Science Bulletin

Primary estimation of Chinese terrestrial carbon sequestration during 2001-2010

Qiufeng Wang, Han Zheng, Xianjin Zhu and Guirui Yu

Citation: Science Bulletin **60**, 577 (2015); doi: 10.1007/s11434-015-0736-9

Sci. Bull. (2015) 60(6):577–590
DOI 10.1007/s11434-015-0736-9

www.scibull.com
www.springer.com/scp

Article

Earth Sciences

Primary estimation of Chinese terrestrial carbon sequestration during 2001–2010

Qiufeng Wang · Han Zheng · Xianjin Zhu · Guirui Yu

Received: 23 October 2014 / Accepted: 15 December 2014 / Published online: 4 February 2015

Abstract Quantifying the carbon budgets of terrestrial ecosystems is the foundation on which to understand the role of these ecosystems as carbon sinks and to mitigate global climate change. Through a re-examination of the conceptual framework of ecosystem productivity and the integration of multi-source data, we assumed that the entire terrestrial ecosystems in China to be a large-scale regional biome-society system. We approximated the carbon fluxes of key natural and anthropogenic processes at a regional scale, including fluxes of emissions from reactive carbon and creature ingestion, and fluxes of emissions from anthropogenic and natural disturbances. The gross primary productivity, ecosystem respiration and net ecosystem productivity (NEP) in China were 7.78, 5.89 and 1.89 PgC a^{-1}, respectively, during the period from 2001 to 2010. After accounting for the consumption of reactive carbon and creature ingestion (0.078 PgC a^{-1}), fires (0.002 PgC a^{-1}), water erosion (0.038 PgC a^{-1}) and agricultural and forestry utilization (0.806 PgC a^{-1}), the final carbon sink in China was about 0.966 PgC a^{-1}; this was considered as the climate-based potential terrestrial ecosystem carbon sink for the current climate conditions in China. The carbon emissions caused by anthropogenic disturbances accounted for more than 42 % of the NEP, which indicated that humans can play an important role in increasing terrestrial carbon sequestration and mitigating global climate change. This role can be fulfilled by reducing the carbon emissions caused by human activities and by prolonging the residence time of fixed organic carbon in the large-scale regional biome-society system through the improvement of ecosystem management.

Keywords Gross primary productivity · Net ecosystem productivity · Ecosystem respiration · Carbon sink · ChinaFLUX

SPECIAL TOPIC: Land-ocean integrated research and development of carbon sink

Q. Wang · H. Zheng · X. Zhu · G. Yu (✉)
Synthesis Research Center of Chinese Ecosystem Research Network, Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences,
Beijing 100101, China
e-mail: yugr@igsnrr.ac.cn

H. Zheng
University of Chinese Academy of Sciences,
Beijing 100049, China

1 Introduction

Terrestrial ecosystems, as sinks of atmospheric CO_2 [1], play an important role in mitigating global climate change [2, 3]. The Intergovernmental Panel on Climate Change (IPCC) identified the objectives and the mechanisms of controlling the global greenhouse gases and provided guidance on the emission reduction targets for countries at different stages of development [4]. Therefore, it is not only an important part of ecosystem and global climate change science [5–7], but also the major scientific and technological outline to fulfill the United Nations Framework Convention on Climate Change and to enhance the management of global and national greenhouse gases [8], to quantify the global and national terrestrial ecosystem productivity and the use and allocation of carbon in a variety of carbon pools or ecological processes, and to assess the spatial patterns and dynamics of terrestrial ecosystem carbon source/sink relationships at a regional scale.

The parameters that characterize the ecosystem productivity and carbon budget components include gross primary productivity (GPP), net primary productivity (NPP), net ecosystem productivity (NEP), net biome productivity (NBP), ecosystem respiration (ER), autotrophic respiration of plants (Ra), heterotrophic respiration of microorganisms (Rh) and respiration of biomes (Rb).

Based on the processes of material production, carbon sequestration, and carbon use and consumption in natural ecosystems, Chapin et al. [5] discussed the logical relationships between GPP and its transformations (e.g., NPP, NEP and NBP) after various types of carbon use and consumption (ER, Ra, Rh and Rb) [5, 9], which provided a useful theoretical framework for the quantitative evaluation of ecosystem productivity, carbon budget components, and spatiotemporal patterns of carbon source/sinks at a regional scale [8].

In recent years, on the basis of the conceptual framework of Chapin et al. [5], the observational techniques and assessment methods to determine the productivity (GPP, NPP, NEP, NBP) and respiration (ER, Ra, Rh, Rb) at different spatial and temporal scales have developed and improved rapidly [5, 10]. Currently, the methods used in the determination of ecosystem productivity and the evaluations of the carbon budget at different spatial and temporal scales include eddy covariance [11], resource inventory [12, 13], airborne laser scanning [14], remote sensing evaluation based on resource satellite observations [15], remote sensing inversion of carbon satellites [16, 17], geographical statistical modeling [18, 19], analysis based on process-based models [20–22] and atmospheric inversion [23, 24]. These technologies have improved continually with their own appropriate spatiotemporal scales, and researchers have also performed meta-analyses based on multi-source data from different approaches [25, 26]. Additionally, comprehensive assessments were conducted on the ecosystem productivity or carbon source/sinks at national, continental and global scales by data-model fusion [7, 27, 28].

Results will be different when different methods are used to assess the productivity of the same region or the world [29]. For example, regional NEP measured by eddy covariance [28] was significantly higher than the value estimated by the inventory method [30]. Researchers' understanding on the results obtained from different methods affect their evaluation of the ecological implications of their results. This is associated with the relaxed definitions of related concepts as well, e.g., ecosystem productivity, carbon storage, carbon loss, and carbon leakage, at different spatial and temporal scales [8]. Thus, Yu et al. [8] redefined the ecological meaning and the conceptual framework for terrestrial ecosystem productivity and different carbon fluxes at regional scales, and preliminarily determined the appropriate spatiotemporal scales and boundary conditions for various observational and assessment methods. This provided a more comprehensive conceptual framework and methodology system for quantifying ecosystem productivity, the carbon cycle and terrestrial carbon sinks at regional scales.

Based on the new conceptual framework proposed by Yu et al. [8] and multi-source data at different spatial and temporal scales, we quantified terrestrial ecosystem productivity and the distribution and consumption of carbon in a variety of ecological processes. The magnitude of the carbon source/sink in China was then approximated. The results provided reference information for the evaluation and analysis of the status of the terrestrial ecosystem carbon budget and for the potential increment of a carbon sink in China. The information can also be used as the important basis for decision-making analyses on carbon management in China.

2 Conceptual framework

Steffen et al. [31] and Chapin et al. [5] defined the relationships among GPP, NPP, NEP and NBP by integrating the driving mechanisms in forming productivity of large-scale regional biome-society system with the changes in carbon storage caused by various natural and anthropogenic disturbances, as well as the characteristics of terrestrial ecosystem carbon exchange at different spatial and temporal scales. In this analysis, based on the conceptual framework proposed by Yu et al. [8] and the biologically controlled processes and the spatiotemporal characteristics of carbon cycle in various natural ecosystems, we reconstructed the processes that affect productivity in a large-scale regional biome-society system that was influenced by natural and anthropogenic factors. The relationships of organic carbon distribution and consumption within different carbon pools and ecological processes were refined (Fig. 1), and then, we defined the ecological meaning of carbon source/sinks at different scales using the evaluation and data acquisition methods for the total regional amounts.

On basis of Fig. 1, we assumed that the entire terrestrial ecosystems in China were a large-scale regional biome-society system. By integrating multi-source data, the carbon fluxes of four key processes were quantified, including carbon fluxes of major natural processes in ecosystems, fluxes of emissions from reactive carbon and creature ingestion, carbon emissions caused by anthropogenic disturbances and the carbon losses caused by natural disturbances.

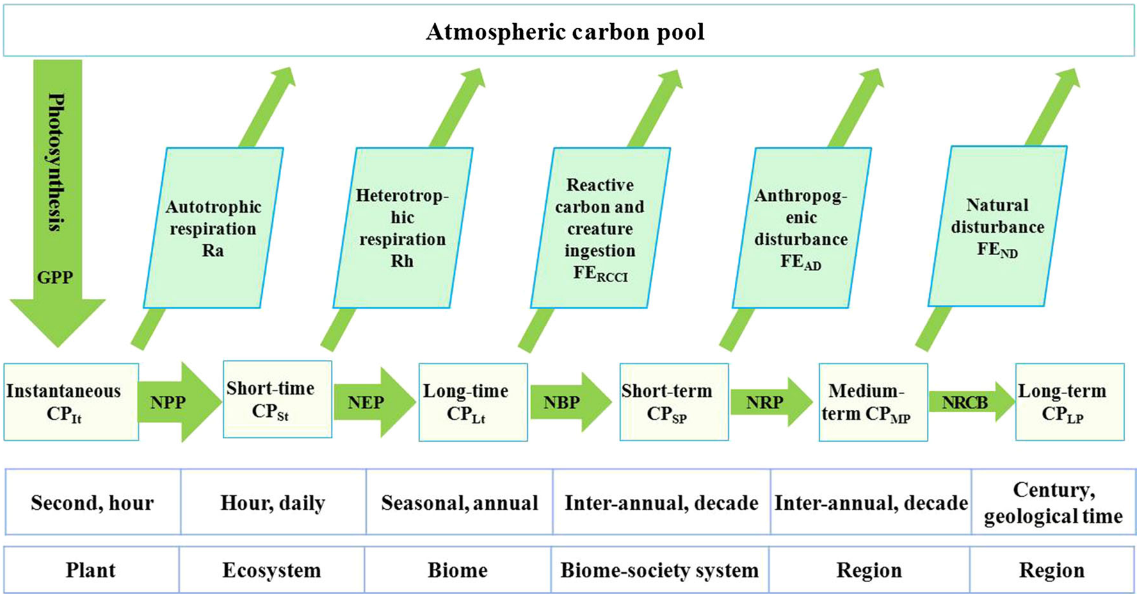

Fig. 1 Processes of transformation of productivity in a large-scale regional biome-society system affected by natural and anthropogenic factors, with long-term carbon exchange components (Redrawn based on Yu et al. [8]). The CP_{It} is carbon sequestration by instantaneous photosynthesis, which is a plant carbon pool at a time scale of seconds or hours. The CP_{St} is carbon stored in plants for a short time, which is a temporal ecosystem carbon pool with diurnal or daily variation. The CP_{Lt} is carbon stored in the biome for a long time, which is a short-time carbon pool with a seasonal or annual dynamic. The CP_{SP} is carbon stored in a regional biome-society system short-term, which is a short-term carbon pool with inter-annual or decadal variations. The CP_{MP} is carbon stored in regional terrestrial ecosystems medium-term, which is a medium-term carbon pool with inter-decadal or inter-century variations. The CP_{LP} is carbon stored in regional terrestrial ecosystems long-term, which is a long-term carbon pool with variations at inter-century or geological time scales. The GPP is gross primary productivity. The NPP is net primary productivity. The NEP is net ecosystem productivity. The NBP is net biome productivity. The NRP is net productivity of a regional biome-society system. The NRCB is the net regional carbon budget. The Ra is autotrophic respiration. The Rh is heterotrophic respiration. The FE_{RCCI} is the flux of emissions from reactive carbon and creature ingestion. The FE_{AD} is the flux of emissions from anthropogenic disturbances. The FE_{ND} is the flux of emissions from natural disturbances

2.1 NEP and carbon fluxes of major natural processes in ecosystems

In natural ecosystems without anthropogenic influences, the GPP produced by photosynthesis is sequentially converted into NPP and NEP through the autotrophic respiration (Ra) and heterotrophic respiration (Rh), as in the following equations:

$$\mathrm{NPP} = \mathrm{GPP} - \mathrm{Ra}, \tag{1}$$

$$\mathrm{NEP} = \mathrm{NPP} - \mathrm{Rh} = \mathrm{GPP} - \mathrm{Ra} - \mathrm{Rh}. \tag{2}$$

The conversion of NPP and NEP to the net carbon sequestration rate of plant populations and ecosystems for a particular geographical unit was easy [8] and provided a useful theoretical framework for analyzing ecosystem carbon fluxes. In general, the NPP was regarded as the material basis of aboveground and belowground biomass in plant communities, whereas the NEP was directly defined as the net carbon sequestration of natural ecosystems and was considered the climate-based potential carbon source/sink in the absence of anthropogenic and natural disturbances [26].

2.2 NBP and fluxes of emissions from reactive carbon and creature ingestion

Fluxes of emissions from reactive carbon (FE_{RC}) and creature ingestion (FE_{CI}) are two key components of carbon consumption in natural ecosystems. The net carbon sequestration after deducting fluxes of emissions from reactive carbon and creature ingestion (FE_{RCCI}) was defined as net biome productivity (NBP), which was the productivity used to accumulate carbon in ecosystems and was calculated as follows:

$$\mathrm{NBP} = \mathrm{NEP} - \mathrm{FE}_{\mathrm{RCCI}} = \mathrm{NEP} - \mathrm{FE}_{\mathrm{RC}} - \mathrm{FE}_{\mathrm{CI}}. \tag{3}$$

The FE_{RC} was the total emission fluxes of non-CO_2 carbon compounds produced by a variety of ecosystem respiration processes, including methane (CH_4), non-methane volatile organic compounds (NMVOC) and carbon monoxide (CO) [32].

The FE_{CI} referred to the total carbon emission fluxes are caused by wildlife ingestion (FE_{CIW}), diseases, pests and rats (FE_{CII}), and human gathering activities within the normal range (FE_{CIH}).

2.3 NRP and flux of emissions from anthropogenic disturbances

For a regional biome-society system influenced by human activities, anthropogenic disturbances strongly affected the carbon emissions from ecosystem. As a consumer in the ecosystem, humans consume ecosystem production in various forms of agricultural and forestry products and return carbon to the atmosphere. Human activities include food and fiber collection, grazing and livestock feeding, timber harvesting and fuel use, and the input and output of agroforestry products through the boundaries. After deducting fluxes of emissions from anthropogenic disturbances ($\mathrm{FE_{AD}}$), the net carbon storage was defined as the net productivity of a regional biome-society system (NRP).

$$\mathrm{NRP} = \mathrm{NBP} - \mathrm{FE_{AD}}. \tag{4}$$

2.4 NRCB and flux of emissions from natural disturbances

Natural disturbances are also important factors causing ecosystem carbon loss at a long-term scale. The net carbon storage in vegetation and soil is the carbon remaining in storage after deducting the fluxes of emissions from natural disturbances ($\mathrm{FE_{ND}}$). This is the terrestrial ecosystem carbon source/sink in the conceptual framework of IPCC and is also the change in carbon storage monitored by inventory methods at mid- and long-term scales. We defined this component as the net regional carbon budget (NRCB) at the medium- or long-term scales, and the NRCB was the net carbon source/sink in terrestrial ecosystems.

In general, the $\mathrm{FE_{ND}}$ included emissions from physical processes ($\mathrm{FE_p}$) such as forest and grassland fires and fluxes of geological carbon leakage ($\mathrm{FL_G}$) such as water erosion ($\mathrm{FL_{Gwa}}$), wind erosion ($\mathrm{FL_{Gwi}}$) and seepage ($\mathrm{FL_{Gs}}$). For local geographical environments, the $\mathrm{FL_{Gs}}$ was defined as the sum of carbon seepage from the earth surface to underground and the carbon fluxes directly caused by organic carbon conversion to soil mineral components during geochemical mineralization processes. Thus, the NRCB of a large geographical region at a long-term scale was calculated as follows:

$$\begin{aligned}\mathrm{NRCB} &= \mathrm{NRP} - \mathrm{FE_{ND}} = \mathrm{NRP} - \mathrm{FE_p} - \mathrm{FL_G} \\ &= \mathrm{NRP} - \mathrm{FE_p} - \mathrm{FL_{Gwa}} - \mathrm{FL_{Gwi}} - \mathrm{FL_{Gs}}\end{aligned} \tag{5}$$

3 Materials and methods

3.1 Assessment methods

(i) Assessment schemes for NEP and carbon fluxes of major natural processes in ecosystems

In this study, we assessed the regional NEP and carbon fluxes of major natural processes based on eddy covariance measurements. By integrating observational data from ChinaFLUX sites and published carbon flux data from other sites in China, Yu et al. [33] found that mean annual temperature (MAT) and mean annual precipitation (MAP) affected the spatial patterns of annual GPP, NEP and ER. Based on the results from Yu et al. [33], Zhu et al. [19] constructed several types of assessment schemes to assess the spatial patterns of carbon fluxes and selected the optimal assessment scheme for GPP as follows:

$$\begin{aligned}\mathrm{GPP} &= 107.02\mathrm{MAT} + 2.18\mathrm{MAP} - 0.10\mathrm{MAT} \times \mathrm{MAP} \\ &\quad - 544.35 \quad \left(R^2 = 0.79,\ n = 41\right).\end{aligned} \tag{6}$$

The optimal assessment scheme for ER was determined by the spatial positive coupling correlation between GPP and ER as follows:

$$\mathrm{ER} = 0.68\mathrm{GPP} + 81.90. \tag{7}$$

The optimal scheme for NEP was then calculated as follows:

$$\mathrm{NEP} = \mathrm{GPP} - \mathrm{ER}. \tag{8}$$

Though the equations above [Eqs. (6)–(8)] are quite simple in form, they have high credibility with the correlation coefficients ranging from 0.8 to 0.9 [19].

The NPP cannot be directly measured by eddy covariance technique, while a large number of studies found that the ratio of Ra to GPP was approximately 0.5 [34–37]. Thus, we speculated that NPP/GPP is also approximately equal to 0.5. To simplify, we estimated the annual NPP, Ra and Rh in China by assuming that NPP/GPP = Ra/GPP = 0.5 and Rh = ER − Ra.

(ii) Assessment schemes for NBP and fluxes of emissions from reactive carbon and creature ingestion

It was extremely difficult to directly observe NBP and fluxes of emissions from reactive carbon and creature ingestion at regional scale. However, much progress has been made in research on $\mathrm{CH_4}$ and NMVOC emissions. Additionally, the proportion of $\mathrm{F_{RC}}$ in the productivity allocation is relatively small. Therefore, we re-estimated $\mathrm{FE_{RC}}$ based on published $\mathrm{CH_4}$ and NMVOC emission data in the literature. The assessment calculations for specific reactive carbon compounds were

$$\mathrm{FE_{RC}} = \mathrm{FE_{CH_4}} + \mathrm{FE_{NMVOC}} + \mathrm{FE_{CO}}, \tag{9}$$

$$\mathrm{FE_{CH_4}} = \mathrm{FE_{Rice}} + \mathrm{FE_{NW}} + \mathrm{FE_{Lake}} + \mathrm{FE_{Plant}}, \tag{10}$$

$$\mathrm{FE_{NMVOC}} = \mathrm{FE_{Plant}}. \tag{11}$$

The $\mathrm{FE_{CH_4}}$, $\mathrm{FE_{NMVOC}}$ and $\mathrm{FE_{CO}}$ in Eq. (9) were emissions of $\mathrm{CH_4}$, NMVOC and CO, respectively. The

FE_{Rice}, FE_{NW}, FE_{Lake} and FE_{Plant} in Eq. (10) were CH_4 emissions from rice paddies, natural wetlands, lakes and terrestrial plants, respectively. The FE_{Plant} in Eq. (11) was the NMVOC emissions from terrestrial plants.

Because of their random occurrence time and intensity and ability to move among regions, carbon fluxes caused by creature ingestion (FE_{CI}) were difficult to evaluate through *in situ* observational methods or zonal statistical methods. In view of the difficulties in calculating FE_{CIW} and FE_{CIH} and their small proportions in the allocation of carbon, we did not calculate them separately in this paper but just calculated the FE_{CII} for different ecosystem types.

For forest ecosystems, in combination with carbon density per unit area [38], inventory data on disaster areas and disaster intensities were used to calculate the carbon emissions caused by diseases, pests and rats in forests [39].

The FE_{CII} in grassland ecosystems was calculated by reference to the computing method for forest ecosystems and used data for disaster areas, disaster intensities and carbon densities per unit area. Data of disaster areas provided by National Bureau of Statistics in 2010 were used. Disaster intensities were estimated by reference to the moderate class data (15 %) in Su et al. [38], whereas the national averaged carbon consumption intensity of grass products per unit area was used as the carbon density per unit area.

The intensity of diseases, pests and rats in cropland ecosystems was small because of the intense artificial management. Hence, the FE_{CII} for cropland was neglected in this study.

(iii) Assessment schemes for NRP and flux of emissions from anthropogenic disturbances

Assessing the carbon consumption caused by anthropogenic disturbances was quite complex because these activities were mainly regulated by the market behavior of goods and were also highly mobile. Therefore, the most feasible method was to approximate the total amounts according to the levels of intra-region macroeconomic activity and the corresponding carbon consumption coefficients. Carbon consumption caused by anthropogenic disturbances (FE_{AD}) was primarily comprised of carbon consumption by agriculture and forestry use (CCU), including carbon consumption of agricultural products (referred to food and fiber) (CCU_C), carbon consumption of grazing and livestock feeding (CCU_G) and carbon consumption of forestry products (e.g., timber, fuel and crude medicine) (CCU_F). Thus, the NRP was calculated as follows:

$$\begin{aligned}\mathrm{NRP} &= \mathrm{NBP} - \mathrm{FE_{AD}} = \mathrm{NBP} - \mathrm{CCU} \\ &\approx \mathrm{NBP} - \mathrm{CCU_C} - \mathrm{CCU_G} - \mathrm{CCU_F}.\end{aligned} \tag{12}$$

The China Statistical Yearbook published economic yields of various crops but did not provide yields of non-food products. Therefore, the CCU_C was calculated with the yields of agricultural products (Y_i), the crop harvest index (HI_i), the water content (Cw_i) and the carbon fraction of dry matter (C_{Ci}) following Zhu et al. [40]:

$$CCU_C = \sum_{i=1}^{n} \{Y_i \times (1 - Cw_i)/HI_i\} \times C_{Ci}, \tag{13}$$

where i represented different crops, HI was the ratio of crop harvest yield to total dry matter, Cw_i referred to published data in the literature, and C_{Ci} was set at 0.45 [40].

The CCU_G was calculated as follows:

$$CCU_G = Y_G \times (1 - Cw_G)/HI_G \times C_{CG}, \tag{14}$$

where Y_G was hay yield. The Cw_G was the water content of the hay, which is set at 14 % according to the national standards. The HI_G was the harvest index of hay, which was set at 1 because the yield referred to the hay used by livestock. C_{CG} was the carbon fraction of dry matter, which was also set at 0.45 [40].

We calculated CCU_F using the harvest yield of forest products and used index as follows:

$$CCU_F = \sum_{i=1}^{n} \{B_i/UI_i\} \times C_{Fi}. \tag{15}$$

In Eq. (15), i was round wood, bamboo and fuel wood, B_i represented the biomass. The UI_i was the rate of use, in which the UI for round wood and bamboo was 0.535 and the UI for fuel wood was 0.65 [40]. The C_{Fi} was carbon fraction of dry matter for forest products with a value of 0.5.

The biomass of round wood, bamboo and fuel wood was obtained according to the yields as follows:

$$B_Y = \rho_Y V_Y, \tag{16a}$$

$$B_Z = nM, \tag{16b}$$

$$B_X = \rho_X V_X. \tag{16c}$$

In Eq. (16), B_Y, B_Z and B_X were the biomass of round wood, bamboo and fuel wood, respectively. The ρ_Y was the basic density of round wood, which was equal to 0.485 t m^{-3} [41]. The V_Y was the annual production of round wood. The n was the tree number of bamboo, and M was the average biomass per individual bamboo, which was 63.46 kg $individual^{-1}$ [41]. The ρ_X was basic density of fuel wood, which was also 0.485 t m^{-3}. The V_X was the annual production of fuel wood.

(iv) Assessment schemes for NRCB and flux of emissions from natural disturbances

Because of the random occurrence in time and location, it was difficult to monitor *in situ* and quantify the effects of natural disturbances mentioned above. Therefore we regarded the disturbance factors as random and obtained their statistical probabilities for a specific region at long-term scales from historical records.

Table 1 Yearly averaged concentrations of dissolved carbon in the major rivers in China

River	$DOC\%$ (mgC L^{-1})	References	$DIC\%$ (mgC L^{-1})	References
Yangtze River	2.07	[43]	20.597	[44]
Yellow River	1.76	[43]	38.892	[44]
Huaihe River	1.986	This study[a]	24.205	[44]
Haihe River	1.986	This study[a]	44.675	[44]
Pearl River	2.0	[43]	20.844	[45]
Songhua River	1.986	This study[a]	6.547	This study[b]
Liaohe River	1.986	This study[a]	6.547	[44]
Qiantang River	2.1	[43]	8.860	[44]
Minhe River	1.986	This study[a]	5.823	[44]

[a] The concentration of DOC for the Huaihe River, Haihe River, Songhua River, Liaohe River and Minhe River was from the averaged concentration of DOC for other rivers (i.e., Yangtze River, Yellow River, Pearl River and Qiantang River) from the literature, because no data were available

[b] The concentration of DIC for the Songhua River was from the data of the Liaohe River, because no data were available

The carbon emissions from fires could have been caused by either natural or anthropogenic sources, which were difficult to distinguish. Based on the assessment method proposed by Fu et al. [39], the carbon emissions caused by forest fires were estimated as follows:

$$FE_{\mathrm{p}} = \sum (A \times M_i \times CF_i) \times 0.5, \tag{17}$$

where A was the burned area, M was fuel density (mass of fuel available for combustion per unit area burned), and CF was the combustion factor (i.e., the fraction of fuel consumed during fires). The i was the fuel component (aboveground biomass, surface litter and dead wood), and 0.5 was the carbon fraction of dry matter. The carbon emissions from grassland fires were negligible because the burned area of grassland was relatively small according to the data from National Bureau of Statistics.

Many studies focused on the carbon leakage caused by water and wind erosion. However, it was likely that local-scale carbon leakage caused by water and wind erosion was transferred to other regions of the study area. Thus, when analyzing the regional carbon budget, clear geographical boundaries were identified and only the components removed outside of the boundaries were considered. Therefore, we recognized the boundaries of China and only analyzed the carbon flowing into the ocean from rivers and considered it to be the carbon leakage caused by water erosion ($\mathrm{FL_{Gwa}}$). Moreover, because of data limitations, only nine major rivers were analyzed in this study. Furthermore, we set the carbon leakage caused by wind erosion 0 by assuming the output equals to the input due to data limitation.

The carbon delivered from rivers to the ocean occurred in four forms, particulate organic carbon (POC), particulate inorganic carbon (PIC), dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC). The flux of particulate carbon (FPC), which was the sum of the fluxes of PIC and POC, was calculated by multiplying the total suspended sediment (TSS) by the concentration of POC ($POC\%$) or PIC ($PIC\%$) as follows [42]:

$$FPIC = TSS \times PIC\%, \tag{18a}$$

$$FPOC = TSS \times POC\%, \tag{18b}$$

where $FPIC$ and $FPOC$ were the fluxes of PIC and POC, respectively. The data for TSS from the nearest site to the river entrance were used.

The flux of dissolved carbon (FDC), which was the sum of fluxes of DIC and DOC, was calculated by multiplying river runoff (R) by the concentration of DOC ($DOC\%$) or DIC ($DIC\%$) as follows:

$$FDIC = R \times DIC\%, \tag{19a}$$

$$FDOC = R \times DOC\%. \tag{19b}$$

In Eq. (19), the $FDIC$ and $FDOC$ were fluxes of DIC and DOC, respectively. The data for runoff from the nearest site to the river entrance were used. The $DOC\%$ and $DIC\%$ of the major rivers in China are shown in Table 1.

In this study, the $\mathrm{FL_{Gwa}}$ was calculated as the sum of FPC and FDC.

Currently, studies are rare on regional carbon seepage processes, particularly studies on the effects on regional carbon balance. Thus, the effects were assumed to be small and were not considered in this study.

3.2 Dataset

(i) *Climate data* The annual climate data including MAT and MAP at a 1 km × 1 km spatial resolution were generated from the data of 756 climate stations from the Climate Meteorological Administration from 2001 to 2010 [19] using the interpolation software AUSPLINE and the 1-km DEM data [46, 47].

(ii) *Vegetation data* The Vegetation Map of China [48] was used to analyze the spatial patterns of the carbon budget for different ecosystem types. The 11 vegetation groups were coniferous forest, mixed forest, broadleaved forest, shrub, meadow, steppe, grass–forb community, desert, swamp, alpine vegetation and planted vegetation, and they were reclassified into four ecosystem types: forest, shrubland, grassland and cropland [19].

(iii) *Social statistics* From the *China Statistics Yearbook 2001–2010* released by the National Bureau of Statistics, we found the data for the production, annual occurrence areas of diseases, pests and rats, and burned area of fires in each province. After 2004, the hay yield data for some provinces and the country were from the National Grassland Monitoring Report released by the Grassland Supervision Division of the Ministry of Agriculture. The yield data of main forestry products including round wood, bamboo and fuel wood for each province were from the *China Forestry Statistics 2001–2010* released by the Ministry of Forestry. The data on runoff and carbon content of the major rivers were from Chinese hydrological data.

4 Results

4.1 GPP, NPP, NEP and ER

Based on the optimal assessment schemes for the spatial patterns of carbon fluxes (Eqs. (6)–(8)), we calculated the total annual GPP, ER and NEP during 2000–2010 (Table 2), which were 7.78, 5.89 and 1.89 PgC a^{-1}[19], respectively. By assuming that the ratio of NPP to GPP was 0.5, the NPP and Ra were both approximately 3.89 PgC a^{-1}. Thus, the NEP accounted for approximately 24.29 % of the total GPP in China.

Table 2 Major natural carbon fluxes of terrestrial ecosystems in China during 2001–2010

Carbon flux	Amount (PgC a^{-1})	Percentage of GPP (%)	Method
GPP	7.78	100	Section 3.1 (i)
NPP	3.89	50	Section 3.1 (i)
NEP	1.89	24.3	Section 3.1 (i)
ER	5.89	75.7	
Ra	3.89	50	Section 3.1 (i)
Rh	2.00	25.7	

4.2 Fluxes of emissions from reactive carbon and creature ingestion and NBP

Reactive carbon compounds in ecosystems include methane (CH_4), non-methane volatile organic compounds (NMVOC) and carbon monoxide (CO). Rice paddies, natural wetlands, lakes and terrestrial plants are the four key sources of CH_4 emissions in terrestrial ecosystems.

The total CH_4 emissions from rice paddies in China were documented in previous studies (Table 3). Briefly, these results might be divided into three categories: (1) Estimates that were simulated primarily from a semiempirical model developed by Huang et al. [49] and the revised model (CH4MOD) [50] ranged from 3.99 to 15.15 TgC a^{-1} [50–57]; (2) estimates that were calculated with emission factors as the main input parameter ranged from 5.56 to 9.50 TgC a^{-1} [58–60]; and (3) estimates that were obtained through a meta–analysis method ranged from 3.90 to 8.52 TgC a^{-1} [61, 62]. By summarizing these results, the CH_4 emissions from rice paddies in China ranged from 3.90 to 15.15 TgC a^{-1}, with an average of approximately 6.43 TgC a^{-1}.

Studies on the total CH_4 emissions from natural wetlands and lakes are rare in China.

In a review of the CH_4 flux measurements from different types of natural wetlands and lakes in different regions of China determined by static chamber method, Chen et al. [61] estimated that the total CH_4 emissions from natural wetlands and lakes (including reservoirs and ponds) in China were 2.02 TgC a^{-1} (ranging from 1.85 to 2.40 TgC a^{-1}) and 0.35 TgC a^{-1} (ranging from 0.25 to 0.44 TgC a^{-1}), respectively.

Additionally, it was reported that terrestrial plants also emit CH_4 under aerobic conditions [63]. Combining the CH_4 emission model of terrestrial plants with an atmospheric chemistry model, Xie et al. [64] simulated the methane emissions from terrestrial plants in China and found the emissions were 8.87 TgC a^{-1}.

Thus, according to Eq. (10), the total CH_4 emissions from terrestrial ecosystems in China ranged from 14.87 to 26.86 TgC a^{-1}, with an approximate average of 17.67 TgC a^{-1}.

Based on the simulation method proposed by Guenther et al. [65, 66], the annual NMVOC emissions from terrestrial vegetation in China were estimated and ranged from 13.23 to 17.1 TgC a^{-1} [67, 68], with an average of 15.17 TgC a^{-1}. Few studies on Chinese CO emissions were found. Hence, based on the global average for CO emissions from vegetation reported by Guenther [32], we approximated the CO emission flux in China, which was 38.50 TgC a^{-1}.

Thus, according to Eq. (9) and the emission fluxes of CH_4, NMVOC and CO, the carbon fluxes of emissions

Table 3 Total CH_4 emissions from rice paddies in China reported in previous studies

Method	CH_4 emission (Tg C a^{-1})	Study period	Reference
A semiempirical model developed by Huang et al. [49]	5.39–10.22	1991–1995	[51]
Revised model of Huang et al. [49]	6.95	2000	[67]
Revised model of Huang et al. [49]	5.63	2007	[54]
CH4MOD	3.99–4.67	1990–2000	[53]
CH4MOD	4.52	2000	[69]
DNDC model	5.7	2000	[55]
Based on a conversion ratio of NPP to CH_4	4.39–5.43	1990–2000	[56]
Model with changing land use	15.15	1991	[57]
Based on emission factor	5.56	–	[58]
Based on emission factor	7.25–9.50	1990	[60]
A category based on organic manure and water regime	6.04 ± 2.77	1993	[59]
Meta-analyses	4.37–7.18	–	[62]
Meta-analyses	3.90–8.52	2008	[61]

from reactive carbon (FE_{RC}) in China ranged from 66.60 to 82.46 TgC a^{-1}, with an average of approximately 71.34 TgC a^{-1} (Table 4). It was difficult to estimate all components of carbon fluxes of emissions from creature ingestion (FE_{CI}) and only emissions caused by diseases, pests and rats in forest and grassland ecosystems were approximated, which were 4.29 and 2.47 TgC a^{-1}, respectively (Table 4). According to Eq. (3), the net biome productivity (NBP) was approximately 1.812 PgC a^{-1}, accounting for 23.29 % of GPP.

4.3 Carbon consumption by agricultural and forestry use (CCU) and NRP

Based on Eqs. (12)–(16), we estimated that the total carbon consumption by agricultural and forestry use (CCU) in China was about 0.806 PgC a^{-1}, of which CCU for agricultural products, hay use and forestry products was 0.631, 0.115 and 0.060 PgC a^{-1}, respectively [40] (Table 5). Thus, the NRP in China was about 1.006 PgC a^{-1} and accounted for about 12.93 % of the GPP.

4.4 Flux of emissions from natural disturbances and NRCB

Many studies were conducted on the global emissions from fires and the results ranged from 1.4 to 3.1 PgC a^{-1} [70–72]. Research on carbon emissions from forest fires was also conducted in China, but large differences were found among the results. The estimates of annual carbon emissions from forest fires in China ranged from 8.55 to 13.9 TgC a^{-1} from 1950 to 2000 in Lü et al. [73] and from 20.24 to 28.56 TgC a^{-1} from 1991 to 2000 in Tian et al. [74, 75]. However, the mean emissions from forest fires in Piao et al. [25] were only 0.003 PgC a^{-1} between 1980 and 2000. In this study, based on the method proposed by Fu

Table 4 Fluxes of emissions from reactive carbon and creature ingestion in China

Disturbance	Amount (TgC a^{-1})	Percentage of NEP	Method
Reactive carbon	71.34	3.78	Section 3.1 (ii)
CH_4	17.67	0.93	Section 3.1 (ii)
NMVOC	15.17	0.80	
CO	38.50	2.04	
Creature ingestion	6.76	0.36	Section 3.1 (ii)
FE_{CIW}	–	–	–
FE_{CII}	6.76	0.36	Section 3.1 (ii)
FE_{CIH}	–	–	–

The FE_{CIW} is the flux of emissions from wildlife ingestion. The FE_{CII} is the flux of emissions from diseases, pests and rats. The FE_{CIH} is the flux of emissions from human gathering activities within the normal range

Table 5 Carbon consumption by agricultural and forestry use (CCU) in China during 2001–2010

Anthropogenic disturbance	Amount (PgC a^{-1})	Percentage of NEP (%)	Method
CCU	0.806	42.65	Section 3.1 (iii)
CCU_C	0.631	33.39	Section 3.1 (iii)
CCU_G	0.115	6.08	
CCU_F	0.060	3.17	

The CCU_C is the carbon consumption of agricultural products. The CCU_G is the carbon consumption of grazing and livestock feeding. The CCU_F is the carbon consumption of forestry products et al. [39], we estimated the total carbon emission from forest fires from 2000 to 2010 in China was 23.81 TgC, with mean annual emissions of approximately 2.16 TgC a^{-1} (Table 6).

The estimates for carbon fluxes delivered from the rivers to the ocean were about 1.8 and 0.081 PgC a^{-1}, according to Raymond et al. [76] and Fang et al. [77], respectively. On basis of the hydrological data of nine major rivers in China and Eqs. (18) and (19), we re-estimated the amounts of carbon flowed into the ocean (Table 7) and considered the sum as the terrestrial carbon leakage caused by water erosion in China, which was about 38.22 TgC a^{-1}.

Thus, according to Eq. (5), the net regional carbon budget (NRCB) was about 0.966 PgC a^{-1} in China and accounted for 12.42 % of the GPP, 24.83 % of the NPP, 53.31 % of the NBP and 96.02 % of the NRP.

Table 6 shows that the carbon emissions from forest fires were relatively small and contributed only about 0.1 % of the NEP, while carbon emissions from water erosion accounted for about 2 % of the NEP.

Table 6 Flux of emissions from natural disturbances in China during 2001–2010

Natural disturbance	Amount (TgC a^{-1})	Percentage of NEP (%)	Method
FE_p	2.16	0.114	Section 3.1 (iv)
FL_G	38.22	2.022	Section 3.1 (iv)
FL_{Gwa}	38.22	2.022	Section 3.1 (iv)
FL_{Gwi}	–	–	–
FL_{Gs}	–	–	–

The FE_p represents the carbon emissions from physical processes (i.e., fires). The FL_G represents the flux of geological carbon leakage such as water erosion (FL_{Gwa}), wind erosion (FL_{Gwi}) and seepage (FL_{Gs})

5 Discussion

5.1 Carbon budget components of terrestrial ecosystems in China

Many researchers have evaluated the key components of carbon budget in China using resource inventory method and process-based ecological models or remote sensing models, as well as the strength of carbon sink of different ecosystem types and nationwide [13, 25, 78]. In this study, however, we proposed a new way to assess the carbon budget of a large region (i.e., large-scale regional biome-society system) from a new perspective.

We assumed that the entire terrestrial ecosystem of China was an independent natural geographical unit. By considering the biogeographical processes that affected components of the carbon budget and the availability of regional data, the terrestrial ecosystem productivity and the carbon fluxes consumed by various natural and anthropogenic activities during 2001–2010 in China were approximated by integrating multi-source data. Then, based on the conceptual model presented in Fig. 1, we drew the relational schema of terrestrial ecosystem productivity and carbon budget components in China (Fig. 2).

Figure 2a shows that terrestrial ecosystems in China had a quite high carbon sequestration capacity, with a gross primary productivity (GPP) of approximately 7.78 PgC a^{-1}. The vegetation autotrophic respiration consumed about half of the total GPP which resulted in 3.89 PgC a^{-1} of net primary productivity (NPP). Heterotrophic respiration consumed 2.0 PgC a^{-1} of NPP and resulted in 1.89 PgC a^{-1} of NEP. Of the NEP, reactive carbon and creature ingestion consumed 0.078 PgC per year, leading to 1.812 PgC a^{-1} of net biome productivity (NBP). Moreover, agricultural and forestry use was an important pathway for carbon consumption, with an average of 0.806 PgC a^{-1}. The NRP in China was thus approximately 1.006 PgC a^{-1}. Additionally, the total carbon leakage from forest fires and various geological processes was about 0.04 PgC a^{-1} at the long-term scale. Finally, the net regional carbon budget (NRCB) in China was about 0.966 PgC a^{-1}, which was equivalent to approximately 42.74 % of the total carbon emissions from fossil fuels in China during 2010.

The carbon budget components of terrestrial ecosystems in China (Fig. 2a) indicated that anthropogenic disturbances had an important effect on the carbon sink of terrestrial ecosystems. Approximately 42.65 % of net ecosystem productivity (NEP) was removed from ecosystems in the form of agriculture, forestry and grass products that were consumed by human activities. The effects of natural disturbances such as water erosion, wind erosion

Table 7 Carbon fluxes flowing to the ocean from major rivers in China (TgC a^{-1})

River	POC	PIC	DOC	DIC	Sum
Yangtze River	3.287	1.522	1.735	17.268	23.812
Yellow River	0.902	3.094	0.032	0.712	4.740
Huaihe River	0.128	0.051	0.071	0.867	1.117
Haihe River	0.000	0.000	0.001	0.013	0.014
Pearl River	0.825	0.285	0.509	5.302	6.921
Songhua River	0.202	0.129	0.090	0.296	0.717
Liaohe River	0.013	0.016	0.005	0.015	0.049
Qiantang River	0.056	0.019	0.038	0.159	0.272
Minhe River	0.127	0.038	0.106	0.311	0.582

The POC is particulate organic carbon. The PIC is particulate inorganic carbon. The DOC is dissolved organic carbon. The DIC is dissolved inorganic carbon

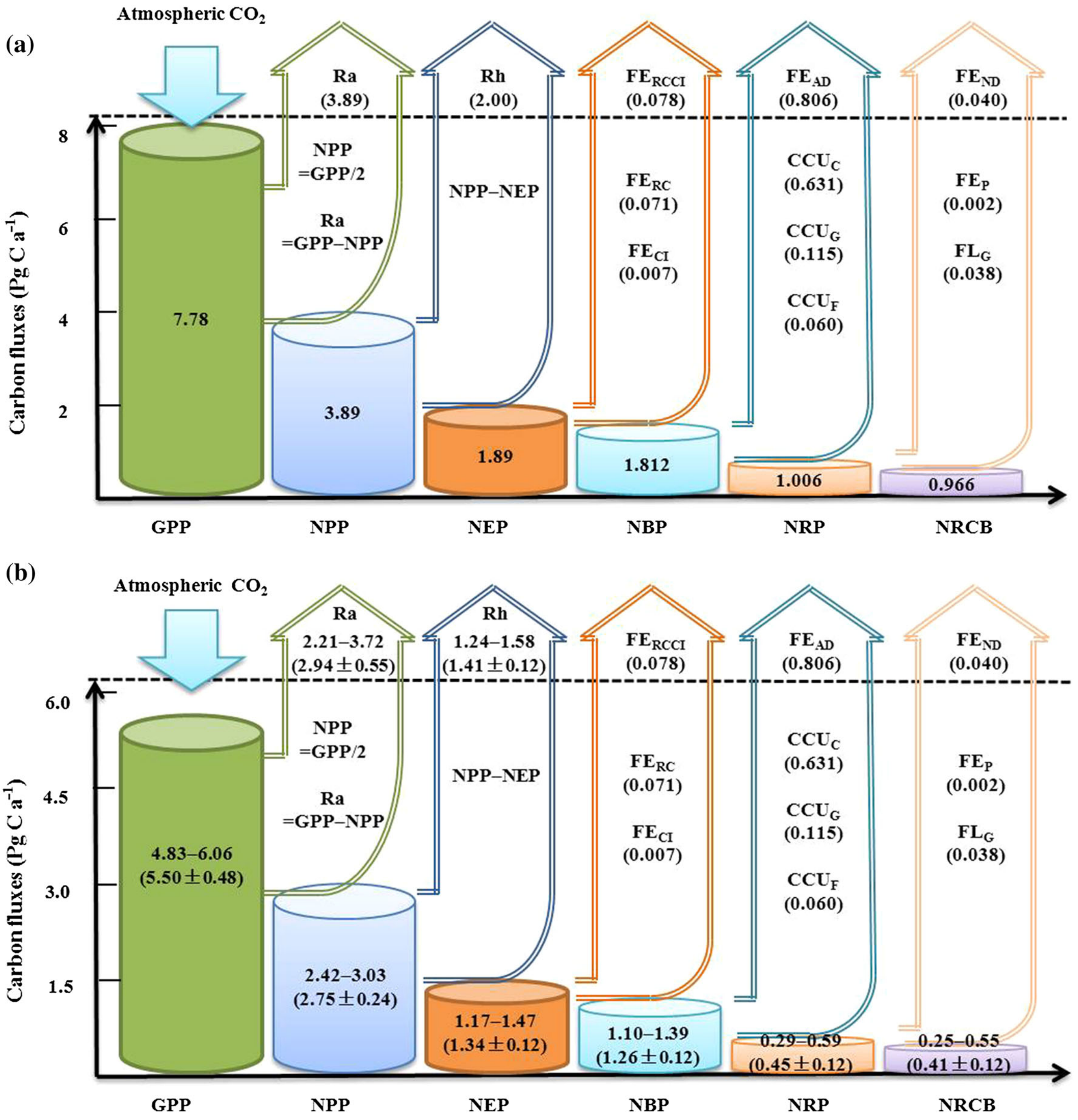

Fig. 2 Carbon budget components and carbon sink/source formation of terrestrial ecosystems in China during 2001–2010. The GPP in **a** and **b** are estimates from this study and from data collected in the literature, respectively. The Ra is autotrophic respiration. The Rh is heterotrophic respiration. The FE_{RCCI} is the flux of emissions from reactive carbon (FE_{RC}) and creature ingestion (FE_{CI}). The FE_{AD} is the flux of emissions from anthropogenic disturbances. The CCU_C is the carbon consumption of agricultural products. The CCU_G is the carbon consumption of grazing and livestock feeding. The CCU_F is the carbon consumption of forestry products. The FE_p is the carbon emission from physical processes such as forest and grassland fires. The FL_G is flux of geological carbon leakage. The GPP is gross primary productivity. The NPP is net primary productivity. The NEP is net ecosystem productivity. The NBP is net biome productivity. The NRP is net productivity of a regional biome-society system. The NRCB is the net regional carbon budget

and fire affected the NEP, but the effects were significantly less than those of anthropogenic disturbances. The carbon emissions caused by human use were up to 0.806 PgC a^{-1}, which was 6.83-fold greater than that caused by various natural disturbances (0.118 PgC a^{-1}). Therefore, it is of great significance to increase the scientific evaluation of carbon management of human activities.

5.2 Relationship of NEP with strength of carbon sink (NRCB) at a regional scale

Large differences exist among the estimations of productivity for the same region or the world when different approaches are used [29]. The NEP estimated in this study differed largely from the carbon sink estimates obtained by other researchers using models [79] and the biomass inventory method [25, 30] because of the ambiguity in the definitions of concepts related to terrestrial ecosystem productivity and carbon budget components.

In general, the net ecosystem exchange determined by eddy covariance method was defined as NEP, whereas the change in carbon storage measured by the biomass inventory method was also defined as NEP. From these definitions, the NEP was regarded as the net carbon budget of ecosystems (NRCB). For natural ecosystems, which had no strong natural and anthropogenic disturbances, previous studies showed that the NEP obtained by the biomass inventory method and eddy covariance method agreed well with each other [80–82]. However, for ecosystems strongly affected by human activities at a regional scale (biome-society system), especially at a long-term scale, anthropogenic and natural disturbances still exist, including food collection, timber harvesting, burning of plant residues, fires, water erosion and other geological processes that cause carbon leakage. Hence, the NEP measured by eddy covariance method will be significantly higher than the NEP obtained by biomass inventory method, and their ecological implications will be significantly different. In this case, the NEP obtained by eddy covariance method could be considered the climate-based potential value of the ecosystem carbon sink, while the NEP obtained by biomass inventory method might be equivalent to NBP, NRP or NRCB.

5.3 Uncertainty in the assessment of carbon sink

Based on the regional carbon fluxes extrapolated from the site flux data and carbon emissions obtained from multiple approaches, we approximated the strength of carbon sink of terrestrial ecosystems in China. And our estimate was significantly higher than that during 1981–2000 based on a variety of ways [25], and was also higher than the sink during 2001–2010 (0.28–0.33 PgC a^{-1}, Table 8) obtained from atmospheric inversion method [24, 83], models [79] and resource inventory method [84, 85]. These differences resulted primarily for two reasons. First, many studies demonstrated that the strength of carbon sink of this decade was obviously larger than the level at the end of last century [79], whereas the estimate in this study corresponded to the period from 2001 to 2010. Second, the GPP used in this study was calculated from climatic factors, which could be regarded as the potential value of GPP under the current climatic conditions. Thus, the GPP used in this study was significantly overestimated compared with the values reported in the previous studies (Table 8).

Although the GPP used in this study was higher than the previous research results, this study provided values of the net ecosystem productivity (NEP) and the ecosystem respiration (ER) nationwide for the first time, which were vital in the evaluation of the strength of the regional carbon sink based on the method proposed in this study. Hence, this GPP was chosen for our study.

Table 8 Results of main carbon fluxes in China during 2001–2010 reported in previous studies

Model	Study period	GPP	NPP	NEP	NRCB	Reference
EC_LUE	2001–2010	6.04	3.02[b]	–	–	[86]
MODIS[a]	2001–2010	5.47	2.74[b]	–	–	[86]
Model tree ensemble approach[a]	2001–2010	6.06	3.03[b]	–	–	[28]
BEPS	2000–2010	5.48[c]	2.74	–	–	[87]
GEOLUE	2000–2004	5.68[c]	2.84	–	–	[88]
GEOPRO	2000	4.83[c]	2.416	–	–	[88]
CASA	2001	4.96[c]	2.478	–	–	[89]
Model tree ensemble approach[a]	2001–2008	–	–	1.02	–	[28]
Atmospheric inversion method	2002–2008	–	–	–	0.31	[83]
Atmospheric inversion method	2001–2010	–	–	–	0.33	[24]
DLEM	2001–2005	–	–	–	0.28	[79]
Resource inventory method	2004–2008				0.29[d]	[84, 85]

[a] GPP and NEP of terrestrial ecosystems in China from MODIS and model tree ensemble approach were extracted from corresponding global database

[b] Only data of GPP were reported. NPP were calculated based on NPP/GPP = 0.5

[c] Only data of NPP were reported. GPP were calculated based on NPP/GPP = 0.5

[d] The strength of carbon sink of vegetation in forest ecosystems (including economic forests) in China was 0.204 PgC a^{-1} during 2004–2008 [84]. By assuming no differences in the strength of carbon sink of forests' soil, grassland and cropland comparing with the level [85] at the end of last century, the national carbon sink was about 0.29 PgC a^{-1}

Additionally, based on the GPP values collected from the literature, we found a much lower carbon sink through our framework, which was comparable to previous studies (Table 8). The mean GPP of terrestrial ecosystems in China based on data collected from the literature was 5.50 ± 0.48 PgC a^{-1}, and the NPP was 2.75 ± 0.24 PgC a^{-1}. Using the relationship between NEP and NPP defined in this study, we calculated the mean NEP as 1.34 ± 0.12 PgC a^{-1} (Fig. 2b). The magnitude of carbon sink obtained with this approach was therefore about 0.41 ± 0.12 PgC a^{-1} (Fig. 2b), which was slightly higher but was consistent with existing research results (Table 8). The 'slightly higher' carbon sink primarily resulted from an underestimation of ER, and hence, the NEP was overestimated. The NEP in this study was obtained primarily from measurements from undisturbed ecosystems, which had a higher ratio of NEP to GPP. The strength of NEP was thereby overestimated, which made the carbon sink slightly higher than previous studies. However, our result was of a similar magnitude from previous studies, which confirmed the credibility of our research approach and that the small uncertainties in other carbon fluxes such as FE_{RC}, FE_{CI}, FE_{AD} and FE_p were acceptable.

Because the GPP used in this study was the climatic potential GPP, the estimated strength of carbon sink can be considered as the climatic-based potential for carbon sink. The strength of actual carbon sink (NRCB) in China in recent years was about 0.28–0.33 PgC a^{-1} (Table 8), accounting for 29 %–34 % of the climatic potential value reported in this study. This confirmed that the terrestrial ecosystems in China have great potential in increasing carbon sinks (about 0.636–0.686 PgC a^{-1}).

Moreover, because of the scarcity of data sources, uncertainties caused by the coherence and couple among multiple data sources are inevitable, whereas our results all focused on the national scale for all carbon fluxes. For example, GPP is a nationwide total amount, which covered all kinds of ecosystem types, though there were no eddy towers in lakes used in generating GPP. Therefore, the mismatch of datasets may also bring some uncertainties to the estimated NRCB, which should be paid more attention.

Finally, the current study only focused on the magnitude of carbon sink in China, whereas the carbon sinks in terrestrial ecosystems of China have obvious spatial variability and more attention should focus on this variability in the future.

Acknowledgment This work was supported by the National Basic Research Program of China (2010CB833504) and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA05050601, XDA05050702).

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Tans PP, Fung IY, Takahashi T (1990) Observational contrains on the global atmospheric CO_2 budget. Science 247:1431–1438
2. Schimel DS, House JI, Hibbard KA et al (2001) Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature 414:169–172
3. Ballantyne AP, Alden CB, Miller JB et al (2012) Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. Nature 488:70–72
4. Solon SD, Qin M, Manning Z et al (eds) (2007) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, 2007. Cambridge University Press, Cambridge
5. Chapin FS, Woodwell GM, Randerson JT et al (2006) Reconciling carbon-cycle concepts, terminology, and methods. Ecosystems 9:1041–1050
6. Houghton RA (2007) Balancing the global carbon budget. Annu Rev Earth Planet Sci 35:313–347
7. Le Quéré C, Andres RJ, Boden T et al (2013) The global carbon budget 1959–2011. Earth Syst Sci Data 5:165–185
8. Yu GR, Wang QF, Liu YC et al (2011) Conceptual framework of carbon sequestration rate and potential increment of carbon sink of regional terrestrial ecosystem and scientific basis for quantitative carbon authentification. Prog Geogr 30:771–787 (in Chinese)
9. Lovett G, Cole J, Pace M (2006) Is net ecosystem production equal to ecosystem carbon accumulation? Ecosystems 9:152–155
10. Yu GR, Wang QF, Zhu XJ (2011) Methods and uncertainties in evaluating the carbon budgets of regional terrestrial ecosystems. Prog Geogr 30:103–113 (in Chinese)
11. Yu GR, Sun XM (2006) Principles of flux measurement in terrestrial ecosystems. Higher Education Press, Beijing (in Chinese)
12. Fang JY, Chen AP, Peng CH et al (2001) Changes in forest biomass carbon storage in China between 1949 and 1998. Science 292:2320–2322
13. Fang JY, Guo ZD, Piao SL et al (2007) Terrestrial vegetation carbon sinks in China, 1981–2000. Sci China Ser D: Earth Sci 50:1341–1350
14. Junttila V, Maltamo M, Kauranne T (2008) Sparse bayesian estimation of forest stand characteristics from airborne laser scanning. Forest Sci 54:543–552
15. Piao SL, Fang JY, Zhou LM et al (2005) Changes in vegetation net primary productivity from 1982 to 1999 in China. Glob Biogeochem Cycle 19:GB2027. doi:10.1029/2004GB002274
16. Guerlet S, Basu S, Butz A et al (2013) Reduced carbon uptake during the 2010 northern hemisphere summer from gosat. Geophys Res Lett 40:2378–2383
17. Basu S, Krol M, Butz A et al (2014) The seasonal variation of the CO_2 flux over tropical Asia estimated from GOSAT, CONTRAIL, and IASI. Geophys Res Lett 41:1809–1815
18. Yu GR, Zheng ZM, Wang QF et al (2010) Spatiotemporal pattern of soil respiration of terrestrial ecosystems in China: the development of a geostatistical model and its simulation. Environ Sci Technol 44:6074–6080
19. Zhu XJ, Yu GR, He HL et al (2014) Geographical statistical assessments of carbon fluxes in terrestrial ecosystems of China: results from upscaling network observations. Glob Planet Change 118:52–61
20. Piao SL, Ciais P, Lomas M et al (2011) Contribution of climate change and rising CO_2 to terrestrial carbon balance in East Asia: a multi-model analysis. Glob Planet Change 75:133–142
21. Huang Y, Yu YQ, Zhang W et al (2009) Agro-C: a biogeophysical model for simulating the carbon budget of agroecosystems. Agric For Meteorol 149:106–129

22. Tao B, Cao MK, Li KR et al (2007) Spatial patterns of terrestrial net ecosystem productivity in China during 1981–2000. Sci China Ser D: Earth Sci 50:745–753
23. Deng F, Chen JM (2011) Recent global CO_2 flux inferred from atmospheric CO_2 observations and its regional analyses. Biogeosciences 8:3263–3281
24. Zhang HF, Chen BZ, van der Laan-Luijkx IT et al (2014) Net terrestrial CO_2 exchange over China during 2001–2010 estimated with an ensemble data assimilation system for atmospheric CO_2. J Geophys Res 119:3500–3515
25. Piao SL, Fang JY, Ciais P et al (2009) The carbon balance of terrestrial ecosystems in China. Nature 458:1009–1013
26. Yu GR, Chen Z, Piao SL et al (2014) High carbon dioxide uptake by subtropical forest ecosystems in the East Asian monsoon region. Proc Natl Acad Sci USA 111:4910–4915
27. Ito A (2011) A historical meta-analysis of global terrestrial net primary productivity: are estimates converging? Glob Change Biol 17:3161–3175
28. Jung M, Reichstein M, Margolis HA et al (2011) Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. J Geophys Res 116:G00J07. doi:10.1029/2010JG001566
29. Houghton RA (2003) Why are estimates of the terrestrial carbon balance so different? Glob Change Biol 9:500–509
30. Pan YD, Birdsey RA, Fang JY et al (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993
31. Steffen W, Canadell J, Apps M et al (1998) The terrestrial carbon cycle: implications for the Kyoto protocol. Science 280:1393–1394
32. Guenther A (2002) The contribution of reactive carbon emissions from vegetation to the carbon balance of terrestrial ecosystems. Chemosphere 49:837–844
33. Yu GR, Zhu XJ, Fu YL et al (2013) Spatial patterns and climate drivers of carbon fluxes in terrestrial ecosystems of China. Glob Change Biol 19:798–810
34. Chapin FS, Matson PA, Vitousek PM (2012) Principles of terrestrial ecosystem ecology, 2nd edn. Springer, New York
35. DeLucia EH, Drake JE, Thomas RB et al (2007) Forest carbon use efficiency: is respiration a constant fraction of gross primary production? Glob Change Biol 13:1157–1167
36. Zhang YJ, Xu M, Chen H et al (2009) Global pattern of NPP to GPP ratio derived from MODIS data: effects of ecosystem type, geographical location and climate. Glob Ecol Biogeogr 18:280–290
37. Zhang YJ, Yu GR, Yang J et al (2014) Climate-driven global changes in carbon use efficiency. Glob Ecol Biogeogr 23:144–155
38. Su H, Zhao J, You D et al (2004) Evaluation of economic losses caused by forest pests disasters in China. For Pest Dis 23:1–6
39. Fu C, Fang HJ, Yu GR (2011) Carbon emissions from forest vegetation caused by three major disturbances in China. J Resour Ecol 2:202–209
40. Zhu XJ, Wang QF, Zheng H et al (2014) Research on the spatiotemporal variation of carbon consumption by agricultural and forestry utilization in Chinese terrestrial ecosystems during 2000s. Quat Sci 34:762–768 (in Chinese)
41. Lun F, Li WH, Wang Z et al (2012) Spatio-temporal changing analysis on carbon storage of harvested wood products in China. Acta Ecol Sin 32:2918–2928 (in Chinese)
42. Zhu XJ, Yu GR, Gao YN et al (2012) Fluxes of particulate carbon from rivers to the ocean and their changing tendency in China. Prog Geogr 31:118–122 (in Chinese)
43. Zhang YL (2008) The response of transport characteristics of riverine organic carbon to regional climate. Earth Environ 36: 348–355 (in Chinese)
44. Li D (2009) The study on the hydro-chemical characteristics and the flux to the sea about the rivers in the east of China. Doctoral Dissertation, East China Normal University (in Chinese)
45. Jiao SL, Gao QZ, Liu K (2009) Riverine DIC and its δ^{13}CDIC of the Xijiang and the Beijiang tributaries in the Pearl River Basin, south China. Acta Sci Nat Univ Sunyatseni 48:99–105 (in Chinese)
46. Hutchinson MF (1995) Interpolating mean rainfall using thin plate smoothing splines. Int J Geogr Inform Syst 9:385–403
47. Hutchinson MF (2002) Anusplin version 4.2 user guide
48. Editorial Committee of Vegetation Map of China (2007) Vegetation map of the People's Republic of China (1:1,000,000)
49. Huang Y, Sass RL, Fisher JFM (1998) A semi-empirical model of methane emission from flooded rice paddy soils. Glob Change Biol 4:247–268
50. Huang Y, Zhang W, Zheng X et al (2006) Estimates of methane emissions from Chinese rice paddies by linking a model to GIS database. Acta Ecol Sin 26:980–987 (in Chinese)
51. Huang Y, Sass RL, Fisher FM (1998) Model estimates of methane emission from irrigated rice cultivation of China. Glob Change Biol 4:809–821
52. Xie M, Wang TJ (2007) Modeling of CH_4 emission from rice paddies and CO emission from biomass burning and their effects on tropospheric oxidizing capacity in China. Acta Ecol Sin 27:4803–4814 (in Chinese)
53. Wang P, Wei L, Du XL et al (2008) Simulating changes of methane emission from rice paddies of China, 1990–2000. Geoinf Sci 10:573–577 (in Chinese)
54. Kai FM, Tyler SC, Randerson JT (2010) Modeling methane emissions from rice agriculture in China during 1961–2007. J Integr Environ Sci 7:49–60
55. Li C, Qiu J, Frolking S et al (2002) Reduced methane emissions from large–scale changes in water management of China's rice paddies during 1980–2000. Geophys Res Lett 29:1972
56. Kang GD, Cai ZC, Zhang ZH et al (2004) Estimate of methane emissions from rice fields in China by climate-based net primary productivity. Chin Geogr Sci 14:326–331
57. Verburg PH, Van Der Gon HACD (2001) Spatial and temporal dynamics of methane emissions from agricultural sources in China. Glob Change Biol 7:31–47
58. Yan X, Akiyama H, Yagi K et al (2009) Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 intergovernmental panel on climate change guidelines. Glob Biogeochem Cycle 23:GB2002. doi:10.1029/2008GB003299
59. Cai ZC (1997) A category for estimate of CH_4 emission from rice paddy fields in China. Nutr Cycle Agroecosyst 49:171–179
60. Li J, Wang M, Huang Y et al (2002) New estimates of methane emissions from Chinese rice paddies. Nutr Cycle Agroecosyst 64:33–42
61. Chen H, Zhu QA, Peng C et al (2013) Methane emissions from rice paddies natural wetlands, lakes in China: synthesis new estimate. Glob Change Biol 19:19–32
62. Yan X, Cai Z, Ohara T et al (2003) Methane emission from rice fields in mainland China: amount and seasonal and spatial distribution. J Geophys Res 108:4505
63. Keppler F, Hamilton JTG, Braß M et al (2006) Methane emissions from terrestrial plants under aerobic conditions. Nature 439: 187–191
64. Xie M, Li S, Jiang F et al (2009) Methane emissions from terrestrial plants over China and their effects on methane concentrations in lower troposphere. Chin Sci Bull 54:304–310
65. Guenther A, Geron C, Pierce T et al (2000) Natural emissions of non-methane volatile organic compounds; carbon monoxide, and oxides of nitrogen from north America. Atmos Environ 34:2205–2230

66. Guenther A, Hewitt CN, Erickson D et al (1995) A global-model of natural volatile organic–compound emissions. J Geophys Res 100:8873–8892
67. Xie M, Wang TJ, Jiang F et al (2007) Modeling of natural NOx and VOC emissions and their effects on tropospheric photochemistry in China. Environ Sci 28:32–40 (in Chinese)
68. Yan Y, Wang ZH, Bai YH et al (2005) Establishment of vegetation VOC emission inventory in China. China Environ Sci 25:110–114 (in Chinese)
69. Huang Y, Zhang W, Zheng X et al (2006) Estimates of methane emissions from Chinese rice paddies by linking a model to GIS database. Acta Ecol Sin 26:980–987 (in Chinese)
70. Schultz MG, Heil A, Hoelzemann JJ et al (2008) Global wildland fire emissions from 1960 to 2000. Glob Biogeochem Cycle 22:GB2002. doi:10.1029/2007GB003031
71. Ito A, Penner JE (2004) Global estimates of biomass burning emissions based on satellite imagery for the year 2000. J Geophys Res 109:D14S05. doi:10.1029/2003JD004423
72. van der Werf GR, Dempewolf J, Trigg SN et al (2008) Climate regulation of fire emissions and deforestation in equatorial Asia. Proc Natl Acad Sci USA 105:20350–20355
73. Lü A, Tian H, Liu M et al (2006) Spatial and temporal patterns of carbon emissions from forest fires in China from 1950 to 2000. J Geophys Res 111:D05313. doi:10.1029/2005JD006198
74. Tian XR, Shu LF, Wang MY (2003) Direct carbon emissions from Chinese forest fires, 1991–2000. Fire Safety Sci 12:6–10 (in Chinese)
75. Tian X, Gao C, Shu L et al (2004) Estimation of direct carbon emissions from Chinese forest fires. Chin Forest Sci Technol 3:87–92
76. Raymond PA, Hartmann J, Lauerwald R et al (2013) Global carbon dioxide emissions from inland waters. Nature 503: 355–359
77. Fang JY, Liu GH, Xu SL (1996) Carbon cycle and its global importance of Chinese terrestrial ecoststems. In: Wang GC, Wen YP (eds) Concentration and emission monitoring of greenhouse gases and related processes. China Environmental Science Press, Beijing, pp 109–128 (in Chinese)
78. Gao YN, Yu GR, Zhang L et al (2012) The changes of net primary productivity in Chinese terrestrial ecosystem: based on process and parameter models. Prog Geogr 31:109–117 (in Chinese)
79. Tian HQ, Melillo J, Lu CQ et al (2011) China's terrestrial carbon balance: contributions from multiple global change factors. Glob Biogeochem Cycle 25:GB1007. doi:10.1029/2010GB003838
80. Ehman JL, Schmid HP, Grimmond CSB et al (2002) An initial intercomparison of micrometeorological and ecological inventory estimates of carbon exchange in a mid-latitude deciduous forest. Glob Change Biol 8:575–589
81. Gough CM, Vogel CS, Schmid HP et al (2008) Multi-year convergence of biometric and meteorological estimates of forest carbon storage. Agric For Meteorol 148:158–170
82. Peichl M, Brodeur JJ, Khomik M et al (2010) Biometric and eddy-covariance based estimates of carbon fluxes in an age-sequence of temperate pine forests. Agric For Meteorol 150:952–965
83. Jiang F, Wang H, Chen JM et al (2013) Nested atmospheric inversion for the terrestrial carbon sources and sinks in China. Biogeosciences 10:5311–5324
84. Zhang CH, Ju WM, Chen JM et al (2013) China's forest biomass carbon sink based on seven inventories from 1973 to 2008. Clim Change 118:933–948
85. Yu GR, He NP, Wang QF (2013) Carbon budget and carbon sink of ecosystems in China: theoretical basis and comprehensive assessment. Science Press, Beijing (in Chinese)
86. Li XL, Liang SL, Yu GR et al (2013) Estimation of gross primary production over the terrestrial ecosystems in China. Ecol Model 261–262:80–92
87. Liu YB, Ju WM, He HL et al (2013) Changes of net primary productivity in China during recent 11 years detected using an ecological model driven by modis data. Front Earth Sci 7:112–127
88. Gao ZQ, Liu JY (2008) Simulation study of China's net primary production. Chin Sci Bull 53:434–443
89. Niu Z, Wang CY (2008) Fundamentals of remote sensing and application of carbon cycle. Science Press, Beijing (in Chinese)