Current Science
CS 5(5), 4461-4475 (2025)
Received 15 June 2025 | **Revised** 10 July 2025 | **Accepted** 13 August 2025 | **Online Available** 18 September 2025
https://doi.org0/10.52845/CS/2025-5-5-12

Current Science

Current Science

OPEN ACCESS

ISSN(O)2795-8639

Original Article

Forest Carbon Sink and its Gross Ecosystem Product Accounting Model and Analysis in China

Zhang Ying[1,*], Zhang Zixuan[1], Zhang Keren[2], Wang Zhichen[3]

[1]School of Economics and Management, Beijing Forestry University, Beijing 100083, China

[2]School of Design, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

[3]Rural Development Institute, Chinese Academy of Social Sciences, Beijing 100732, China

[*]Corresponding Author: Zhang Ying

Abstract:

Abstract: According to the 9th latest China Forest Resources Inventory data, Report on Comprehensive Monitoring and Evaluation of China's Forest and Grassland Ecology in 2021 etc., the forest carbon sink's Gross Ecosystem Product (GEP) of China in 2013 to 2021 are calculated, the GEP model of forest carbon sink accounting is constructed based on the accounting method of GEP. The study results show that China's forest carbon storage and carbon sink increased from 2013 to 2021, with an average annual growth of 2.44% and 5.72% respectively, the value of forest carbon storage and forest carbon sink increased separately by 1.50% and 0.70% annually, the proportion of forest carbon sink GEP in GDP decreased at the same time. The study also shows that during 2013-2021, with forest carbon sink GEP as the dependent variable and forest carbon storage as the independent variable, the accounting model of forest carbon sink GEP is a quadratic equation, the model R^2 is 0.805, and the relative error is 8.88%, which has statistical significance and prediction accuracy. The research believes that the future GEP development should reduce the intermediate consumption of forest ecosystem, improve the output efficiency, and strengthen the basic data monitoring and statistics etc..

Key words: forest carbon sink, ecosystem services, ecological products, GEP accounting, statistical monitoring

1. Introduction

Gross Ecosystem Product (GEP) is an indicator proposed and promoted by the International Union for Conservation of Nature (IUCN) to account for the total output of ecosystems. Its main objective is to develop a system of indicators to measure the contribution of ecosystems to people, equivalent to Gross Domestic Product (GDP), the main indicator in the existing System of National Accounts (SNA). Although controversial, GEP accounting has been widely used in China and *Ecosystem Assessment Guidelines for Gross Ecosystem Product Accounting* has been officially promulgated at the national level in China[1,2]. A number of provincial and municipal local standards and specifications have also been issued in Zhejiang Province, Guizhou Province, Nanjing City and Huangshan City *etc*. to promote the development of GEP accounting in China. Based on China's forest inventory data and China Forestry and Grassland Statistical Yearbook, *etc*., this paper accounts for China's forest carbon sink GEP in accordance with *Ecosystem Assessment Guidelines for Gross Ecosystem Product Accounting* (Draft for Comments) officially promulgated in China and the *SEEA-EEA* of the United Nations[3] (That is the System of Environmental-Economic Accounting–Experimental Ecosystem Accounting, for short SEEA-EEA, which is the United Nations Statistical Commission launched SEEA experimental ecosystem accounting in March 2013), and tries to build a GEP accounting model of forest carbon sink and make a comparative analysis. This study is to revise and improve the relevant indicators and better align with the existing national economic accounting system, so as to provide a reference for China's high-quality development and low-carbon green economic development.

In fact, accounting for GEP began in the 1990s, when scientists recognized the important role of ecosystem service functions for human survival and development, and only then began to study the valuation of different ecosystem service functions[4]. In particular, as related research continued, some scientists discovered and concluded that the ecological environment itself has a high value of services. In 1993, the United Nations *et al*. established the System of Environmental-Economic Accounting (SEEA) marked a new stage in the study of environmental accounting. In 1997, Costanza *et al*. published a study on the value of global ecosystems and natural assets in *Nature*, in which he classified ecosystem service functions into four broad categories, namely ecological provisioning services, ecological regulating services, ecological cultural services and ecological support services, which play different roles for human survival, development and economic activities[5]. Actually, the concept of GEP can be traced back to 1990 Khanna and Saraswat, two scholars on R&D (Research & Developing) inputs in environmental science and technology in India, in their study, the concept of gross écologie product (GEP) was introduced[6]. Wofsy *et al*. of Harvard University published research on forest CO_2 exchange models in *Science* in 1993, and proposed the concept of GEP based on Net Primary Productivity (NPP) measurements from a forest ecosystem perspective[7], and Waring of Oregon State University and others also proposed a similar concept[8], at which point GEP accounting was simply an extension of ecosystem NPP measurement. Since Costanza *et al*. developed a global accounting of the value of ecosystem services in 1997, which led to ecosystem service evaluation shift from a single field of ecology to a multidisciplinary approach combining ecology and economics etc., and the concept of GEP accounting is constantly expanding and updating. As a result, the core of GEP accounting has gradually shifted from an emphasis on the net productivity of ecosystems to the value of ecosystems, and thus to the core of accounting for gross ecosystem services. Since then, foreign research results have been advocated and brought into China through IUCN etc.. With the efforts of many Chinese scholars, GEP-related research has been enriched and a basic accounting framework has been formed, and GEP has gradually become synonymous with the accounting of the value of ecosystem services, developing from a simple ecological concept at the beginning to a more complete ecological value accounting system, and serving as an important complement to the national economic accounting system of GDP accounting[9,10].

Among the studies related to ecosystem value accounting, the most representative are Ouyang *et al*. (2013)[10] in China, they defined GEP as the sum of the value of goods and services provided by ecosystems for human survival and development (i.e. the sum of the value of ecosystem products, the value of regulating services and the value of cultural services), and argued that GEP can be accounted for in terms of both physical and value quantities, using the physical quantity of ecosystem services with the help of prices to the value quantity is derived. Many researchers have used the GEP indicator as an object of research on the value of ecosystem services. The UN and others have also introduced GEP indicators for the first time in the latest revised version of *SEEA-EEA*[3,11-12]. In recent years, pilot work on ecosystem service accounting has also been made in China, using Guangxi, Guizhou, Sichuan, Lishui, Zhejiang and the Qinling nature reserve as pilot areas[13]. In 2022, the National Development and Reform Commission issued the document *Ecosystem Assessment Guidelines for Gross Ecosystem Product Accounting* (Draft for Comments),which states that ecological products are the contributions of goods and services of ecosystems for economic and other human activities and used, including material supply, regulating services and cultural services, and clarifies the concept of GEP as the sum of the value of all ecological goods and services in a region over a certain period of time, i.e. the total value of ecological goods[1,14]. In the *SEEA-EEA*, the UN states that GEP is the sum of the value of ecosystem services provided by all ecosystem assets within an ecosystem accounting area, less the value of ecosystem services imported from outside that ecosystem accounting area (e.g. the inflow of water from outside China rivers) and so on. In contrast, issues such as imports of ecosystem services are not seen in the GEP accounting [15].

In terms of regional, watershed and different ecosystem GEP accounting, Ouyang (2013)[10], Yang (2019)[13], and Zhang (2022)[16] and others have constructed corresponding accounting systems according to the ecological characteristics of different regions, and analyzed GEP accounting for various regions such as Guizhou, Sichuan province and Yarlung Tsangpo River Basin in China, respectively. Ma (2017)[17], Lin (2023)[18] and other scholars conducted GEP accounting for different types of ecosystems, such as terrestrial ecosystems and aquatic ecosystems, respectively. For example, Jin and Bian (2013) carried out a study on the ecological civilization accounting method based on energy value and GEP in Xuzhou City, Jiangsu Province[19].

Therefore, from the origin of GEP accounting and China's development, China's GEP accounting is still at an early stage of development, and although a series of standards and norms have been introduced, a unified system of standard indicators and methods has not yet been formed, and there are still some controversies in relevant studies, such as product value accounting without deducting the contribution of labour and capital inputs, exaggerating the contribution of ecosystem, regulating services and cultural services in the accounting. Some of the price parameters for regulating services and cultural services, such as the price of carbon sink etc., are also somewhat unreasonable and the valuation is arbitrary. In particular, there is not enough research on the theory and mechanism of GEP accounting, and basic research is weak and less integrated with economics, statistics and other multidisciplinary disciplines[20]. GEP accounting is also faced with the lack of elementary statistics and monitoring data, can not timely reflect the regional ecosystem changes and other risks etc.[21]. Therefore, there is still a great challenges to improve GEP accounting in China.

2 Methodology and data

2.1 Methodology

The research methodology is mainly based on the GEP accounting approach. Specifically, according to *Ecosystem Assessment Guidelines for Gross Ecosystem Product Accounting* in China and SEEA-EEA of the United Nations, the GEP accounting methodology is as follows[22,11]:

$$GEP = EMV + ERV + ECV \qquad (1)$$

$$EMV = \sum_{i=1}^{n} EM_i \times PM_i \qquad (2)$$

$$ERV = \sum_{j=1}^{m} ER_j \times PR_j \qquad (3)$$

$$ECV = \sum_{k=1}^{a} EC_k \times PC_k \qquad (4)$$

In Eqs. (1)-(4), GEP is the gross ecosystem product, EMV is the ecosystem material goods value, ERV is the ecosystem regulatory services value, and ECV is the ecosystem cultural services value. EM_i is the quantity of ecosystem material goods of category i and PM_i is the price of ecosystem material goods of category i; ER_j is the material quantity of ecosystem regulating services of category j and PR_j is the price of ecosystem regulating services of category j; EC_k is the material quantity of cultural services of ecosystem k and PC_k is the price of cultural service products of ecosystem k[22]. In the field of national economic accounting, the quality of materials is often referred to as physical quantity[3,11-12].

The specific contents, indicators and methods of GEP accounting can referring to the *Standard for Assessment of Forest Ecosystem Service Functions* (GB/T 38582-2020) compiled by the National Forestry and Grassland Administration, officially issued by the State Administration for Market Regulation and Standardization Administration in 2020[1](Table 1). In this study, according to Shi's research and the relevant regulations of the National Bureau of Statistics, P. R. China, the content of support services in ecosystem is not included as it is an intermediate input [23].

Table 1. Indicator systems for the valuation of ecosystem services

Primary index	Secondary index	Tertiary index	Monetary value method
Support Services	soil conservation	Soil retention value	Alternative engineering method
		Maintain the value of soil N	shadow price method
		Maintain the value of soil P	shadow price method
		Maintain the value of soil K	shadow price method
		Maintains organic matter in the soil	Shadow price method
	Nutrient retention of forest trees	N nutrient retention accumulation value	shadow price method
		P nutrient retention accumulation value	shadow price method
		K nutrient retention accumulation value	shadow price method
Regulating services	water conservation	Regulated water value	Alternative engineering method
		Value of water purification	Cost analysis method
	carbon fixation and oxygen release	Carbon sequestration value	Carbon tax law
		Oxygen release value	Shadow price method
	Purify the atmosphere	Value of SO_2 absorption	Cost analysis method
		Value of chloride absorption	Cost analysis method
		Value of nitrogen oxides absorption	Cost analysis method
		Dust retention value	Cost analysis method
		Provides negative ion value	Shadow price method
	Forest protection	Value of wind and sand control	market price approach
Supply services	Biodiversity protection	Value of biodiversity conservation	opportunity cost method
	Forest product supply	Value of forest products and by-products	market price approach
Cultural services	Forest recreation	Forest tourism value	Tourism revenue method

Source: 23.

2.2 Data Sources and Time Range

The main data for GEP accounting of forest carbon sink are obtained from the China Forest Resources Report (2014-2018), China Forestry and Grassland Statistical Yearbook (2019-2021), Report on Comprehensive Monitoring and Evaluation of China's Forest and Grassland Ecology in 2021 and China Statistical Yearbook (2022) and related studies[24-25]. Specifically, data on forest area, stock and forestry output value are mainly from the China Forest Resources Report (2014-2018). Data on annual increase and decrease of forest area and standing stock, GDP, forestry investment, carbon emission and carbon sink are obtained from China Statistical Yearbook and China Forestry and Grassland Statistical Yearbook, etc. Some of the data collected, such as forest carbon sink trade, were obtained from relevant research reports[16]. The time range of the accounting is defined as 2013 to 2021, of which the 8th and 9th National Forest Inventories is 2009 to 2018, with the 8th Forest Inventory covering the period 2009-2013 and the 9th Forest Inventory covering the period 2014-2018. Specifically, the start of the period was 2013, the last year of the 8th forest inventory period, and the end of the period was 2021, the latest year of release of forest resource inventory official data in China by National Forestry and Grassland Administration. As for the 9th forest inventory, is mainly for comparative analysis with the 8th forest inventory in this study. The main reason is after the 9th forest resources inventory, the state cancelled the official publication of forest resources inventory detailed data, and instead released the Comprehensive Monitoring and Evaluation Report of Forest and Grassland Ecology in China[25]. Therefore, some indicators of some officially published forest resources inventory systems have also changed, and it is impossible to conduct comparative analysis of forest resources inventory detailed data after 2018 (the 9th forest resources inventory) , but only the comparative analysis of the 8th and 9th forest resources inventory detailed data can be carried out. The data for 2019-2021 are mainly from the latest comprehensive monitoring and evaluation report of forest and grassland ecology in China.

According to the latest statistical data of "China's Forest and Grassland Resources and Ecological Status in 2021" released by the National Forestry and Grassland Administration, China's forest area in 2021 was 3.46 billion mu (about 231 million ha), the forest coverage rate was 24.02%, the forest stock was 19.493 billion m^3, the grassland area was 3.968 billion mu (about 265 million ha), and the comprehensive vegetation coverage of grassland was 50.32%. The total annual output of fresh grass was 595 million t, and the total carbon storage of forest and grass vegetation was 11.443 billion t[26]. Therefore, in the calculation of GEP accounting model, the latest statistical monitoring data of these forest resources are also referred to.

3 Results

3.1 Physical Quantity Accounting

The physical carbon sink is accounted for using the stock conversion method, which should include carbon sink from forest trees, understorey vegetation and forest land. Since the carbon sink of understorey vegetation and forest land do not change significantly within one year, only the carbon sink of forest trees are calculated, but not those of understorey vegetation and forest land. The calculation formula was adopted from the accounting formula of Li (2006)[27], namely:

$$C_f = V_f \times \delta \times \rho \times \gamma = V_f \times 1.9 \times 0.5 \times 0.5 \quad (5)$$

In Eq. (5). C_f is the forest carbon sink, t; V_f is the volume of the tree stock, m^3; δ is the coefficient of conversion of stand volume to biomass storage, also known as the biomass expansion factor, usually 1.90; ρ is the coefficient of conversion of stand biomass storage to biomass, i.e. bulk density, usually 0.45-0.50 t/m^3, in this study 0.5 t/m^3; γ is the coefficient that converts the dry mass of biomass into carbon sequestration, i.e. the carbon content rate, generally taken as 0.5[28]. Based on the data of the 8th and 9th National Forest Inventories and the above calculation formulas, the calculated forest carbon stock and carbon sink in China in 2013 and 2018 are shown in Table 2.

Table 2. Physical accounting table of forest carbon stock and carbon sink from 2013 to 2018 in China*

Items	Openning carbon stock (2013) (100 million t)	Closing carbon stock (2018) (100 million t)	Carbon sink (variation) (100 million t)
Total	76.35	87.90	11.55
Wooded land and forest carbon stock	70.20	81.03	10.83
Arbor forest	70.20	81.03	10.83
Protection forest	37.75	41.89	4.13
Special purpose forest	10.31	12.44	2.13
Timber forest	21.86	25.72	3.86

Fuelwood forest	0.28	0.27	-0.01
Economic forest	0.00	0.71	0.71
Bamboo forest	-	-	-
Sparse woods	0.50	0.48	-0.02
Shrub land	-	-	-
Unwoodland	-	-	-
Other	-	-	-
Four-side tree planting	1.90	2.23	0.33
Scattered trees	3.75	4.17	0.42
Natural Forest	58.41	64.94	6.53
Natural arbor forest	58.41	64.94	6.53
Protection forest	33.76	36.36	2.60
Special Purpose Forest	9.51	11.80	2.29
Timber forest	14.49	16.50	2.02
Fuelwood forest	0.26	0.25	0.25
Economic forest	0.00	0.02	0.02
Bamboo forest	-	-	-
Sparse woods	-	-	-
Shrub land	-	-	-
Unwoodland	-	-	-
Planted forest	-	-	-
Artificial forest	-	-	-
Artificial arboreal forest	11.79	16.09	4.30
Protection forest	3.99	5.53	1.54
Special Purpose Forest	0.41	0.63	0.22
Timber forest	7.37	9.22	1.85
Fuelwood forest	0.02	0.02	0.00
Economic forest	0.00	0.70	0.70
Bamboo forest	-	-	-
Sparse woods	-	-	-
Shrub land	-	-	-
Unwoodland	-	-	-

*Note: Since China cancelled the official publication of detailed data of forest resources inventory after the 9th forest resources inventory, only the comparative analysis of forest carbon sink of the latest 8th and 9th forest resources inventory was carried out.

From the above calculation results (Table 2), it can be seen that from 2013 to 2018, China's forest carbon stock increased. The forest carbon stock was 7.635 billion t in 2013 and 8.79 billion t in 2018, with an average annual increase of 3.58%. During the 8th forest inventory, the annual net growth of forest stock in China was 283 million m^3, and the annual increase of forest carbon sink was 135 million t. During the 9th forest inventory, the annual net growth of forest stock was 570 million m^3 [29], and the annual increase of forest carbon sink was 271 million t, which also increased by an average of 14.95% in 2013-2018 (Figure 1).

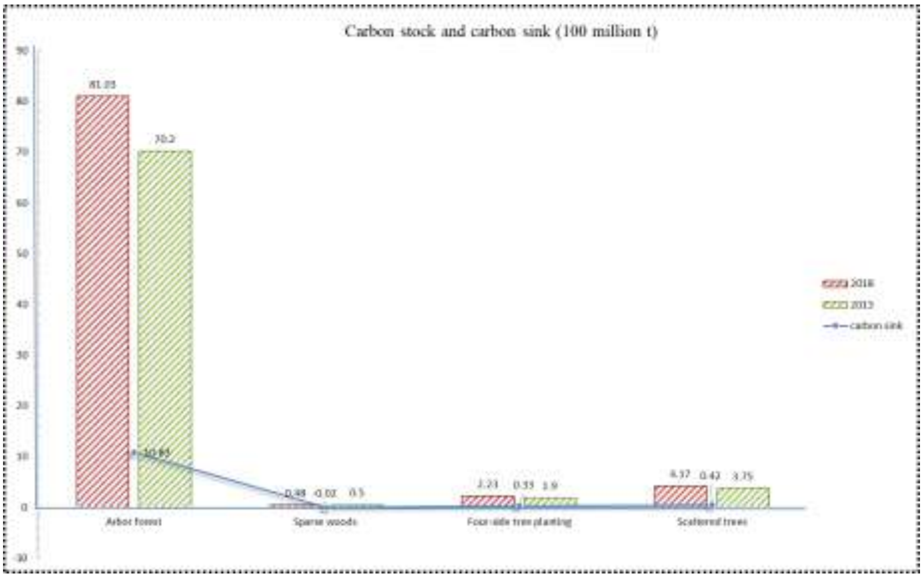

Figure 1 Comparison of forest carbon stock and carbon sink in 2013 and 2018

The results of the accounting of forest carbon stock and carbon sink in kind also show that, both the carbon stock of natural and planted forests and the total forest carbon stock increased over the accounting period. The carbon stock of planted forests increased by an average of 8.84% per year, compared to 2.68% for natural forests, and the total forest carbon stock increased by an average of 3.58% per year. Carbon stock in planted forests are growing faster than in natural forests. In terms of the growth of forest carbon sink, the growth of carbon sink in planted forests is higher than that in natural forests, which is related to the increasing forest growing stock of planted forests in China. In addition, according to the monitoring data of China's forest resources inventory, during the 8th forest resources inventory, the total biomass of forest vegetation nationwide was 17,002 million t, and the total carbon stock reached 8,427 million t[29]; during the 9th forest resources inventory, the total biomass of forest vegetation was 18,802 million t, and the total carbon stock was 9,186 million t[30]. These actual monitoring data are very close to the results accounted for in this study, and the monitoring results compared with the carbon stock accounting results of the 8th forest resources inventory data, the accuracy rate is 90.60%; compared with the carbon stock accounting results of the 9th forest resources inventory data, the accuracy rate is 95.69%, indicating that the accounting results have some reliability.

Similarly, according to the latest statistical data of China's forest and grassland resources and ecological status monitoring in 2021 released by the State Forestry and Grassland Administration, China's forest stock in 2021 is 19.493 billion m^3 [26], and China's forest carbon stock in 2021 calculated according to Eq. (5) is 9.259 billion t. From 2018 to 2021, forest carbon stock is increase by 1.75% annually, the average annual net growth rate of forest stock is 891 million m^3, equivalent to an annual growth rate of 423 million t of forest carbon sink. Therefore, from 2013 to 2021, forest carbon stock is grow at an average annual rate of 2.44%. Based on the previous average annual increase of 271 million t of forest carbon sink in 2013-2018, the average annual increase of forest carbon sink from 2013 to 2021 is about 5.72%.

3.2 Monetary Value Accounting

According to the study by Zhang *et al.* (2010)[31], the optimal price of forest carbon sink in China is US$10.11 to US$15.17/t. If the upper limit of this price is calculated[32], based on the average exchange rate of US$ to RMB 6.9451 and 6.6174 in 2013 and 2018 published by the China Foreign Exchange Trade Centre (2023)[33], the prices of forest carbon sink in 2013 and 2018 are RMB 105.36 and 100.39/t respectively. Therefore, the monetary values of China's forest carbon sink in 2013 and 2018 are shown in Table 3.

Table 3. Monetary value accounting table of forest carbon sink from 2013 to 2018 in China[*]

Items	Openning carbon stock (2013) (100 million RMB)	Closing carbon stock (2018) (100 million RMB)	carbon sink (variation) (100 million RMB)
Total	8044.24	8824.20	779.96
Wooded land and forest carbon stocks	7396.27	8134.24	737.97
Arbor forest	7396.27	8134.24	737.97
Protection forest	3977.66	4204.92	227.26
Special purpose forest	1086.00	1248.61	162.61
Timber forest	2303.12	2582.31	279.19
Fuelwood forest	29.53	27.02	-2.51
Economic forest	0.00	71.39	71.39
Bamboo forest	-	-	-
Sparse woods	53.05	47.81	-5.23
Shrub land	-	-	-
Unwoodland	-	-	-
Other	-	-	-
Four-side tree planting	200.68	223.45	22.77
Scattered trees	395.10	418.69	23.59
Natural Forest	6153.66	6518.86	365.20
Natural arbor forest	6153.66	6518.86	365.20
Protection forest	3557.27	3650.25	92.98
Special Purpose Forest	1002.42	1184.95	182.53
Timber forest	1526.40	1656.86	130.45
Fuelwood forest	27.39	25.29	-2.10
Economic forest	0.00	1.51	1.51
Bamboo forest	-	-	-
Sparse woods	-	-	-
Shrub land	-	-	-
Unwoodland	-	-	-
Planted forest	-	-	-
Artificial forest	-	-	-
Artificial arboreal forest	1242.19	1615.39	373.19
Protection forest	420.39	554.67	134.28
Special Purpose Forest	43.54	63.66	20.12
Timber forest	776.71	925.46	148.74
Fuelwood forest	2.00	1.72	-0.28
Economic forest	0.00	69.88	69.88
Bamboo forest	-	-	-
Sparse woods	-	-	-
Shrub land	-	-	-
Unwoodland	-	-	-

[*]Note： Same as Table 2.

From the accounting results in Table 3, it can be seen that the value of China's forest carbon sink was RMB 804.424 billion yuan in 2013 and 882.420 billion yuan in 2018, with an average annual increase of about 1.87%, which is mainly due to the change in carbon stock. Among the changes in the value of forest carbon stock, the value of carbon stock in planted forests is increasing, with an average annual increase of 1.78%, and the value of carbon stock in natural forests is also increasing, with an average annual increase of 2.05%. The average annual growth rate of the value of carbon stock in natural forests is higher than the average annual growth rate of the value of carbon stock in planted forests.

In addition, according to the accounting data of the physical quantity of forest carbon sink in 2013 and 2018, the value of forest carbon sink in China was 14,223 million yuan and 27,206 million yuan in 2013 and 2018 respectively. The increase in the value of carbon sink is also mainly due to changes in the physical quantity of carbon stock. In 2013 and 2018, the total output value of forestry in China was 4,460 billion yuan and 807.51 billion yuan[32], and the calculated value of forest carbon sinks in 2013 and 2018 accounted for about 0.32% and 0.34% of the total output value of forestry in the period, respectively. In 2021, the proportion of forest carbon sink in forestry output value decreased to 0.076%, this is mainly due to the falling price of carbon sequestration.

In terms of forest carbon sink value accounting in 2021, according to the information provided by the State Foreign Exchange Trading Center(2023)[33], the average exchange rate between RMB and US dollar in 2021 is 6.4515, an increase of 6.92% compared with the average exchange rate in 2020. According to the average upper limit of the optimal price of China's forest carbon sink by Zhang *et al*. (2010)[31], the optimal price of China's forest carbon sink in 2021 is 97.87 yuan /t, the calculated value of China's forest carbon stock and carbon sink in 2021 is 906.189 billion yuan and 15.041 billion yuan respectively.Therefore, in terms of value calculation, from 2013 to 2021, the value of forest carbon storage and forest carbon sink increased separately by 1.50% and 0.70% annually, and the growth rate of both is significantly lower than the growth of their physical quantity.

3.3 Carbon Sinks GEP Accounting

GEP is specifically defined as the sum of the values of final material goods and services provided by ecosystems for human well-being and sustainable economic and social development, i.e. the sum of “ecological goods”. These mainly include the material goods, regulating services and cultural services provided by ecosystems[10], forest carbon sink are also ecological goods. Therefore, in line with the methodology recommended by the UN for the calculation of the Gross Ecological Product in the SEEA-EEA[11], forest resources are treated here as ecosystems and the intermediate consumption of the forest ecosystem itself is deducted from the GEP accounting of forest carbon sink, with forest support services being part of this intermediate consumption. In addition, according to the *Industrial classification for national economic activities*, the entire forest production process includes primary, secondary and tertiary sectors[34] and the intermediate consumption component is also deducted in the forest carbon sink production process. Input-output analysis facilitates the calculation of the intermediate consumption component.

Input-output analysis focuses on the breadth and depth of inter-industry linkages by calculating direct consumption coefficients and indirect consumption coefficients. In particular, the direct consumption coefficient reflects the quantity relationship between intermediate products and final products, and the total consumption coefficient reflects the quantity relationship between intermediate products and final products (Complete consumption = direct consumption + all indirect consumption). The formulae for calculating the direct consumption coefficient and the indirect consumption coefficient are:

$$a_{ij} = X_{ij} \,/\, X_j \tag{6}$$

$$B_{ij} = a_{ij} + b_{i1}a_{1j} + b_{i2}a_{2j} + \cdots\cdots + b_{ij}a_{ij} + \cdots\cdots + b_{ip}a_{pj} \tag{7}$$

In Eq. (6)-(7), a_{ij} denotes the direct consumption coefficient, which refers to the quantity of product i directly consumed by the production of unit j of product j. X_{ij} denotes the quantity of product i consumed by the sector producing product j, and X_j denotes the total output of the sector producing product j. B_{ij} denotes the complete consumption coefficient, which is the sum of the direct and indirect expense of the products of each sector by the production of unit j of product j. $b_{ip}a_{pj}$ denotes the pth round of indirect expense of product i by product j. According to the study of He, the complete consumption coefficient of Beijing's forest industry (mainly wood processing and furniture manufacturing) ranged from 0.44 to 0.48 from 1992 to 2005 [35], and the results of this study are somewhat representative[22]. Therefore, according to the results of this study, the value of China's forest carbon stock in 2018 is RMB 882.420 billion yuan, and the GEP of forest carbon sink is RMB 14.147-15.235 billion. Similarly, the calculated forest carbon sink GEP for 2021 is 6.618-7.222 billion yuan. From 2013 to 2021, the average annual growth rate calculated by the lower limit of complete consumption coefficient for forest carbon sink GEP is higher than the average annual growth rate of GDP in the same period, which also reflects the real contribution of China's forest carbon sink to China's economic development. In fact, according to Zhang *et al*. study, the growth rate of eaGDP (environmentally adjusted GDP) from forest carbon sink was 9.17% from 2013 to 2021, which exceeded the average growth rate of GDP in the same period about annual average 6%, but the impact of China's forest carbon sink on the economy, especially on GDP was about 0.002% ~0.004%[36], and the GEP of China's forest carbon sink accounted for 0.0058%-0.0063% of China's total GDP of RMB 114.40 trillion in 2021 [37]. Therefore, the accounting results of China's forest carbon sink GEP not only reflect the positive benefits generated by China's forest carbon sink in improving the ecological environment, preventing and mitigating disasters, and improving people's quality of life etc., but also the GEP share of the national GDP in 2021, which fully illustrates the important role of China's forests in social and economic development and ecological environmental protection etc.

Therefore, according to the formula $y = y_1 + (y_2 - y_1)\cdot(x - x_1)/(x_2 - x_1)$ calculated by linear interpolation method, y is the inserted GEP value, x is the year in which y is inserted, x_1 and x_2 are the opening and closing years of the inserted GEP, and y_1 and y_2 are the GEP values of the forest carbon sink in the opening and closing years respectively. Accordingly, the calculated GEP of forest carbon sink and forest carbon stock from 2013 to 2021 is shown in Table 4, and the change of forest carbon sink GEP is shown in Figure 2.

Table 4. GEP of forest carbon sink and forest carbon stock from 2013 to 2021 in China*

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021
GEP of forest carbon sink (GEP_{fc})(100 million RMB)	62.58	74.01	85.43	96.86	108.28	119.71	101.87	84.02	66.18
Forest carbon stock(fc_s) (100 million t)	76.35	78.66	80.97	83.28	85.59	87.9	89.46	91.03	92.59

*Note:GEP of forest carbon sink (GEP_{fc}) takes the lower limit of 6.618-7.222 billion yuan.

Here, forest carbon sink GEP as the dependent variable GEP_{fc}, forest carbon stock as the independent variable fc_s, the year of 2013 to 2021 is the time t (t = 1, 2,... , 9), statistical software SPSS25 was used for model fitting, and the model of forest carbon sink GEP was obtained as follows:

$$GEP_{fc} = -4620.872 - 0.648 \cdot {fc_s}^2 + 110.734 \cdot fc_s \quad (8)$$

It can be seen from the model processing summary that R=0.897, R^2=0.805, Adjusted R^2=0.740, the Std. Error of the Estimate =9.918, the ANOVA of the model Sig.=0.007<0.05. Therefore, the independent variable fc_s has 80.5% explanatory power for dependent variable

GEP_{fc}, the quadratic model passed the test and had statistical significance. The variance analysis and test of the model are shown in Table 5 and Table 6.

Table 5. ANOVA*

Items	Sum of Squares	df	Mean Square	F	Sig.
Regression	2432.625	2	1216.313	12.366	0.007
Residual	590.157	6	98.359		
Total	3022.782	8			

*The independent variable is fc_s , R=0.897, R^2=0.805, Adj. R^2=0.740, Std. Error of the Estimate=9.918.

Table 6. Coefficients

Items	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
fc_s	110.734	23.576	32.273	4.697	0.003
${fc_s}^2$	-0.648	0.139	-31.967	-4.652	0.003
(Constant)	-4620.872	993.818		-4.65	0.004

The value of forest carbon stock from 2013 to 2021 was substituted into Eq. (8), and the predicted value of forest carbon sink GEP from 2013 to 2021 was obtained respectively. Among them, the forest carbon stock in 2014 is 7.866 billion t, and the forest carbon stock in 2020 is 8.946 billion t, and the forest carbon sink GEP in 2014 and 2020 is 7.866 billion yuan and 9.103 billion yuan respectively. Compared with the actual forest carbon sink GEP in 2014 and 2020, the forest carbon stock in China is 7.866 billion yuan. The relative errors were 8.14% and 6.69%, respectively. Therefore, the average relative error of GEP accounting model of forest carbon sink in China from 2013 to 2021 is 8.88%, which has high accuracy and scientificity.

According to the Comprehensive Monitoring and evaluation report of China's forest and Grassland Ecology in 2021 by the National Forestry and Grassland Administration, by 2030, the national forest coverage rate will reach about 25%, and the forest stock volume will reach 19 billion m^3 [25]. Therefore, the predicted GEP of China's forest carbon sink in 2030 will be 9.487 billion yuan.

In this way, we get the carbon sink GEP accounting model, and can use it to predict the forest carbon sink GEP in China.

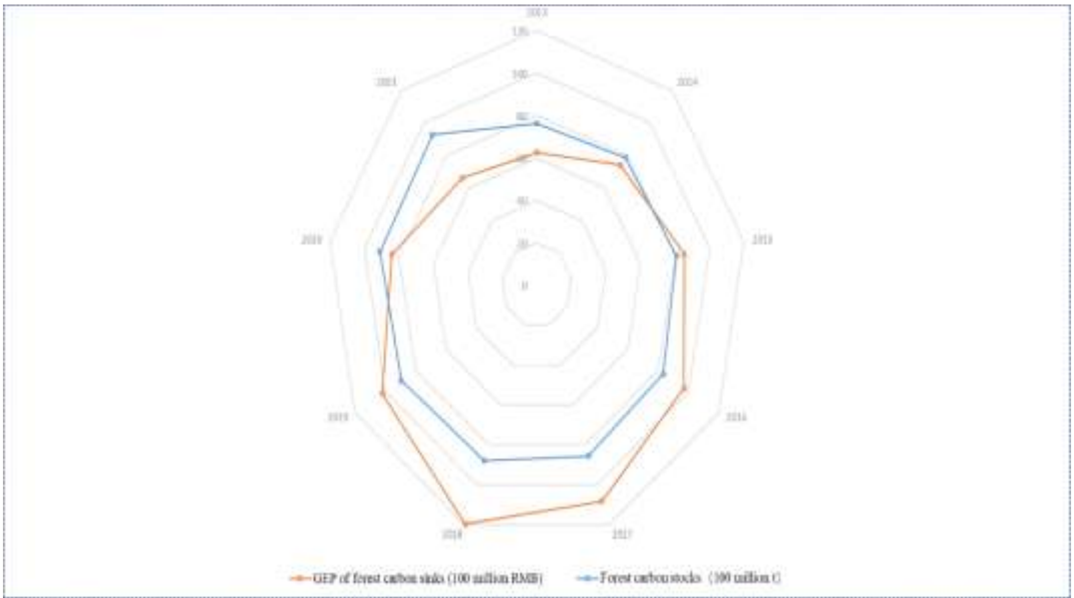

Figure 2. Radar map of forest carbon sink GEP and forest carbon stock changes from 2013 to 2021

4 Discussion

4.1 The Intermediate Consumption of Forest Carbon Sink Production Is Large, Which Itself Has Limited Influence on Economic Development

Forests are important terrestrial ecosystems that play an important role in combating global climate change. Forest carbon sink can act as both reservoirs and absorbers of greenhouse gases, and can also become sources of greenhouse gas emissions due to deforestation, forest degradation, fires, etc. As can be seen from the process of GHG accounting of forest carbon sink in China, relevant studies have shown that the total consumption coefficient for forest carbon sink production is 0.44-0.48 [35], which means that to produce one unit of forest carbon sink, 0.44-0.48 units of materials from this sector and other sectors are consumed, while the final output is about 0.52-0.56. Therefore, from this perspective, the intermediate consumption of forest carbon sink production is large, and its basic impact on other sectors is obvious, but its impact on economic development is limited, and it is necessary to reduce the intermediate consumption, improve the management level of forest resources and scientific and technological innovation capacity etc. to improve the productivity and output efficiency of forests[12], which is very important for China's high-quality development and green low-carbon development.

4.2 The Output Efficiency of Forest Carbon Sink Should Be Improved

In the process of forest carbon sink production, as the intermediate consumption is large, it is therefore necessary to improve the output efficiency of forest carbon sink by improving the management level and accelerating technological progress. On the one hand, increasing net forest productivity in terms of the physical output of the forest carbon sink, thereby increasing the carbon sink of forests; on the other hand, the price of forest carbon sink should be improved, a sound market system for forest carbon trading should be established in China, and the trading mechanism of the carbon sink market should be improved, etc. to ensure the healthy development of carbon market trading.

4.3 Improving the Main Productivity of Forest Resources is the Fundamental of Improving Carbon Sink

Material goods, cultural goods and ecological goods are the three types of products that support socio-economic development and modern human existence[36]. The production of forest carbon sink is a socially productive activity and is resource-based, requiring the necessary inputs. Therefore, increasing the productivity of key forest resources is fundamental to increasing forest carbon sink. Research shows that, for every 1m^3 increase in forest stock volume, an average of 1.83t CO_2 is absorbed and 1.62t O_2 is released[15]. Therefore, increasing the GEP of China's forest carbon sink and improving the productivity of the main body of forest resources are fundamental to increasing forest carbon sink.

5 Conclusion

Through the accounting of China's forest carbon sink in 2013 and 2021, compared with the GEP accounting content of the United Nations "SEEA-EEA", we can see:

(1) In 2013, the GEP of China's forest carbon sink accounted for 1.36% of the total GDP of 59.3 trillion yuan in that year, and 0.0058% of the total GDP of 114.40 trillion yuan in 2021. From 2013 to 2021, the proportion of forest carbon sink GEP in GDP decreased. In addition, the total physical amount of forest carbon sink is constantly increasing, and the forest carbon storage from 2013 to 2021 increased from 7.635 billion t in 2013 to 9.259 billion t in 2021, an increase of 1.624 billion t. The research results also show that when the contribution of forest carbon sink to GDP increases in China, the products and services provided by other sectors of the national economy increase[30], indicating that the role of forest carbon sink to climate change and the contribution of national economy are increasing.

(2) In the stock accounting of forest carbon sink, in 2013, the value of China's forest carbon stock was 804.424 billion yuan, and in 2021, the value of forest carbon stock was 906.189 billion yuan. From 2013 to 2021, the value of forest carbon stock increased by 101.765 billion yuan, with an average annual growth rate of 1.50%, lower than the average annual GDP growth rate of 6.00% in the same period. It shows that the total forest carbon storage in

China is increasing both in terms of physical quantity and value, but its increase rate is less than that of GDP in the same period. Therefore, from a global perspective, although China's provision of forest carbon sink products to serve climate change is increasing, its increase potential needs to be strengthened.

(3) In recent years, although China's forest growth is greater than consumption, the results of the 8th forest resources inventory also show that the forest area increased from 195 million ha in the 7th to 208 million ha in the 8th, a net increase of 12.23 million ha; The forest coverage rate increased from 20.36% in the 7th to 21.63% in the 8th, an increase of 1.27 percentage points; Forest stock increased from 13.721 billion m^3 in the 7th to 15.137 billion m^3 in the 8th, a net increase of 1.416 billion m^3 [29]. The results of the 9th forest resources inventory also show that the consumption of forests is less than the growth of resources. From the accounting results of forest carbon sink GEP in 2013-2021, it can be seen that the intermediate consumption of forest carbon sink production in China is large, which has an obvious fundamental effect on other sectors. The complete consumption coefficient of forest carbon sink production is about 0.44-0.48, which also reflects the reduction of intermediate consumption of forest carbon sink production. Improving the efficiency of forest carbon sink output and the productivity of forest resources is an important part of forest carbon sink management in the future.

(4) The GEP accounting results of forest carbon sink also show that the value of forest carbon storage is much higher than the value of forest carbon sink flow, and forest carbon sink GEP accounting model and forest carbon storage is a quadratic equation with nonlinear change in China. In 2013, the value of forest carbon stock was 10.31 times that of carbon sink flow, and in 2021 it was 11.31 times, an increase of nearly one times. Therefore, from the perspective of the management and utilization of forest resources, it reflects the smaller proportion of the use of forest carbon sink flow in China, the increase is not big. In the management and utilization of forest resources, it should improve the level of forest resource management and then improve the productivity of forest resource, which is the main direction of future efforts to improve the level of forest carbon sink in China.

Acknowledgements: The study is supported by the National Natural Science Foundation of China (72173011), here we would like to express our heartfelt thanks.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author Contributions: Zhang Ying designed the research, wrote the paper, and drew figures. Zhang Zixuan conducted the analysis, and exchanged ideas, and prepared the final version of the manuscript. Zhang Keren and Wang Zhichen helped with data collection and analysis. All authors contributed to the article and approved the submitted version.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 72173011).

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary Material: The Supplementary Material for this article can be found online at: http://www.canre.org.cn/info/2092/87503.htm

References

1. 1.State Administration for Maket Regulation, Standardization Administration, P. R. China. *Ecosystem assessment Guidelines for gross ecosystem product accounting* (Draft for Comments) (GB/T XXXXX—XXXX), September 30,2020 (2020).
2. 360 Encyclopedia. *Gross ecosystem product*. https://baike.so.com/doc/7312527-7542124.html, 2022-12-09 (2022).

3. United Nations, European Commission, International Monetary Fund, Organisation for Economic Cooperation and Development, & World Bank. *System of Environmental-Economic Accounting 2012—Central Framework*. United Nations. https://seea.un.org/sites/seea.un.org/files/seea_cf_final_en.pdf (2014).
4. Daily, G. C. *Nature's Services: Societal dependence on natural ecosystems*. Island Press, Washington D C (1997).
5. Costanza, R., Darge, R., Groot, R., *et al*. The value of the world's ecosystem services and natural capital. *Nature* **386**, 253-260 (1997).
6. Khanna, P., & Saraswat, N. Perspectives on R&D in environmental science and technology in India. *Current Science* **59**, 351–356 (1990).
7. Wofsy, S. C., Goulden, M.L., Munger, J.W., Fan, S.M., Bakwin, P. S., Daube, B.C., Bassow, S. L. & Bazzaz, F.A. Net exchange of CO_2 in a mid-latitude forest. *Science* **260**, 13 14-1317 (1993).
8. Waring, R. H., Runyon, J., Goward, S.N., Mc Creight, R., Yoder, B. & Ryan, M.G. Developing remote sensing techniques to estimate photosynthesis and annual forest growth across a steep climatic gradient in western Oregon, U.S.A. *Studia Forestalia Suecica* **191**, 33-42 (1993).
9. Waring, R H, Law, B E, Goulden, M L, *et al*.. Scaling gross ecosystem production at Harvard Forest with remote sensing: a comparison of estimates from a constrained quantum-use efficiency model and eddy correlation. *Plant, Cell and Environment* **18**, 1201-1213 (1995).
10. Ouyang, Z. Y., Zhu, C. Q., Yang, G. B., Xu, W. H., Zheng, H., Zhang, Y., Xiao, Y. Gross ecosystem product: concept , accounting framework and case study. *Acta Ecologica Sinica* **33**, 6747-6761 (2013).
11. United Nations, European Commission, International Monetary Fund, Organization for Economic Cooperation and Development, & World Bank. *System of Environmental-Economic Accounting 2012—Experimental Ecosystem Accounting*. United Nations. https://seea.un.org/sites/seea.un.org/files/seea_eea_final_en_1.pdf (2014).
12. United Nations, European Commission, International Monetary Fund, Organization for Economic Cooperation and Development, & World Bank. *System of Environmental-Economic Accounting 2012—Applications and Extensions*. United Nations. https://seea.un.org/sites/seea.un.org/files/ae_final_en.pdf (2017).
13. Yang, M., Xiao, X., Ouyang, Z. Y., *et al*. Ecosystem regulation services accounting of gross ecosystem product (GEP) in Sichuan province. *Journal of Southwest Minzu University* (Natural Science Edition) **45**, 221-232 (2019).
14. State Forestry and Grassland Administration, P. R. China. *Criteria for Assessment of forest ecosystem Services* (GB/T 38582-2020). Beijing: State Administration for Market Regulation, Standardization Administration, p. 1-19 (2020).
15. Zhang, Y. L., Han, B. L., Sun, F. F. Research on the accounting system and management application of gross ecosystem product (GEP) - Shenzhen as an example. *Acta Ecologica Sinica* **17**, 1-12 (2023).
16. Zhang, J., Zou, Z. Y. Research on calculation and application of GEP in Brahmaputra River Basin. *Ecological Economy* **38**, 167-172+227 (2022).
17. Ma, G.X., Yu, F., Wang, J. N., *et al*. Measuring gross ecosystem product (GEP) of 2015 for terrestrial ecosystems in China. *China Environmental Science* **37**, 1474-1482 (2017).
18. Lin, Y. Q. g, Chen, M., Zhang J. Y., *et al*. Accounting system of gross water ecosystem product and its application. *Water Resources Protection* **39**, 234-242 (2023).
19. Jin, D., Bian, Z. F. The Accounting of Ecological Civilization in Xuzhou Based on Energy and Gross Ecosystem Production. *China Land Science* **27**, 88-94 (2013)..
20. Bai, Y., Li, H., Wang, X. Y., *et al*. Evaluating Natural Resource Assets and Gross Ecosystem Products Using Ecological Accounting System: A Case Study in Yunnan Province. *Journal of Natural Resources* **32**, 1100-1112 (2017).
21. Lu, J, Yan, H F. China's first provincial ecosystem gross product accounting standard released. *Guangming Daily*,2020-10-28 (2020).
22. Ouyang, Z.Y., Lin, Y. Y., Song, C. S. Research on Gross Ecosystem Product (GEP):

case study of Lishui City, Zhejiang Province. *Environment and Sustainable Development* **6**, 80-85 (2020).
23. Shi, F Q. Introduction to the Accounting Standard for Total Value of Ecological Products (Trial) . *China Statistics* (11), 45-47 (2023).
24. Zhang, Y., Hou, Y. Z., Wei, X. Z., *et al*. The Green Accounting for Forests in Beijing. *Journal of Beijing Forestry University* **30**, 23 2-237 (2008).
25. National Forestry and Grassland Administration. *Report on Comprehensive Monitoring and Evaluation of China's forest and grassland Ecology in 2021*. Beijing: China Forestry Publishing House, p.4-10.(in Chinese) (2023)
26. Wu, Z. Z. National Forestry and Grassland Administration published forest and grassland resources and ecological status in China in 2021. https://www.forestry.gov.cn/c/www/lczy/28646.jhtml, 2022-11-23. (in Chinese) (20 22)
27. Li, S. L. *Research on forest carbon sink*. Harbin: Northeast Forestry University Press, pp.100-101 (2006).
28. Zhao, L., Yin, M. F., Chen, X. F., *et al*. Summary of the Research Methods of Forest Carbon Sink Accounting. *Journal of Northwest Forestry University* **23**, 59-63 (20 08).
29. National Forestry and Grassland Administration. *China forest resources report (2014-2018)*. Beijing: China Forestry Publishing House, p. 3-12 (2020) .
30. National Forestry and Grassland Administration. *China Forestry and Grassland Statistical Yearbook* (2021). Beijing: China Forestry Publishing House, p.21-25 (2022).
31. Zhang, Y., Wu, L. L., Su, F., *et al*. An accounting model for forest carbon sinks in China. *Journal of Beijing Forestry University* **32**, 194-200 (2010).
32. National Forestry and Grassland Administration. *China Forestry and Grassland Statistical Yearbook* (2019), Beijing: China Forestry Publishing House, p.22-23 (2020b).
33. China Foreign Exchange Trade System. *Annual average exchange rate of RMB*. https://www.chinamoney.com.cn/chinese/bkccpr/. 2023-05-31 (2023).
34. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of China. *Industry Classification of National Economy* (GB/T 4754-2017). Published 2017-06-30, implemented 2017-10-01.Beijing, p.1-216 (2017).
35. He, X. J. Research on the evolution of industrial dependence and the pull of manufacturing industry on the economy in Beijing based on input-output coefficient. *Journal of Industrial Technological Economics* **29**, 97-102 (2010).
36. Zhang, Y., Zhou, X., Qin, Q. F., *et al*. Value accounting of forest carbon sinks in China. *Journal of Beijing Forestry University* **35**, 124-131 (2013).
37. National Bureau of Statistics. *China Statistical Yearbook* (2022). Beijing: China Statistic Publishing House, p.18-20 (2022).