atmosphere

Article

Assessing Carbon Sink Capacity in Coal Mining Areas: A Case Study from Taiyuan City, China

Fan Chen [1,2], Yang Liu [3], Jinkai Guo [4], He Bai [4], Zhitao Wu [2], Yang Liu [1,*] and Ruijin Li [1,*]

1 Institute of Environmental Science, Shanxi University, Taiyuan 030006, China
2 School of Environment and Resource, Shanxi University, Taiyuan 030006, China
3 Shanxi Dibao Energy Co., Ltd., Taiyuan 030006, China
4 Taiyuan Dongshan Wang Feng Coal Industry Co., Ltd., Taiyuan 030006, China
* Correspondence: 4747@sxu.edu.cn (Y.L.); lirj@sxu.edu.cn (R.L.)

Abstract: Climate warming and air pollution are atmospheric environmental problems that have aroused broad concern worldwide. Greenhouse gas emissions are the main cause of global warming. In addition to reducing carbon emissions, increasing carbon sink capacity and improving environmental quality are essential for building green and low-carbon enterprises under carbon peak and carbon neutrality goals. Currently, the research on the methods and application of carbon sink capacity assessment in coal mining enterprises is limited. Given this, this study estimated the carbon absorption, carbon storage, and net ecosystem productivity of a typical coal mining area in Taiyuan City, China, and compared the characteristics and applicability of the three methods. The results showed the following: (1) The total carbon absorption (carbon sink) of the mining area in 2021 was 117.39 t, the primary source of which is forest land. (2) The total carbon storage in the mining area in 2021 was 29,561.96 t. From different land use types, the carbon storage in the mining area mainly came from forest land (27,867.73 t); from the perspective of carbon pool, soil carbon storage (21,970.96 t) had the most significant contribution to the carbon storage of mining areas. (3) The net ecosystem productivity of the mining area in 2021 was 781.97 g/(m^2·a), indicating that the ecosystem of the mining area was a carbon sink. (4) The three estimation methods differed in the current case. The estimation method for carbon absorption is the simplest, and the results are the most intuitive. The estimation method for net ecosystem productivity is the most complex. The carbon sink estimation via carbon storage needs to collect two years of data. Enterprises should assess the carbon sink capacity of mining areas based on existing conditions and data. This study proposes methods for estimating carbon sink capacity in mining areas, which have positive practical significance for the low-carbon green development of coal mine enterprises.

Keywords: coal mining; carbon sink capacity; estimation method; Taiyuan

check for updates

Citation: Chen, F.; Liu, Y.; Guo, J.; Bai, H.; Wu, Z.; Liu, Y.; Li, R. Assessing Carbon Sink Capacity in Coal Mining Areas: A Case Study from Taiyuan City, China. *Atmosphere* **2024**, *15*, 765. https://doi.org/10.3390/atmos15070765

Academic Editor: Dmitry Belikov

Received: 2 June 2024
Revised: 22 June 2024
Accepted: 24 June 2024
Published: 27 June 2024

1. Introduction

Coal mining can release large amounts of methane (CH_4). Fuel consumption and coal gangue stacking processes in mining areas can also release carbon monoxide (CO), carbon dioxide (CO_2), and sulfur dioxide (SO_2). CH_4 and CO_2 are significant contributors to global warming. Global warming can cause various adverse climate and environmental changes, threatening human production and development. In addition, coal mining also affects the pattern and function of ecosystems to varying degrees. Under the goal of carbon peak and carbon neutrality, industrial development is moving toward green and low-carbon methods. Coal mining enterprises' green and low-carbon development has included carbon reduction, carbon sink elevation, and green mine construction [1]. For enterprises, in addition to utilizing efficient methods of reducing carbon emissions, elevating the carbon sink capacity of mining areas is also vital for achieving carbon neutrality goals and building green and low-carbon coal mining areas [2].

Carbon sink capacity refers to the ability of a coal mine (vegetation and soil) to absorb and store CO_2, which is a crucial factor in determining its efficiency and the sustainability of carbon neutralization. Constructing green mines involves a lot of carbon sink calculation research. After understanding the current situation of carbon sink capacity in mining areas, enterprises can reasonably formulate plant and land types for greening and reclamation, which is of great significance for enhancing the carbon sink capacity of mining areas, achieving the low-carbon development of enterprises, and ecological protection. Therefore, coal mining production enterprises hope to use simple and effective carbon sink accounting methods to evaluate their carbon sink capacity. They also provide data support for building green and low-carbon mining area evaluation indicators by accumulating years of research data related to carbon sinks. However, there is still limited research on calculating and analyzing carbon sinks in mining areas [1].

Numerous scholars have conducted research on carbon sinks in mining areas from different perspectives, such as estimating carbon sinks using carbon absorption coefficients [3–5], quantitatively assessing carbon storage in mining areas [6–10], estimating the net primary productivity (NPP) of vegetation [11,12], constructing an ecological carbon sink system in coal mining areas [13], ecological restoration and emission reduction in mining areas [14], and so on. Net ecosystem productivity (NEP), considering NPP and soil microbial respiration (R_h), is an essential indicator for quantitatively describing regional carbon sources/sinks objectively [15,16].

Coal mining can cause damage to the ecological environment of mining areas, such as surface subsidence, the loss of arable land, and vegetation regression, which can lead to a sharp decline in the carbon sink function of the mining area ecosystem [17]. Accurate carbon sink data can be obtained promptly through carbon sink accounting. Based on carbon sink data, enterprises can further conduct ecological construction and enhance the carbon sink capacity of mining areas. Carbon absorption, carbon storage, and NEP are indicators for quantifying the carbon sink capacity of mining areas. However, the applicability of various methods for assessing the ability to absorb carbon in mining areas has not yet been studied comprehensively.

Shanxi is a major coal-producing province in China, with many coal production enterprises. This study estimated the carbon sink capacity of a typical mining area in Taiyuan of Shanxi province based on carbon absorption, carbon storage, and NEP methods. Also, this study discussed the applicability of three estimation methods in mining areas. It provided positive strategies for elevating the carbon sinks of mining areas, which can be a reference for evaluating carbon sink capacity in similar mining areas. It positively influences the construction of green and low-carbon mining areas.

2. Materials and Methods

2.1. Study Area

This study selected a specific underground coal mine in Wanbailin District, Taiyuan City, Shanxi Province (Figure 1). The mining area is 235.36 hm^2, with high terrain in the south, low terrain in the north, and a small water area. The mining area belongs to a temperate continental semi-arid climate, with an average annual temperature of 10.39 °C and an average yearly precipitation of 470.70 mm. The research area has abundant coal resources. The coal production of this coal mine in 2021 was 415,500 t. The enterprise's revenue reached RMB 127.39 million in 2021 by selling coal inside and outside the province. However, the coal mining process will damage the ecological environment of the mining area and then affect the carbon sink capacity of the mining area.

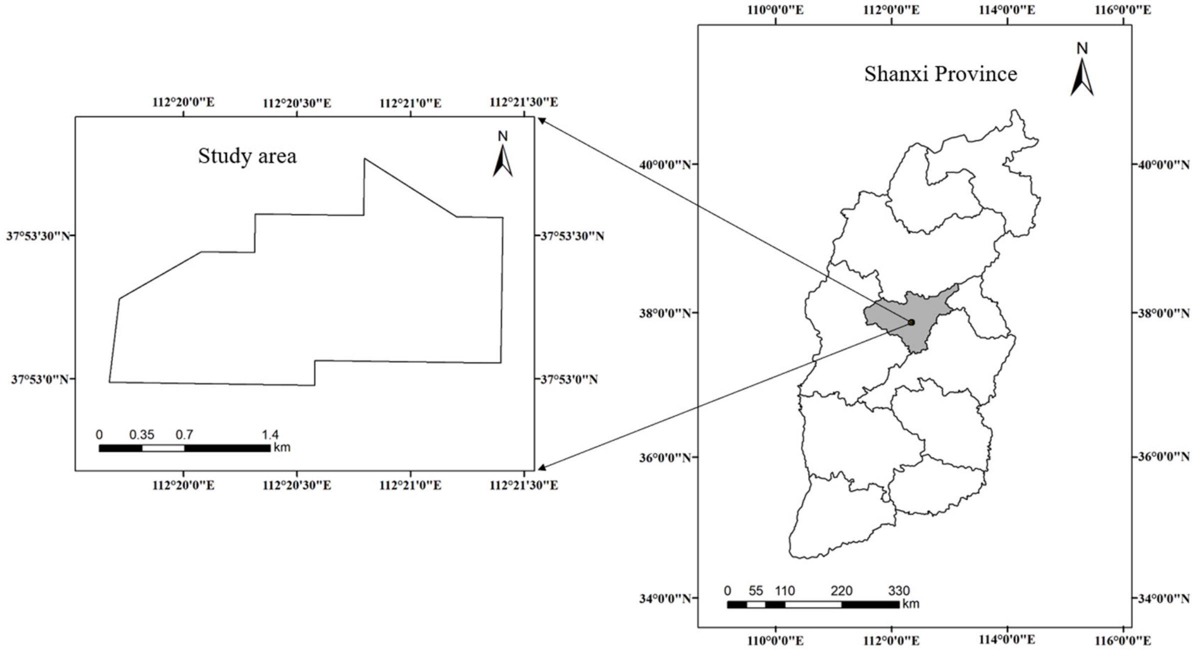

Figure 1. Schematic of the study area.

2.2. Data Source and Processing

2.2.1. Data Source

We used the data to estimate the carbon sink capacity of the mining area in this study. These data include land use and meteorological information from the report on coal mines (Coal Resource Development and Utilization, Mine Environmental Protection, and Land Reclamation Plan) in 2021. Meteorological data were on the average annual temperature and precipitation.

2.2.2. Data Processing

The land use types in mining areas are classified according to China's national standard (Land Use Status Classification, https://openstd.samr.gov.cn/bzgk/gb/newGbInfo?hcno=224BF9DA69F053DA22AC758AAAADEEAA (accessed on 21 May 2024)) (Table 1). It is mainly divided into cultivated land, forest land, grassland, land for mining and industry, residential areas, transportation, water area, some land for water conservation facilities, and other land. Among them, land for mining and industry, land for residential areas, and land for transportation all belong to construction land.

Table 1. Land use types in coal mining areas.

Land Use Type	Area in 2021 (t/hm^2)	Notes
Cultivated land	5.66	
Forest land	201.75	
Grassland	0	Undivided in 2021
Land for mining and industry	7.16	Belonging to construction land
Land for residential area	7.76	
Land for transportation	3.89	
Water area and land for water conservancy facilities	0.35	Abbreviated as water area
Other land	8.79	

There are differences in land use types in different periods of mining areas. For example, the land use type of coal mine in 2013 was grassland, but there was no division in 2021. This study added grassland based on the land use types in the mining area in 2021 and calculated this area as 0. It can comprehensively obtain the land use types of the mining area and avoid the lack of carbon absorption coefficient and carbon density data when calculating its future carbon sink capacity.

By comparing existing research, this study provides the following explanation for construction land and water areas: land for mining and industry, land for residential areas, and land for transportation all belong to the "three categories" of construction land in the Land Management Law of the People's Republic of China. Water area and land for water conservancy facilities are abbreviated as water area.

Based on collected land use and meteorological data, three carbon sinks (carbon absorption, carbon storage, and NEP) were calculated using the formula below.

2.3. Using Carbon Absorption Coefficient to Estimate Carbon Absorption

By referring to relevant research on land use carbon sources/sinks at home and abroad, the estimation of carbon sources/sinks in mining areas was based on land use area [3,5]. The carbon absorption was calculated using the carbon absorption coefficient, which means that the annual absorption of a specific land use type was obtained by multiplying the area of that part by the corresponding carbon absorption coefficient.

This study focused on quantifying the carbon sink of land use in mining areas and estimated the carbon absorption of cultivated land, forest land, grassland, water area, and other land. We used the total carbon absorption of mining areas to represent the carbon sink of mining areas and accumulated the carbon absorption of different land use types. The formula is as follows:

$$C_t = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} A_i \times H_i \quad (1)$$

where C_t is the total amount of carbon absorption in the mining area (t); C_i is the carbon absorption of the i-th type of land use (t); and A_i is the area of the i-th type of land use (hm^2). The carbon absorption coefficient (H_i) refers to vegetation's ability per unit land cover area to absorb carbon dioxide through photosynthesis, usually expressed as the amount of absorbed carbon dioxide (t) per the area of vegetation (hm^2). In this study, H_i is the carbon absorption coefficient of the i-th type of land use (t/hm^2), whose values of different land use types are from the existing literature [3,5,18–21]; n is the number of land use types, and in the process of calculating carbon absorption, this study identified 5 types of land use, that is, n is 5.

The results of carbon absorption are shown in Table 2.

Table 2. Carbon absorption coefficients of different land types.

Land Use Type	Carbon Absorption Coefficient (t/hm^2)	Source
Cultivated land	0.007	An et al. [3]
Forest land	0.581	Cao and Cui. [19]; Zhang et al. [21]
Grassland	0.021	Zhan et al. [5]; Zhang et al. [21]
Water area	0.253	Cao and Cui. [19]; Zhang et al. [21]; Zhong et al. [18]
Other land	0.005	Han et al. [20]; Zhang et al. [21]; Zhong et al. [18]

2.4. Using Carbon Density to Estimate Carbon Storage

2.4.1. Estimation of Carbon Storage

This study refers to the carbon storage module in the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model to estimate the carbon storage of mining areas [22]. The mining area ecosystem can be divided into four primary carbon pools as follows: aboveground biomass carbon pool, underground biomass carbon pool, soil carbon pool, and dead organic carbon pool. The carbon storage of a specific land use type is obtained by multiplying the area of that part with its corresponding carbon density. Then, the carbon storage of each land use type is summed up to obtain the total carbon storage of the mining area. The formula is as follows:

$$C_{i\text{-}total} = C_{i\text{-}above} + C_{i\text{-}below} + C_{i\text{-}soil} + C_{i\text{-}dead} \quad (2)$$

$$C_{total} = \sum_{i=1}^{n} C_{i\text{-}total} \times A_i \quad (3)$$

where $C_{i—total}$ is the carbon density of the i-th type of land use (t/hm^2); $C_{i—above}$ is the aboveground carbon density of the i-th type of land use (t/hm^2); $C_{i—below}$ is the underground carbon density of the i-th type of land use (t/hm^2); $C_{i—soil}$ is the soil carbon density of the i-th type of land use (t/hm^2); $C_{i—dead}$ is the carbon density of dead organic matter in the i-th type of land use (t/hm^2); C_{total} is the total amount of carbon storage in the mining area (t); A_i is the area of the i-th type of land use (hm^2); and n is the number of land use types. In the process of calculating carbon storage, this study identified eight types of land use, namely, n is 8.

2.4.2. Selection and Calibration of Carbon Density

Appropriate carbon density data are crucial for estimating carbon storage in mining areas. Due to the lack of measured data in the study area, this study referred to the research results of Zhang et al. [23], Liu et al. [7], Wang et al. [24], Zhang et al. [25], Fan. [26], Sun. [27], Wang et al. [28], and Xu et al. [10] and selected the carbon density data used in the surrounding areas and other mining areas of the study area. The preliminary selected carbon density can be found in the Supplementary Materials.

The carbon density in different regions also needs to consider the influence of temperature and precipitation. The average annual temperature and precipitation significantly impact biomass carbon density, and the effect of temperature on soil carbon density can be ignored (correction formula can be found in Fu et al. [9]). The corrected carbon density is shown in Table 3. The carbon density of dead organic matter refers to the research results of Liu et al. [7], and 1/10 of the aboveground carbon density is taken as the carbon density of dead organic matter.

Table 3. Corrected carbon density.

Land Use Type	Aboveground Carbon Density (t/hm^2)	Underground Carbon Density (t/hm^2)	Soil Carbon Density (t/hm^2)	Carbon Density of Dead Organic Matter (t/hm^2)
Cultivated land	1.65	0.32	87.09	0.16
Forest land	28.67	5.98	100.61	2.87
Grassland	3.35	2.10	78.84	0.33
Land for mining and industry	0.03	0	61.55	0
Land for residential area	0	0	50.07	0
Land for transportation	0	0	47.77	0
Water area	0.02	0	0	0
Other land	0.81	0.14	18.76	0.08

2.5. Using NPP to Estimate NEP

2.5.1. Estimation of NPP

First, the estimation of NPP in this study was based on the Miami model [29], which has the following equation:

$$\mathrm{NPP_T} = 3000/\left(1 + e^{1.315 - 0.119\mathrm{T}}\right) \quad (4)$$

$$\mathrm{NPP_R} = 3000\left(1 - e^{-0.000664\mathrm{R}}\right) \quad (5)$$

where T is the average annual temperature (°C); R is the average annual precipitation (mm); NPP_T is the net primary productivity of vegetation calculated based on the average annual temperature $[g/(m^2 \cdot a)]$; and NPP_R is the net primary productivity of vegetation calculated based on the average annual precipitation $[g/(m^2 \cdot a)]$.

Then, according to Liebig's law of the minimum, the minimum values of NPP_T and NPP_R are selected as the net primary productivity of vegetation in the mining area.

2.5.2. Estimation of NEP

Research has shown that NEP can be calculated as the difference between NPP and R_h [30]. When NEP > 0, it indicates that the carbon fixed by vegetation is more than the carbon emitted by soil microbial respiration, and the ecosystem behaves as a carbon sink. Conversely, it is a carbon source. R_h was estimated using the soil respiration model established by Pei et al. [31]. The calculation formulas for NEP and R_h are as follows:

$$\mathrm{NEP} = \mathrm{NPP} - \mathrm{R_h} \quad (6)$$

$$\mathrm{R_h} = 0.22 \times \left(e^{(0.0913T)} + \ln(0.3145R + 1)\right) \times 30 \times 46.5\% \quad (7)$$

where the units of NEP, NPP, and R_h are $g/(m^2 \cdot a)$; T is the average annual temperature (°C); and R is the average annual precipitation (mm).

3. Results

3.1. Carbon Absorption in Mining Areas

The total carbon absorption in the mining area is 117.39 t (Table 4), among which the total carbon absorption of forest land is 117.22 t, accounting for 99.86% of the total carbon absorption in the mining area. Among various land use types in mining areas, forest land is the main carbon sink, and the carbon absorption effect of forest land is the most significant. In addition, due to the large proportion of forest land in the total mining area, the carbon absorption coefficient of forest land is higher than that of other types.

Table 4. Estimation results of carbon absorption in the mining area in 2021.

Land Use Type	Cultivated Land	Forest Land	Grassland	Water Area	Other Land
Carbon absorption (t)	0.04	117.22	0	0.09	0.04

3.2. Carbon Storage in Mining Areas

The total carbon storage in the mining area is shown in Table 5. There are significant differences in carbon storage among different land use types, with forest land accounting for 94.27% of the total carbon storage in the mining area. Soil carbon storage in mining areas (21,970.96 t) > aboveground carbon storage (5800.85 t) > underground carbon storage (1209.51 t) > dead organic matter carbon storage (580.63 t). From the perspective of the carbon pool, the soil carbon storage in the mining area is the largest, accounting for 74.32% of the total carbon storage in the mining area. Soil carbon storage is the primary source of carbon storage in mining areas.

Table 5. Estimation results of carbon storage in the mining area in 2021.

Land Use Type	Aboveground Carbon Storage (t)	Underground Carbon Storage (t)	Soil Carbon Storage (t)	Dead Organic Matter Carbon Storage (t)	Total Carbon Storage (t)
Cultivated land	9.34	1.81	492.93	0.91	504.99
Forest land	5784.17	1206.47	20,298.07	579.02	27,867.73
Grassland	0	0	0	0	0
Land for mining and industry	0.21	0	440.70	0	440.91
Land for residential area	0	0	388.54	0	388.54
Land for transportation	0	0	185.83	0	185.83
Water area	0.01	0	0	0	0.01
Other land	7.12	1.23	164.90	0.70	173.95
Mining area	5800.85	1209.51	21,970.96	580.63	29,561.96

3.3. NEP Estimation in Mining Areas

According to Formulas (4)–(7), the NPP and R_h of the mining area in 2021 were calculated as 805.25 g/(m^2·a) and 23.28 g/(m^2·a), respectively, and the NEP value in the mining area was 781.97 g/(m^2·a).

4. Discussion

4.1. Discussion on Estimation Results and Their Methods

4.1.1. Discussion on Carbon Absorption and Its Estimation Methods

The method for calculating carbon absorption in this study is based on existing research and has a certain degree of reliability. However, this method still has some shortcomings. For cultivated land, the presence of crops is reflected in the carbon sink. Still, the carbon sink effect is insignificant, and the carbon absorption coefficient is taken as 0.007 t/hm^2 [3]. Some consider arable land a carbon source, with a carbon emission coefficient of 0.497 t/hm^2 [21]. There is a dispute over carbon sources and sinks in grassland and water areas. Due to the focus of this study on the carbon sink capacity of mining areas, various land use types are considered carbon sinks.

The carbon absorption and storage estimation methods show that selecting the carbon absorption coefficient and density is critical. Currently, there is no unified carbon absorption coefficient, leading to uncertainty in estimating carbon sinks. As discussed earlier on carbon absorption and its estimation methods, the results of this study are still reliable.

Based on remote sensing image data from different study periods, the researchers can also obtain the spatiotemporal distribution characteristics of carbon sources/sinks in the study area. It is an important direction for the further study of carbon sinks in mining areas.

4.1.2. Discussion on Carbon Storage and Its Estimation Methods

By estimating the changes in carbon storage over different periods, the carbon sink of the study area can be obtained [32–34]. However, based on the enterprise's existing data, this study only estimated the carbon storage of the mining area in 2021. It did not obtain the carbon sink of the mining area in 2021. Liu et al. [7] found that carbon storage in mining areas can reflect their carbon sink function, and it is clear that carbon storage in mining areas is a vital means for achieving the goal of carbon neutrality. Therefore, the carbon storage obtained in this study also has positive implications for mining areas.

The calculation of carbon storage based on the InVEST model has certain limitations. The only factor affecting carbon storage in this model is land use change, ignoring the impact of interannual changes in carbon density [35]. Using the InVEST model to estimate carbon storage has been applied to the ecosystem of mining areas [10], demonstrating its applicability in estimating carbon storage in mining areas. The InVEST model focuses on the estimation and variation of carbon storage itself [7], and this study only uses the calculation principle of this model to obtain the carbon storage of mining areas. Due to land use data limitations, this study could not analyze the changes in carbon storage in mining areas. If land use data can be based on the remote sensing image data of mining areas, the research results of this model can be more comprehensive.

4.1.3. Discussion on NPP and Its Estimation Methods

NEP reflects the annual carbon change stored in the ecosystem of the mining area (vegetation and mineral soil), indicating whether the ecosystem is a carbon sink or a carbon source, concerning the atmosphere. A positive value for NEP shows that an area is a carbon sink, whereas a negative value displays a carbon source. Estimating NEP values can assess the carbon sink capacity in the coal mining area. Increasing NEP might be an efficient way to improve eco-environmental quality and neutralize carbon in the mining ecosystem. It will promote the green and low-carbon development of coal mining enterprises.

Currently, the methods for verifying NPP include comparing it with measured values, research results from others, and remote sensing data [36]. Due to the difficulty in obtaining measured values and remote sensing data, this study adopts the method of verifying others' research results.

Taiyuan is a resource-based province (based on coal) in the central region of China with severe air pollution characteristics. The basin topography of these areas is also not conducive to the diffusion of pollutants. Taiyuan has a north temperate continental climate, with an average annual rainfall of 456 mm and an average yearly temperature of 9.5 °C. This is close to the current coal mining areas (Table 6). In this study area, The Miami model used in this study to estimate NPP is a climate model, and the estimated NPP is also known as potential NPP. In Table 6, the estimated NPP_T in this study is close to the results of Wuzhong City and Zhongning County in Ningxia Province, China, as these areas have similar temperatures. The NPP_R value is similar to the results of Guyuan City and Longde County in Ningxia due to similar precipitation. According to Liebig's law of the minimum, the NPP value of the mining area is 805.25 $g/(m^2 \cdot a)$. The NPP estimated using the Miami model in this study is reliable. The coal production of this coal mine in 2021 was 415,500 t, along with CH_4 and CO_2 emissions. Elevating the carbon sink capacity will help achieve green and low-carbon development in the coal mining areas, while understanding carbon sink capacity is vital for taking positive measurements.

Table 6. Research results of this study and NPP results of Zhang et al. [37].

Study Area	T	R	NPP_T	NPP_R
This study	10.39	470.70	1441.09	805.25
Wuzhong City	10.19	189.45	1423.53	353.02
Zhongning County	10.15	196.89	1419.51	365.69
Guyuan City	7.12	439.30	1156.51	754.81
Longde County	5.76	500.11	1043.70	843.23

Note: T represents average annual temperature, R represents average annual precipitation, NPP_T represents NPP calculated based on average annual temperature, and NPP_R represents NPP calculated based on average annual precipitation. Their units are, in order, °C, mm, $g/(m^2 \cdot a)$, and $g/(m^2 \cdot a)$.

The Carnegie–Ames–Stanford approach (CASA) model is a common method for estimating NPP. This study summarized some research results of others using the CASA model, as shown in Table 7. The CASA model requires more basic data compared to the Miami model. In Table 7, the NPP estimated using the Miami model [805.25 $g/(m^2 \cdot a)$] is more than two times that of the CASA model [about 300 $g/(m^2 \cdot a)$]. Cai et al. [38] found that the NPP simulated by the CASA model is higher than that of the Miami model, and the research results of the CASA model are more accurate. Sun et al. [39] found that the estimated results (potential NPP) based on climate models are 2–4 times higher than those based on other models. These are consistent with the results of this study. To make the estimated NPP more accurate, the CASA model can be used for future in-depth research.

Table 7. Results of this study and others using the CASA model on NPP.

Study Area	Estimation Results of NPP [$g/(m^2 \cdot a)$]	Study Time (Year)	Method	Source
This study	805.25	2021	Miami model	
Fenhe River Basin	291.57	From 2000 to 2015	CASA model	Tian et al. [40]
Shanxi Province	273.67	From 2000 to 2019	CASA model	Su et al. [41]
Loess Plateau	300.74	From 2001 to 2019	CASA model	Song et al. [42]
Lvliang contiguous poverty areas	241.24–331.70	From 2000 to 2018	CASA model	Sun et al. [43]

4.1.4. Discussion on R_h, NEP, and Their Estimation Methods

In addition to using monthly average temperature and precipitation, researchers also use the average annual temperature and precipitation to calculate R_h. Based on annual meteorological data, Wang. [44] estimated that the average R_h of the Xizang grassland ecosystem from 2000 to 2014 was 17.59 g/(m^2·a). This study's method of estimating R_h using annual meteorological data proves feasible.

The estimation results of NEP are influenced by NPP and R_h [30]. Chen [15] estimated NPP in the western Sichuan Plateau based on the CASA model and R_h based on the soil respiration model, thereby estimating NEP in the region. This result is significant for studying the carbon sink capacity and ecological environment governance in the western Sichuan Plateau. Wang et al. [36] studied the NEP of the Yellow River Basin based on the CASA model and soil respiration model, which provides a reference basis for achieving the goal of carbon neutrality in the Yellow River Basin. In future research, studying the NPP of mining areas based on the CASA model can make the estimation results of NEP more accurate and have a more critical reference value for enhancing the carbon sink of mining areas.

4.2. Evaluation of Methods for Estimating Carbon Sink Capacity in Mining Areas

The degree of difficulty of application for different methods for assessing carbon sink capacity varies. Based on enterprise land use and meteorological data, this study provided three methods for estimating carbon sink capacity in mining areas (Table 8). The three methods have various advantages and disadvantages. The carbon absorption method is relatively simple and requires fewer data. The carbon storage method requires relatively more data, and the difficulty of estimation will correspondingly increase. Although the NEP method is complex, quantifying carbon sink is more objective and requires relatively fewer data. Estimating the carbon sink with the change data of carbon storage (based on carbon density) for two years is necessary. Under the situation of carbon reduction and increase, enterprises must assess carbon sink capacity according to their actual situation. This study provides carbon sink assessment methods for different enterprises, enabling enterprises to find suitable methods for carbon sink estimation, and has positive practical significance for improving carbon sink in mining areas.

Table 8. Evaluation of methods for estimating carbon sink capacity in mining areas.

Index	Units	Main Estimation Methods	Advantage	Disadvantage	Notes
Carbon absorption	t	The product of carbon absorption coefficient and area	The simplest method	The carbon absorption coefficient is not yet unified	Carbon absorption is also known as a carbon sink.
Carbon storage	t	The product of carbon density and area	The method is relatively simple	The InVEST model ignores the influence of interannual changes in carbon density; at least two years of carbon storage data are required to obtain carbon sink capacity.	Carbon sink refers to the increase in carbon storage over two years.
NEP	g/(m^2·a)	NPP minus R_h	The most complex method	Affected by NPP and R_h calculation results, the estimation accuracy of NPP is relatively low.	NEP with a positive value represents carbon sink.

Applying and optimizing the estimation method and data of carbon sink capacity in mining areas can make research results more accurate, which is of great significance for enterprises in implementing carbon neutrality goals. Thus, coal enterprises should choose the proper carbon sink estimation method in mining areas, improve carbon absorption accuracy, and strengthen the research on carbon absorption coefficient. Expanding the carbon sink estimation data in mining areas is necessary. Combining existing datasets and improving ground survey data within the mining area can enhance the accuracy of enterprises' carbon sink estimation.

4.3. Novelty and Limitations for Estimating Carbon Sink Capacity in Mining Areas

This study provides three feasible methods for assessing carbon sinks in coal mining areas. This study only recommends NEP as an evaluation index for quantifying carbon sink capacity in mining areas. As far as we know, this study adopts NEP for the first time to quantify carbon sinks in mining areas, which is of great significance for enterprises to improve carbon sinks.

There are some limitations to estimating carbon sink capacity in mining areas.

(1) Since the enterprise's land use and meteorological data are only one year old, this study failed to analyze the carbon sink capacity of the mining area in different periods. The enterprise urgently needs to strengthen land use and meteorological data collection. Liu [45] used land use, meteorological, and NPP datasets to study NPP on the Loess Plateau. Therefore, future research efforts could try to use the existing datasets.

(2) According to the estimation methods of carbon absorption and carbon storage, it is necessary to select the carbon absorption coefficient and density separately for their estimation. Currently, there is no unified carbon absorption coefficient, leading to uncertainty in estimating carbon sinks [46]. As discussed earlier on carbon absorption and its estimation methods, the results of this study are still reliable. This study corrected for carbon density but did not consider the differences in carbon sink capacity among vegetation types and ages (such as differences in carbon sink capacity among vegetation types and ages) [10]. Subsequent research can subdivide vegetation types and conduct field measurements to improve the accuracy of carbon storage calculations.

(3) Since the composition and structure of geological formations can vary widely, it may affect the ability to store CO_2 securely. Some formations may leak stored CO_2 over time, reducing their effectiveness as a long-term carbon sink. In addition, there is uncertainty about how long the stored CO_2 will remain stable. Leakage over time could undermine the effectiveness of coal mines as a carbon sink. Thus, considering this effect may significantly improve the reliability and effectiveness of the assessment of carbon storage.

4.4. Countermeasures for Coal Mining Enterprises to Stabilize Carbon Sinks in Mining Areas

In recent years, countries have explored coping strategies to deal with global warming caused by the increase in greenhouse gases. China is striving to achieve the goal of carbon peak and carbon neutrality. Reducing carbon and increasing carbon sink are important topics of concern to enterprises at present. Providing countermeasures for coal mining enterprises to stabilize the carbon sink in mining areas is conducive to enterprises' green and low-carbon transformation and development.

(1) Adapting to local conditions and improving carbon sinks for different land use types are beneficial. Coal mining enterprises may enhance the carbon sink capacity of vegetation in mining areas from the perspective of planting areas and selecting proper plants to increase carbon sink. Enterprises may improve the carbon sink of this area through vegetation restoration. Regarding vegetation selection, selecting plant species that are suitable for growing in the local climate and soil environment and have high carbon sink capacity is practical.

(2) Strengthening ecological construction in mining areas is essential. To reduce the damage of coal mining to the carbon sequestration capacity of mining areas, coal mining enterprises should integrate the concept of carbon neutrality into the environmental governance process in mining areas. Enterprises should focus on planning and design, restoring the ecology, and improving carbon sink capacity for land that needs to be reclaimed. Planting plants and constructing protective forests in the available land and reclaimed areas of the mining area can improve the ecological environment of the mining

area, thereby increasing carbon sinks, enhancing carbon storage capacity, and protecting the ecological environment.

(3) Applying and improving methods are suitable for estimating carbon sink capacity. Coal mining enterprises should choose the appropriate method of the carbon sink estimation proposed in this study to calculate the carbon sink effect in the mining area. They should also consider expanding the scope of carbon sink calculation by adding different types of land (including land that needs to be reclaimed) and other vegetation carbon sinks.

(4) Monitoring and collecting carbon sink data in mining areas helps determine the carbon sink capacity. Coal mining enterprises need to monitor the vegetation and soil in the mining area year by year, collect data information on the dynamic changes in enterprise carbon sinks, and lay a foundation for improving carbon sinks. Under the right conditions, enterprises can achieve economic benefits in the carbon emissions trading market through the Carbon sink afforestation projects.

(5) Carrying out carbon sink management can enhance the increasing carbon sink work. Coal mining enterprises should combine carbon sinks with carbon emissions and performance evaluation. Enterprises will improve their awareness of carbon emission reduction and carbon sinks and establish a set of indicators and operational methods suitable for the operation and management of carbon reduction and carbon sinks.

5. Conclusions

This study selected a coal mine in Shanxi Province, China, and evaluated carbon sink capacity using three methods (carbon absorption, carbon storage, and NEP). The total carbon absorption of the mining area in 2021 was 117.39 t, with forest land being the main carbon sink in the mining area. The total carbon storage capacity of the mining area in 2021 was 29,561.96 t. From different land use types, the carbon storage in mining areas mainly comes from forest land (27,867.73 t). The NEP of the mining area in 2021 is 781.97 $g/(m^2 \cdot a)$, indicating that the ecosystem of the mining area is a carbon sink. Each indicator can reflect the carbon sink capacity of mining areas. The carbon absorption method is relatively simple, while the NEP method is complex. The carbon storage method falls in between the others. We proposed that NEP is a potential indicator for assessing the capacity of mining area carbon sinks.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/atmos15070765/s1: Table S1: Preliminary selected carbon density.

Author Contributions: F.C.: formal analysis, methodology, writing—original draft. Y.L. (Yang Liu 1), J.G., and H.B.: data curation. Z.W.: Funding acquisition. Y.L. (Yang Liu 2): conceptualization, investigation, resources. R.L.: conceptualization, supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Shanxi Provincial Science and Technology Innovation Talent Team of China (202204051001010).

Institutional Review Board Statement: This study did not involve humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article or Supplementary Materials.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

CASA: Carnegie–Ames–Stanford approach; CH_4: methane; CO: carbon monoxide; CO_2: carbon dioxide; InVEST: Integrated Valuation of Ecosystem Services and Trade-offs; NPP: net primary productivity; NEP: net ecosystem productivity; R_h: soil microbial respiration; RMB: renminbi; SO_2: sulfur dioxide.

References

1. Wang, J.; Yang, M.; Liu, B.; Zhu, Q. Carbon sources/sinks and emission reduction and sink enhancement in green mining: A Review. *J. China Coal Soc.* **2024**, *49*, 1597–1610. [CrossRef]
2. Yang, B.; Bai, Z.; Fu, S.; Cao, Y. Division of carbon sink functional areas and path to carbon neutrality in coal mines. *Int. J. Coal Sci. Technol.* **2022**, *9*, 48. [CrossRef]
3. An, Y.; Bian, Z.; Dai, W.; Dong, J. Analysis on the gas carbon source and carbon sink in coal mining: A case study of Jiawang, Xuzhou. *J. China Univ. Min. Technol.* **2017**, *46*, 415–422. [CrossRef]
4. Qiu, S.; Yu, Q.; Niu, T.; Fang, M.; Guo, H.; Liu, H.; Li, S. Study on the landscape space of typical mining areas in Xuzhou City from 2000 to 2020 and optimization strategies for carbon sink Enhancement. *Remote Sens.* **2022**, *14*, 4185. [CrossRef]
5. Zhan, S.; Zhang, X.; Chen, X.; Zhou, Y.; Long, L.; Xu, Y. Effects of landuse change on spatial and temporal patterns of carbon sources/sinks in Huainan mining area from 2000 to 2020. *Bull. Soil Water Conserv.* **2023**, *43*, 310–319. [CrossRef]
6. Hou, H.; Zhang, S.; Ding, Z.; Huang, A.; Tian, Y. Spatiotemporal dynamics of carbon storage in terrestrial ecosystem vegetation in the Xuzhou coal mining area, China. *Environ. Earth Sci.* **2015**, *74*, 1657–1669. [CrossRef]
7. Liu, Y.; Wei, J.; Bi, Y.; Peng, S.; Yue, H.; He, X. Spatiotemporal dynamic change analysis of carbon storage in desertification open-pit mine. *J. China Coal Soc.* **2022**, *47*, 214–224. [CrossRef]
8. Ma, T. *Study on Calculating the Carbon Sink of Coal Mining Subsidence Wetland in Xuzhou Pan'an Lake*; China University of Mining and Technology: Xuzhou, China, 2022.
9. Fu, Y.; He, Y.; Chen, W.; Xiao, W.; Ren, H.; Shi, Y.; Hu, Z. Dynamics of carbon storage driven by land use/land cover transformation in coal mining areas with a high groundwater table: A case study of Yanzhou coal mine, China. *Environ. Res.* **2024**, *247*, 118392. [CrossRef] [PubMed]
10. Xu, L.; He, Z.; Liu, X.; Zhang, K.; Wu, M. Study on spatio-temporal variation and prediction of land use-carbon storage in high groundwaterlevel mining area. *Coal Sci. Technol.* **2024**, *52*, 355–365. [CrossRef]
11. Wang, X.; Han, J.; Lin, J. Response of land use and net primary productivity to coal mining: A case study of Huainan city and Its mining areas. *Land* **2022**, *11*, 973. [CrossRef]
12. Yang, F.; Wang, J.; Zhang, C.; Li, J.; Xie, H.; Zhuoge, Z. The Impact of human activities on net primary productivity in a grassland open-pit mine: The case study of the Shengli mining area in inner mongolia, China. *Land* **2022**, *11*, 743. [CrossRef]
13. Liu, X.; Yan, Y.; Liu, W.; Huang, Z. System construction and the function improvement of ecological carbon sink in coal mining areas under the carbon neutral strategy. *Environ. Sci.* **2022**, *43*, 2237–2240. [CrossRef]
14. He, Z.; Luo, L.; Du, Y.; Gou, L. Countermeasures to realize ecological restoration and emission reduction and increase of sinks in mining areas under the background of carbon neutrality. *Multipurp. Util. Miner. Resour.* **2022**, *2*, 9–14. [CrossRef]
15. Chen, J. *Research on Spatiotemporal Changes and Impact Mechanisms of Carbon Sources/Sinks in the Ecosystem of the Western Sichuan Plateau*; Chengdu University of Information Technology: Chengdu, China, 2020.
16. Chuai, X.; Qi, X.; Zhang, X.; Li, J.; Yuan, Y.; Guo, X.; Huang, X.; Park, S.; Zhao, R.; Xie, X.; et al. Land degradation monitoring using terrestrial ecosystem carbon sinks/sources and their response to climate change in China. *Land Degrad. Dev.* **2018**, *29*, 3489–3502. [CrossRef]
17. Yuan, M.; Li, M.; Liu, H.; Lv, P.; Li, B.; Zheng, W. Subsidence monitoring base on SBAS-InSAR and slope stability analysis method for damage analysis in mountainous mining subsidence regions. *Remote Sens.* **2021**, *13*, 3107. [CrossRef]
18. Zhong, J.L.; Qi, W.; Dong, M.; Xu, M.H.; Zhang, J.Y.; Xu, Y.X.; Zhou, Z.J. Land use carbon emission measurement and risk zoning under the background of the carbon peak: A case study of Shandong province, China. *Sustainability* **2022**, *14*, 15130. [CrossRef]
19. Cao, Y.; Cui, J. Analysis on the spatiotemporal pattern and prediction of carbon sources and sinks of land use in Heilongjiang province under the background of dual carbon. *China Resour. Compr. Util.* **2023**, *41*, 231–234, 238.
20. Han, F.; Kasimu, A.; Wei, B.; Zhang, X.; Aizizi, Y.; Chen, J. Spatial and temporal patterns and risk assessment of carbon source and sink balance of land use in watersheds of arid zones in China–a Case study of Bosten lake Basin. *Ecol. Indic.* **2023**, *157*, 111308. [CrossRef]
21. Zhang, J.; Zhang, C.; Dong, H.; Zhang, L.; He, S. Spatial–temporal change analysis and multi-scenario simulation prediction of land-use carbon emissions in the Wuhan urban agglomeration, China. *Sustainability* **2023**, *15*, 11021. [CrossRef]
22. Xie, L.; Bai, Z.; Yang, B.; Fu, S. Simulation analysis of land-use pattern evolution and valuation of terrestrial ecosystem carbon storage of Changzhi city, China. *Land* **2022**, *11*, 1270. [CrossRef]
23. Zhang, Y.; Shi, X.; Tang, Q. Carbon storage assessment in the upper reaches of the Fenhe River under different land use scenarios. *Acta Ecol. Sin.* **2021**, *41*, 360–373. [CrossRef]
24. Wang, C.; Luo, J.; Qing, F.; Tang, Y.; Wang, Y. Analysis of the driving force of spatial and temporal differentiation of carbon storage in Taihang mountains Based on InVEST model. *Appl. Sci.* **2022**, *12*, 10662. [CrossRef]
25. Zhang, C.; Xiang, Y.; Fang, T.; Chen, Y.; Wang, S. Spatio-temporal evolution and prediction of carbon storage in Taiyuan ecosystem under the influence of LUCC. *Saf. Environ. Eng.* **2022**, *29*, 248–258. [CrossRef]
26. Fan, J. *Evaluation of Land Ecological Restoration in Arid and Semi-Arid Mining Areas-Taking Shendong Mining Area as an Example*; Inner Mongolia Normal University: Hohhot, China, 2023.
27. Sun, Y. *Analysis on the Changes and Influencing Factors of Ecosystem Services in Qinshui Coalfield*; Shanxi University of Finance & Economics: Taiyuan, China, 2023.

28. Wang, B.; Zhen, Z.; Xi, R.; Chen, X.; Qiao, Q. Land use and carbon stock changes in Taiyuan under different scenarios. *Environ. Sci. Technol.* **2023**, *46*, 219–227. [CrossRef]
29. Zhou, K.; Du, J.; Shen, X.; Pu, G.; Zhang, D.; Dang, X. Spatial and temporal variability of vegetation net primary productivity in Qiangtang national nature reserve under climate change. *Chin. J. Agrometeorol.* **2021**, *42*, 627–641. [CrossRef]
30. Lyu, J.; Fu, X.; Lu, C.; Zhang, Y.; Luo, P.; Guo, P.; Huo, A.; Zhou, M. Quantitative assessment of spatiotemporal dynamics in vegetation NPP, NEP and carbon sink capacity in the Weihe river Basin from 2001 to 2020. *J. Clean. Prod.* **2023**, *428*, 139384. [CrossRef]
31. Pei, Z.; Zhou, C.; Ouyang, H.; Yang, W. A carbon budget of alpine steppe area in the Tibetan Plateau. *Geogr. Res.* **2010**, *29*, 102–110.
32. Piao, S.; Fang, J.; Ciais, P.; Peylin, P.; Huang, Y.; Sitch, S.; Wang, T. The Carbon balance of terrestrial ecosystems in China. *Nature* **2009**, *458*, 1009–1013. [CrossRef] [PubMed]
33. Piao, S.; He, Y.; Wang, X.; Chen, F. Estimation of China's terrestrial ecosystem carbon sink: Methods, progress and prospects. *Sci. China Earth Sci.* **2022**, *65*, 641–651. [CrossRef]
34. Piao, S.; Yue, C.; Ding, J.; Guo, Z. Perspectives on the Role of Terrestrial Ecosystems in the 'Carbon Neutrality' Strategy. *Sci. China Earth Sci.* **2022**, *65*, 1178–1186. [CrossRef]
35. Deng, Z.; Ding, W.; Pu, X.; Lyu, Y.; Wang, Y. Spatial-temporal distribution of carbon storage in Qilian mountain national park Based on InVEST model. *Bull. Soil Water Conserv.* **2022**, *42*, 324–334, 396. [CrossRef]
36. Wang, F.; Cao, Y.; Zhou, S.; Fan, S.; Jiang, X. Estimation of vegetation carbon sink in the Yellow River Basin ecological function area and analysis of its main meteorological elements. *Acta Ecol. Sin.* **2023**, *43*, 2501–2514. [CrossRef]
37. Zhang, J.; Li, J.; Wang, Y.; Zhang, Y.; Jing, L.; Li, J. Climate change in arid regions of Northwest China and its impact on potential grassland productivity. *Ecol. Sci.* **2020**, *39*, 182–192. [CrossRef]
38. Cai, Y.; Zheng, Y.; Wang, Y.; Wu, R. Analysis of terrestrial net primary productivity by improved CASA model in Three-river headwaters region. *J. Nanjing Univ. Inf. Sci. Technol. Nat. Sci. Ed.* **2013**, *5*, 34–42. [CrossRef]
39. Sun, Q.; Li, B.; Li, F.; Zhang, Z.; Ding, L.; Zhang, T.; Xu, L. Review on the estimation of net primary productivity of vegetation in the Three-River HeadwaterRegion, China. *Acta Geogr. Sin.* **2016**, *71*, 1596–1612. [CrossRef]
40. Tian, H.; Bi, R.; Zhu, H.; Yan, J. Driving factors and gradient effect of net primary productivity in Fenhe River Basin. *Chin. J. Ecol.* **2019**, *38*, 3066–3074. [CrossRef]
41. Su, S.; Jin, D.; Zhang, T. Characteristics temporal and spatial change and impact factors of net primary productivity of vegetation in Shanxi province. *J. Shanxi Agric. Sci.* **2022**, *50*, 551–558. [CrossRef]
42. Song, W.; Xu, X.; Lin, Y.; Chen, L. Spatial and temporal variation and driving forces for the net primary productivity of vegetation on the Loess Plateau. *J. Beijing For. Univ.* **2023**, *45*, 29–42. [CrossRef]
43. Sun, C.; Qiao, P.; Wang, J.; Wang, H.; Sun, J. Spatio-temporal variation characteristics of net primary productivity in Lvliang contiguous poverty areas since 2000. *Acta Ecol. Sin.* **2022**, *42*, 277–286. [CrossRef]
44. Wang, W. *Temporal and Spatial Variation of Carbon Source Carbon Sinks in Tibet Grassland Ecosystem and Its Relationship with Climate Factors*; Chang'an University: Xi'an, China, 2019.
45. Liu, Z. *Temporal and Spatial Dynamics of Vegetation Net Primary Productivity and Its Climate Driving Factors Analysis in the Loess Plateau of China*; Northwest Agriculture & Forestry University: Xianyang, China, 2022.
46. Huang, H.; Jia, J.; Liu, S.; Chen, D. Analysis of spatial-temporal evolution and influencing factors of carbon sinks in Yangtze River economic belt from 2000 to 2020. *Res. Environ. Sci.* **2023**, *36*, 1564–1576. [CrossRef]