	[25,47,57]

In addition, there are several problems with the data selection and matching between data with different precision. The usage statistics and some of the calculation coefficients are greatly influenced by subjective factors. Second, this study involved multi-element research, and there may be differences in the selection of the calculation methods. A large number of practical experiments and repeated validation are needed in the future to improve the accuracy of the estimation results and to ensure applicability in different regions.

We consider carbon emissions from methane and CO emissions, and carbon emissions from the use of agriculture, forestry, and grasses (e.g., food, fuelwood, grazing, livestock raising, etc.). Carbon emissions from physical processes such as forest and grassland fires and fluxes of carbon seepage from rivers. Finally, we believe that the NBP of China's terrestrial ecosystem from 2000 to 2018 was only 0.21 Pg C/yr^1, and the results of the study are close to those of previous studies (Figure 6). In summary, the data we estimated can meet the precision requirements of the study, and these datasets will provide support for carbon neutrality and global carbon cycle research in China.

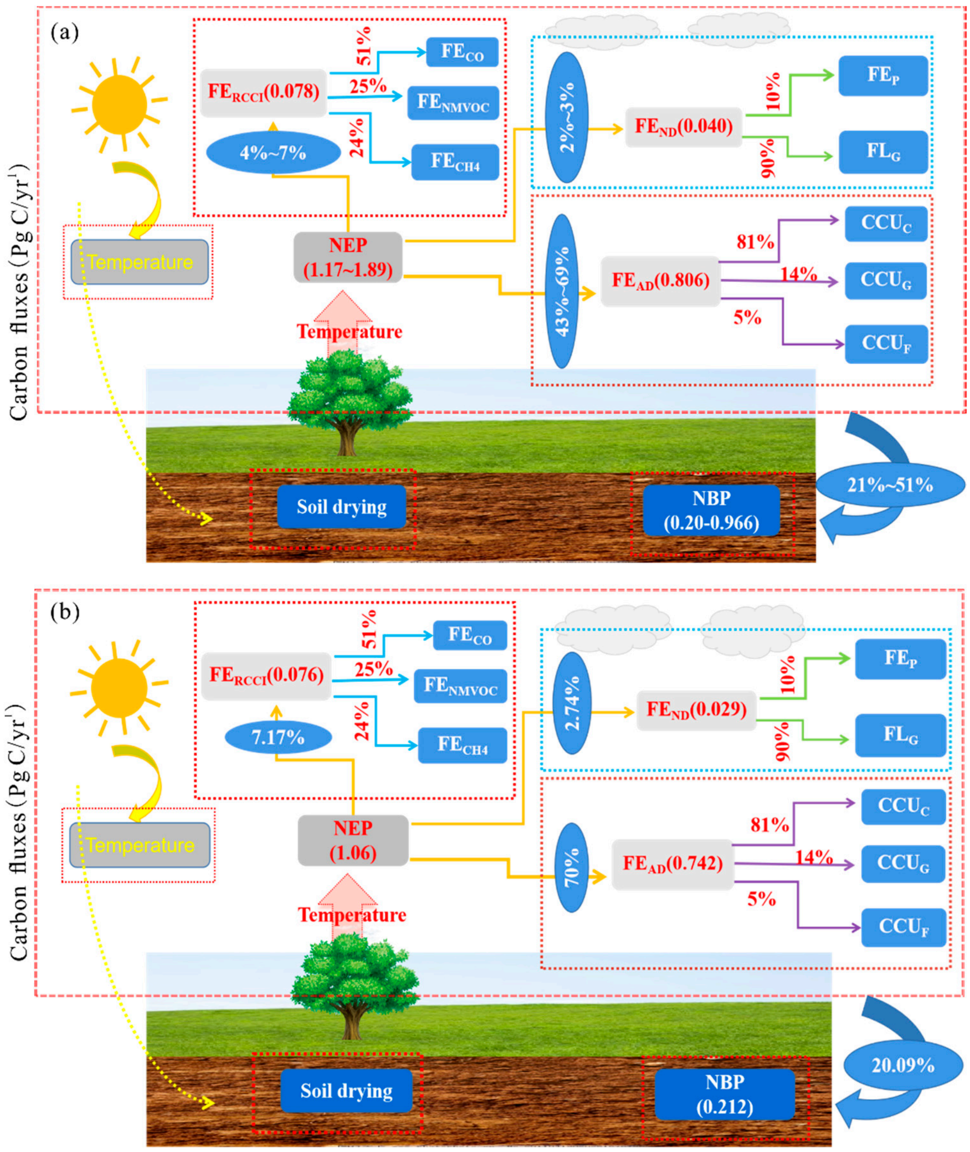

Figure 6. Carbon budget components and carbon sink/source formation of terrestrial ecosystems in China during 2000–2018. The NEP in (**a**,**b**) are estimated from this study and data collected in the literature, respectively.

5. Conclusions

Terrestrial ecosystem carbon storage is very important in influencing global warming as a carbon source/sink of atmospheric carbon dioxide. To this end, we used multi-source data to estimate the NBP of terrestrial ecosystems in 31 provincial-level administrative regions in China from 2000 to 2018, discussed their spatial distribution patterns and evolution characteristics, and obtained the following main conclusions:

(1) The total amount of NBP in China is about 0.21 Pg C/yr^1. It increased at a rate of 0.19 Tg C/yr^1 over the study period;
(2) The high value of NBP is mainly distributed in southwest and south China, among which Yunnan Province has the highest NBP (0.09 Pg C/yr^1), accounting for about 43% of the total NBP in China. Northwest and central China are weak carbon sinks or carbon sources, with the lowest value in Tibet (−0.048 Pg C/yr^1);
(3) The relative contribution rates of carbon emission fluxes caused by anthropogenic disturbances (harvesting of agricultural and forestry products) and natural disturbances (fires, pests, etc.) are 70% and 9.87%, respectively.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11081244/s1.

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