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Forest Carbon Sequestration Potential in China under Different SSP-RCP Scenarios

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Abstract: The estimation of forest carbon sequestration and its economic value as a carbon sink are important elements of global carbon cycle research. In this study, based on the predicted forestland changes under the future shared socioeconomic pathways SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5, the growth equations of different tree species were fitted using forest inventory data, and the biomass conversion factor continuum function method was used to estimate forest vegetation carbon fixation at the national scale. The carbon sink potential of the forest ecosystems in 2020–2100 was estimated under the three scenarios. Under the three social scenarios, the fixed amount of forest carbon in China exhibits a significant upward trend. Forest area increases the most, and carbon sequestration increases the most rapidly under SSP1-RCP2.6. The carbon sequestration level in Southwest China is higher than in other parts of the country, and those in Northwest and East China are lower than the national average. In order to continuously improve the carbon sequestration capacity of terrestrial ecosystem resources in China, the following actions are recommended: strengthen the protection projects of natural forests in various regions, improve the level of forest management, and gradually achieve the goal of carbon neutrality in China.

Keywords: climate change; carbon sequestration; forest ecosystems; carbon sequestration potential

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1. Introduction

Climate change has become a major challenge in sustainable human development in the 21st century, and combating climate change is a central task for achieving global sustainable development today and in the future and will have a direct impact on the modernization process of developing countries. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) confirmed that the global climate has undergone unprecedented changes over the past century [1]. The Sixth Assessment Report of the IPCC further confirmed that global warming has occurred over the past 100 years and clarified the important impact of human activities on climate change [2]. Global climate change will not only cause irreversible impacts on ecosystems but also pose serious threats to food, water, ecological, environmental, energy, economic, and other security needs [3,4].

Since 2007, China has been the world's biggest carbon emitter, accounting for approximately 30% of global emissions annually [5]. To promote the achievement of sustainable development goals and its responsibility to improve human wellbeing, China announced its vision of "carbon peaking" and "carbon neutrality" in 2020 [6]. Among the various measures to achieve the dual-carbon goal, the nature-based solution [7–9] proposes a path to harmonize human beings with nature, which aims to motivate member countries to participate more actively in climate change issues and to use resources wisely. Forest ecosystems have a significant impact on regulating the climate and carbon cycle and mitigating climate warming, and they play a vital role in maintaining the global ecological balance. Approximately 50% of organic carbon in the terrestrial biosphere can be stored by forests, and global forests can increase CO_2 sequestration by 32% [10]. Forest carbon sinks are currently the most cost-effective way to reduce emissions and play an important role in mitigating climate change. Specifically, the activity of carbon sinks in vegetation and soil can be influenced by the absorption of CO_2 from the atmosphere through photosynthesis [11]. Therefore, enhancing forest carbon sinks is considered an important means to reduce carbon emissions and has become an important strategy for mitigating climate change [12,13].

Data from the 9th China Forest Inventory showed that China's forest area reached 220 million hectares in 2018, with a forest cover of 22.96% and a planted forest area of 80 million hectares, making China the world's fastest growing country in terms of planted forest area [14,15]. Thus, China has become a leading force in global greening, and its forest ecosystems, as a whole, behave as carbon sinks and play an important role in reducing carbon emissions. Domestic studies on forest carbon sequestration have mainly focused on carbon sequestration [16–20] and carbon sink measurements [21,22] since the founding of the People's Republic of China. At present, forest carbon sequestration measurement methods mainly include the biomass [23], stem volume, eddy covariance [24], biomass inventory, close chamber [25], relaxed eddy accumulation (REA) [26], model simulation [27], and stable isotope [28] methods, but the biomass method is the most widely used and more direct and accurate method, and the scale of research is at the provincial and national levels [29]. For example, Fang et al. [30] estimated the carbon sink of terrestrial vegetation in China from 1981 to 2000 based on the continuous biomass conversion factor method and concluded that China's forest biomass carbon stock increased from 4.3PgC in the early 1980s to 5.9PgC in the early 2000s. Piao et al. [31] analyzed the terrestrial carbon balance of China and its driving mechanisms during the 1980s and 1990s through three different methods. Zhang et al. [32] estimated the potential afforestation areas under current and future climatic conditions based on the natural climatic vegetation distribution in China. By the 2070s, the potential afforested land could increase by 33.1 million ha. In addition, the State Forestry and Grassland Administration has proposed that China should further conduct afforestation and increase the total forest volume from 2016 to 2050. By 2050, the national forest cover should be stabilized at more than 26%, and the total carbon sequestration of forest vegetation could reach 13 PgC [33].

China's forest ecosystems have great potential for carbon sequestration over the next 40 years, especially with newly planted forests that can effectively mitigate the impacts of climate change [34,35]. However, forests have dual functions as carbon sinks and sources, and the direction of their functions and the magnitude of their outcomes depend, to a large extent, on different levels of socioeconomic development and forest management [36]. The latest coupled model intercomparison project (CMIP6) [37] showed that by coupling shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs), researchers can examine multiple future global climate change scenarios to measure the relationship between different socioeconomic development patterns and climate change and can provide more reliable climate change predictions [38,39]. Therefore, it is important to estimate and predict the carbon sequestration potential of China's forest resources in combination with different future socioeconomic development levels to fully characterize the value of forest carbon sinks. It is also of great value to achieve the strategic goals of carbon peaking and carbon neutrality and accomplish the expected tasks of forestry development in China.

2. Materials and Methods

2.1. Data Sources

We used the future land-use (FLUS) dataset from 2015 to 2100 [40]. This land-use dataset is based on climate data from SSP-RCP scenarios, as well as land-use data as driving factors. The dataset extracts the demand for different land-use types from the Land-Use Harmonization (LUH2) [41] (https://luh.umd.edu/) (accessed on 20 November 2022). and then uses the FLUS model for a 5-year period from 2015 to 2100 to simulate future land use. The FLUS model is used to simulate land-use changes due to human activities and natural influences, as well as future land-use scenarios, and is now one of the most widely used domestic simulation models in China. Compared with the LUH2 data, this dataset has a higher spatial resolution and is more suitable for simulating different forestry policy scenarios.

Combining the existing studies and data availability, the following three representative scenarios were selected for the study: SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5 (Table 1).

Table 1. Characteristics of different SSP-RCP scenarios.

Scenario	
SSP1-RCP2.6	Combination of low societal vulnerability and low forcing level, with substantial land-use change (in particular, increased global forest cover)
SSP2-RCP4.5	Combination of intermediate societal vulnerability and intermediate forcing level
SSP5-RCP8.5	Combination of high societal vulnerability and high forcing level

China's forest resources inventory data are the data of the national distribution, which is based on the results of a sample survey. The forest resources inventory data used in this study include data on the area and storage volume of tree forests by their age group structure (young, middle-aged, near-mature, mature, and over-mature forests) for each dominant tree species (group) in all provinces in mainland China, and the data are derived from the results of the ninth national (2014–2018) forest resources inventory [42–44]. The pre-processing of forest resources inventory data refers to the "technical regulations for continuous forest inventory" [45].Tree species (groups) with similar physiological and ecological characteristics are consolidated in each region's forest resources inventory to obtain the area and accumulation data of the dominant tree species (groups) by age group. The criteria for the classification of age groups refer to the "Division of Age Classes and Age Groups of Major Tree Species" [46].

2.2. Estimation of Forest Carbon Sequestration

The carbon sequestration potential of forests depends mainly on two aspects: the growth of forest area and the change in carbon density due to forest growth [47]. In this paper, forest carbon sequestration was estimated referencing Li's study [48] on the attribution of forest carbon sequestration and its changes:

$$\mathrm{M} = \mathrm{A} \times \mathrm{D} \tag{1}$$

where M is forest carbon sequestration (PgC) or storage volume (m^3), A is forest area (hm^2), and D is forest carbon density (MgC/hm^2) or storage volume per unit area (m^3/hm^2). Because ln(M) = ln(A) + ln(D), the relative change rates of M, A, and D over time (m, a, and d) are the direct result of differentiating the equation over time:

$$\mathrm{dln(M)/dt} = \mathrm{dln(A)/dt} + \mathrm{dln(D)/dt} \tag{2}$$

where dln(M)/dt, dln(M)/dt, and dln(M)/dt represent forest carbon sequestration or storage volume, forest area, and carbon density or storage volume per unit area, respectively. The rate of change in forest carbon sequestration or storage, forest area, carbon density or accumulation are expressed per unit area with time t.

The IPCC guidelines for national GHG inventories express GHG emissions/removals (ΔC) as the product of activity level data and emission factors:

$$\Delta C = AD \times EF \tag{3}$$

where AD is the activity level, which can be the forest area by forest type, forest age, climate zone, etc. for the forest carbon sink/emissions, and EF is the emission factor, which can be the carbon sequestration rate or carbon emission rate per unit area for the forest carbon sink/emissions. For the prediction of forest carbon sink potential, the focus is on the prediction of forest area change and carbon sequestration rate per unit area.

Based on the above calculation methods, this study used the biomass expansion factor method to calculate the carbon sequestration of the aboveground and belowground biomass carbon pools of the forest [49]:

$$Cveg = A \times V \times WD \times BEF \times CF \tag{4}$$

where Cveg is the carbon fixation of forest vegetation (MgC), A is the stand area (hm^2), V is the forest sequestration per unit area (m^3/hm^2), WD is the wood density of the tree species (Mg/m^3), and BEF is the biomass expansion factor (unitless) to convert the trunk biomass of the tree species to aboveground biomass; CF is the average carbon content of the tree species (MgC/Mg).

Referring to Li's methods [50] for predicting the future carbon sink potential of existing tree forests, the area and sequestration of trees from the ninth forest inventory data period are assumed to represent the average level in 2015; the existing level of forest disturbance and existing natural environmental conditions are assumed to continue in future projections, and the area of each dominant tree species (group) is assumed to stay the same. Only the age class changes and the sequestration increases. This is calculated by subdividing the age groups of each dominant tree species (group) in 2015 by one age class every 5 years, combining the renewal harvesting cycles of different tree species, and assuming that the area of each age class (j) within the same age group is the same, as follows:

$$A_{i,j,t} = A_{i,t} \times \frac{5}{(T_{i,max} - T_{i,min}) + 1} \tag{5}$$

where $A_{i,t}$ is the area (hm^2) of Age Group i in year t of the base year (set as 2015), and $A_{i,\,j,\,t}$ is the area (hm^2) of Age Class j subdivided by Age Group i in year t.

After 5 years, Age Group i has the area of $A_{i,j,t}$ in Age Group i + 1, and Age Group $i - 1$ has the area of $A_{i-1,k,t}$ in Age Group i. Thus,

$$A_{i,t+5} = A_{i,t} - A_{i,j,t} + A_{i-1,k,t} \tag{6}$$

where $A_{i,t+5}$ is the area of Age Group i in year t + 5 (hm^2), and $A_{i-1,k,t}$ is the area of age class k subdivided by Age Group $i - 1$ in year t (hm^2).

This calculation process considers the growth of the unit area accumulation of each age group of each dominant tree species (group) over time, which is consistent with the growth law of trees. As an analogy, we can estimate the area and accumulation of each age group at 5-year intervals from 2020 to 2100 and use the same IPCC woody-source biomass method to calculate the biomass carbon sequestration and carbon density of each dominant tree species (group) at various points in the future by combining the accumulation per unit area equation and the age of the dominant tree species in each province.

The new afforestation potential for 2020–2100 is calculated using a high-resolution simulation of land use for 5-year periods between 2020 and 2100 using the land-use simulation model (FLUS). The sum of the existing forest potential and the future new afforestation potential is the carbon sink potential of China's tree forests for 2020–2100.

2.3. Forest Growth Curve Fit

Single wood growth equations and stand growth and harvest simulations are mostly for a specific sample point or small area and are limited in their application to regions due to issues such as tree species composition, stand age, stand quality, and competition effects. In contrast, for the stand sequestration in different regions, the species and ages are key factors in calculating forest biomass and carbon sequestration; therefore, different growth equations should be used for different species in different regions. According to the carbon sink measurement and monitoring guidelines for afforestation projects [51], we selected the widely used Richards' equation and the logistic equation to fit the tree growth equation. According to previous studies, growth equations with inflection points (Richards', logistic) fit more accurately than growth equations without inflection points (Mitscherlich) [52,53]. The parameters used for the calculation of carbon sequestration can be found in Table 2. Then, using the sample data from the national forest inventory as the data source, the spatial method was used instead of the time method to fit the growth curves of various forest species in different regions of China, and the storage amount per unit area was calculated:

$$V = \frac{a}{1 + b * e^{-c*A}} \quad (7)$$

where V is the single plant wood volume; A is the tree age; and a, b, and c are parameters.

Table 2. Parameters used to estimate carbon sequestration in China from 2020 to 2100.

Tree Types	Biomass Expansion Factor	Wood Density	Carbon Fraction
Pines	1.4	0.4649	0.51
Hardwood species	1.79	0.6062	0.5
Softwood species	1.54	0.4222	0.5
Abies and Picea	1.53	0.3071	0.49
Mixed Coniferous	1.3	0.3902	0.52
Mixed Broadleaf	1.95	0.5222	0.44
Mixed conifer and deciduous forests	1.3	0.4754	0.5

3. Results

3.1. Dynamics of Forest Carbon Sequestration

Based on the future shared socioeconomic pathways SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5, we estimated forest carbon sequestration additions (Table 3).

Table 3. Estimation of forest carbon sequestration change from 2025 to 2100 (TgC).

	SSP-RCP126	SSP-RCP245	SSP-RCP585
2025	58.166	58.307	58.045
2030	61.669	61.763	61.627
2035	65.684	65.266	65.489
2040	69.974	69.057	69.843
2045	74.818	72.911	73.397
2050	78.983	75.522	75.590
2055	83.268	78.338	77.718
2060	86.849	81.142	79.704
2065	90.197	83.998	81.740
2070	92.568	86.064	82.914
2075	92.893	88.031	84.143
2080	93.375	89.870	85.197
2085	94.324	91.632	86.301
2090	94.133	92.906	86.809
2095	95.990	94.433	87.512
2100	99.378	95.898	88.172

We can summarize the changes in forestland area in all regions of the country from 2020 to 2100. In comparing the base year with the future change in forest area, the forest shows a stable expansion trend in the different scenarios. In the SSP1-RCP2.6 scenario, the increase in forest area between 2020 and 2070 is significantly higher than those in the other two scenarios, and the forest area reaches 2,240,626 km^2 in 2070, which is the maximum forest area between 2020 and 2100 in the three scenarios. There is a short decline after 2070 and another increase in 2090 (Figure 1a). In the SSP2-RCP4.5 scenario, the forest area shows a steady upward trend from 2020 to 2100, reaching 219,782 km^2 in 2100 (Figure 1a). Compared with the other two scenarios, the change in forest area under SSP2-RCP4.5 is significantly flatter. The inflection point of SSP5-RCP8.5 appears earlier, in 2040, and maintains a dynamic equilibrium state after 2040 (Figure 1a). The forest area in the SSP5-RCP8.5 scenario is always smaller than that in the other two scenarios, which indicates that the high-emission scenario has an impact on forest area and that forest expansion requires human effort.

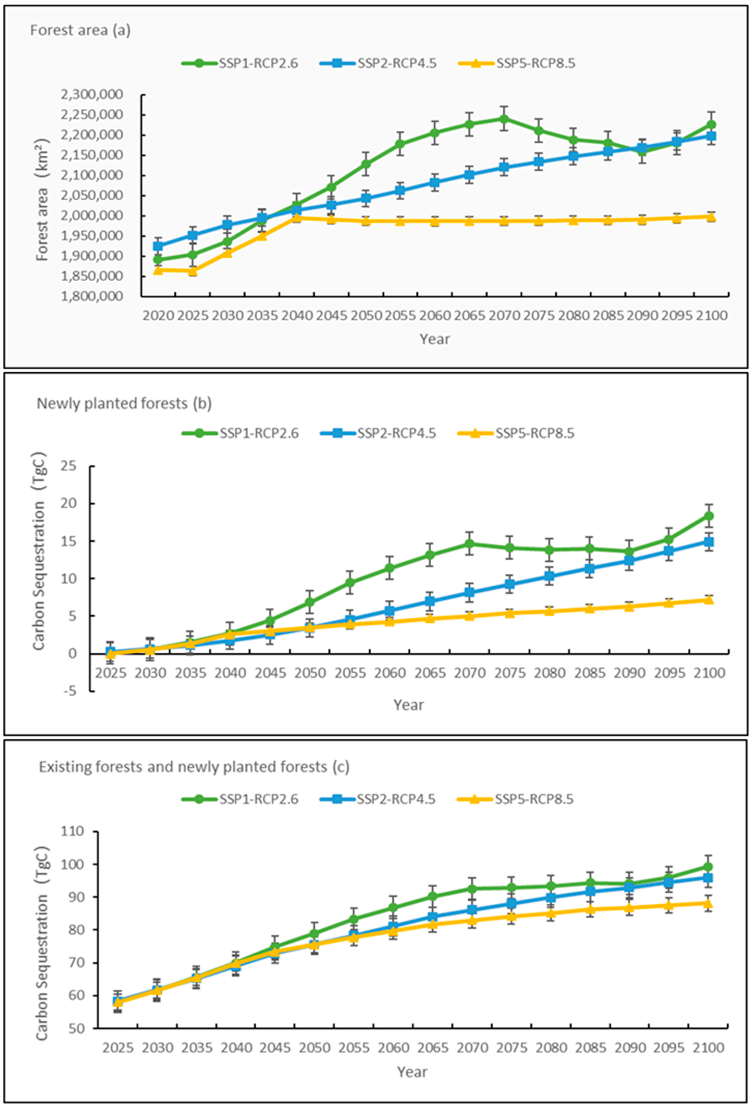

Figure 1. Forest carbon sequestration under different scenarios. (**a**) Change in forest area in 2020–2100 under the influence of different climate scenarios; (**b**) change in carbon sequestration of newly planted forests under different climate scenarios; (**c**) sum of future carbon sequestration of existing forests and newly planted forests in the future.

In the next 80 years, with the transformation of the social and economic path of sharing from SSP1-RCP2.6 to SSP5-RCP8.5, China's forest carbon sequestration will generally show a downward trend. Carbon sequestration continues to grow positively under the SSP2-RCP4.5 and SSP5-RCP8.5 scenarios and maintains a continuous growth trend (Figure 1c). The carbon sequestration increases from 55.004 Tg in 2020 to 81.142 Tg (SSP2-RCP4.5) and 79.704 Tg (SSP5-RCP8.5) in 2060, an increase of 26.138 Tg and 24.7 Tg, respectively. After 2040, the increase in carbon sequestration in the SSP5-RCP8.5 scenario gradually slows down, and the rate of increase is lower than that of the SSP2-RCP4.5 scenario (Figure 1c). In the SSP1-RCP2.6 scenario, carbon sequestration increases, then decreases, and then increases again. A turning point is reached in 2070, and in 2090, carbon sequestration rises again, with the highest carbon sequestration in the SSP1-RCP2.6 scenario being 99.378 Tg in 2100.

3.2. Spatial Variations of Forest Carbon Sequestration

We analyzed the changes in carbon sequestration in different regions of China in order to implement different business policies for different geographical types (Figure 2). The following analysis was carried out using the change of carbon sequestration from 2020 to 2060 as an example.

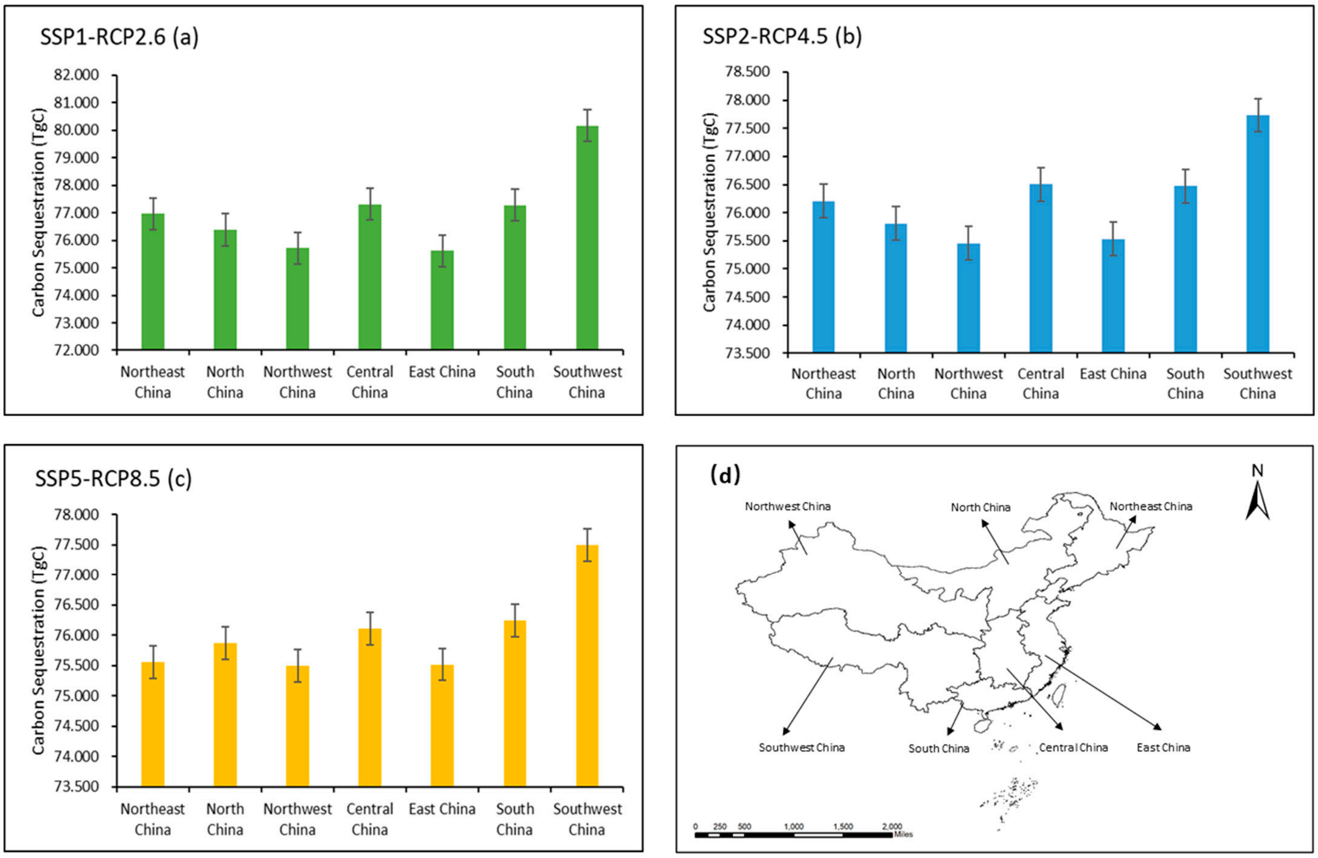

Figure 2. Changes in China's forest carbon sequestration (TgC) in different regions from 2020 to 2060 under different scenarios (**a**–**c**). The forests in China were divided into seven regions in (**d**): Northwest China, including Gansu, Ningxia, Qinghai, Shaanxi, and Xinjiang; North China, including Hebei, Inner Mongolia, and Shanxi, as well as Beijing and Tianjin; Northeast China, including Heilongjiang, Jilin, and Liaoning; Southwest China, including Guizhou, Sichuan, Yunnan, and Tibet, as well as Chongqing; Central China, including Jiangxi, Henan, Hubei, and Hunan; East China, including Fujian, Anhui, Jiangsu, Shandong, Zhejiang, and Shanghai; and South China, including Guangdong, Guangxi, and Hainan.

By analyzing the slope of the carbon storage curve, it can be seen that the trend of forest carbon storage from 2020 to 2060 is consistent under different scenarios. Then, we performed a one-way ANOVA analysis of carbon stocks in different regions. The mean value of carbon sequestration by region were: 78.465 TgC (Southwest China), 76.663 TgC (South China), 76.24 TgC (Northeast China), 76.24 TgC (Central China), 76.019 TgC (North China), 75.556 TgC (Northwest China), and 75.554 TgC (East China). The ANOVA result P value was 0.003. Therefore, the statistical results were significant, indicating that there are significant differences in carbon sequestration in different regions. The carbon sequestration of forests in the northeastern and southwestern regions were higher, but they were lower in the northwestern and eastern regions of China (Figure 2). The carbon sequestration level in Southwest China was higher than that in other parts of the country, while the northeastern, northern, central, and southern regions were on par with the national average, and Northwest and East China were lower than the national average. Due to the differences in climate and geographical factors, the distribution of forests in these regions varies slightly, and therefore, the contribution of carbon sequestration from these regions varies. Except for North China and Northwest China, the carbon sequestration of all regions was SSP1-RCP2.6 > SSP2-RCP4.5 > SSP5-RCP8.5, and the carbon sequestration of North China and Northwest China were significantly lower under the SSP2-RCP4.5 scenario, which is closely related to the forest area in this region being influenced by climate. The increase of carbon storage in Southwest China can effectively indicate that China's natural forest protection project and comprehensive desertification control project have good implementation results. In the future, natural forests and plantations in Southwest China will be important tools for increasing the sinking of China's terrestrial ecosystems.

4. Discussion

4.1. Comparison with Findings of Other Studies

Forests are major components of terrestrial ecosystems and play a very important role in combating climate change. The carbon sinks of terrestrial ecosystems in China, estimated based on national forest inventory data, ranged from 101.1 to 119.4 Tg C yr^{-1} in other studies [30,31,54]. The carbon sinks assessed based on a single terrestrial biosphere model ranged from 40 to 170 TgC yr^{-1} [31,55–57]. However, compared with the results of other studies calculated using similar methods, the carbon sequestration change of Chinese forest ecosystems estimated in this study was lower [49,58–61]. This may have been because only objective factors of climate change were considered in the future carbon sequestration projections, and anthropogenic solution measures in the context of future climate change were not considered. For example, returning farmland to forest and natural forest protection projects are effective initiatives in China for addressing climate change issues. The results of this study, which only considered the effects of climate change factors, were much lower than those of studies considering future forestry plantation plans, which also indicates that China's forest ecosystems have greater potential still to sequester carbon and increase oxygen and that planned afforestation projects can largely improve terrestrial ecosystem environments and increase their ecological and economic values. However, our estimates ignore the impact of realistic factors, such as pests, forest fires, and deforestation. These factors all cause carbon that is already fixed in wood to be released back into the atmosphere, which can have a negative impact on the environment. High temperatures and droughts increase the probability of forest fires, which in turn lead to the release of carbon from wood, leading to higher temperatures [62].

4.2. Uncertainty

Forest ecosystems have complex spatial and temporal heterogeneity and extensive internal linkages, which must be addressed in the study of forest ecosystem carbon sequestration, making it difficult to predict the future (2020–2100) carbon sequestration potential of Chinese forests. There are several reasons for the uncertainty. First, China has a large forest area and a complex distribution of tree species, so this study used the logistic equation to fit the relationship between storage and forest age. It also combined some of the smaller tree species with similar growth habit and characteristics but did not estimate the storage of all tree species, and this combination may affect the accuracy of the equation fitting for some tree species and may have easily resulted in underestimation for young forests. In addition, due to the lack of relevant studies, we used the same parameters for the calculation. Since the differences in tree age levels are not taken into account, the results are highly uncertain, and more experimental data are needed for revision. Second, anthropogenic forestry projects, such as natural forest resource protection projects and reforestation projects, were not considered. In the estimation of the carbon sequestration potential of new forests, land use was simulated using the FLUS model to estimate the future increase in forest area, and this estimation method only considers the impact of future climate change without considering the impacts of forestry policies and other human activities on forest areas. Only objective factors were considered, and subjective initiatives of the forestry sector were ignored.

We also ignored the uncertainty that disturbance and restoration processes create for forest carbon sequestration. Disturbances can manifest as sudden forest fires, pests and diseases, and earthquakes and other natural disasters. These natural disasters occur with high frequency and are difficult to predict. At the same time, climate change will also have an impact on the probability of natural disasters. The degradation and restoration of ecosystems is mainly reflected in the natural death of trees and regular man-made felling. Forest management is conducive to the sustainable development of forest health. However, most of the current research on the above issues focuses on the qualitative description stage, which needs further study.

5. Conclusions

In this study, we simulated the spatial and temporal dynamics of land use and forest carbon sequestration in China under the SSP1-RCP2.6, SSP2-RCP4.5, and SSP5-RCP8.5 scenarios for the future (2020–2100). The results of the future land-use simulations showed that the land-use changes were significantly different in the different scenarios. Based on these simulations, during the period of 2020–2060, the carbon sequestration of China's forest ecosystems will increase by 86.849 TgC (SSP1-RCP2.6), 81.142 TgC (SSP2-RCP4.5), and 79.704 TgC (SSP5-RCP8.5). By 2100, the carbon sequestration of China's forest ecosystems will increase by 99.378TgC (SSP1-RCP2.6), 95.898TgC (SSP2-RCP4.5), and 88.172TgC (SSP5-RCP8.5). Under the three social scenarios, the fixed amount of forest carbon in China follows a significant upward trend. Forest area increases the most and carbon sequestration increases the most rapidly under SSP1-RCP2.6. This is followed by SSP2-RCP4.5, while SSP5-RCP8.5 has the smallest increment. The carbon sequestration level in Southwest China is higher than that in other parts of the country, while the northeastern, northern, central, and southern regions are on par with the national average, and the levels in the northwestern and eastern regions of China are lower than the national average. As forests are the most influential land-use type for carbon storage in terrestrial ecosystems, their carbon sequestration capacity can be increased through afforestation or forest management. As countries continue to pay attention to global climate issues, accounting for carbon sequestration in terrestrial ecosystems and studying the potential for increasing carbon sinks will gradually become a key research issue in the future. To continuously improve the monitoring level of terrestrial ecosystem resources in China, it is recommended that, based on the current forest resources inventory, the survey content should be gradually increased; the verification of shrub forests, economic forests, and open forests should be refined; and research on soil carbon pools and carbon pools of dead wood should be strengthened. In addition to promoting protection projects such as returning farmland to forests in each region, we should also improve the management level of existing forests in each region and adopt different forest management plans for different forest types and tree species in different regions, according to local conditions, to gradually contribute to the goal of carbon neutrality in China.

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