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Scenario Paths of Developing Forest Carbon Sinks for China to Achieve Carbon Neutrality

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Abstract: To explore the role of forest carbon sinks in achieving carbon neutrality, the cointegration regression method and scenario analysis are utilized to forecast the long-term development trend of China's forest carbon sinks up to the year 2100 and their impact on carbon neutrality. The results show that: (1) Under routine, accelerated, and strengthened ecological civilization scenarios (or RECS, AECS, and SECS, respectively), China's forests are projected to absorb 531–645 million tons of carbon by 2050 and 2.32–4.69 billion tons of carbon by 2100, respectively, and the value of the strengthened scenario will be markedly higher than that of the routine scenario. (2) Driven by slower growth in forestry investment, China's forest carbon sinks growth in all three scenarios peak by 2050 and then slow in a U-trend, with the growth rate in the SECS 0.45 percentage points higher than that of AECS, and the growth rate in the AECS 0.44 percentage points higher than that of RECS. (3) Under SECS, forest carbon sinks can help China achieve its carbon neutrality goal in 2054 (before the target date of 2060) with cumulative forestry investment of 53.3 trillion yuan and an annual investment growth rate of about 6.3%. Therefore, this study provides a deeper understanding than previous works of the important role of forest carbon sinks in achieving carbon neutrality.

Keywords: carbon neutrality; forest; carbon sinks; scenario analysis; China

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1. Introduction

1.1. Carbon Neutrality Has Become the Fundamental Way to Address Global Climate Change

There is growing recognition of the role of forest carbon sinks in offsetting carbon emissions to reduce the threat of global warming. One example of this recognition is the International Union for Conservation of Nature (IUCN)-initiated Bonn Challenge which has committed to the restoration of 350 million hectares of forest by 2030, estimated to have the potential to sequester up to 14% of global carbon emissions [1,2]. The global achievement of the 2 °C and even stricter 1.5 °C targets for temperature control require a reversing of global warming [3]. The key to reaching those targets is to achieve a global carbon emissions peak as soon as possible and then to achieve carbon neutrality by mid-century.

The central challenge to slow, stop, and reverse global warming is to reach carbon neutrality after the carbon emissions peak. Of course, different countries each have their own specific role to play. For example, the task for developed regions, represented by Europe and America, which have achieved the goal of a carbon peak, is to achieve carbon neutrality as quickly as possible. Developing countries, including China and India, face the dual task of achieving a carbon peak and carbon neutrality. Therefore, developing countries such as China need an effort several times that of developed countries to attain the goal of carbon neutrality and the realization of the ecological civilization society based on the climate civilization.

It is encouraging that the Chinese government, as the policymaker for the largest developing country, reaffirmed its commitment in September 2020 despite the COVID-19 crisis to achieve a peak in carbon emissions before 2030 and to achieve carbon neutrality before 2060. Their announcement was followed on 20 January 2021 by the U.S. Biden Administration's goal of carbon neutrality by 2050. Together, the world's largest economy and second-largest carbon emitter and the second-largest economy and largest carbon emitter have announced their respective carbon neutrality road maps. Other countries have similarly announced carbon-neutral pathways. For example, as the first country in the world to make a carbon-neutral road plan, Britain passed the Climate Change Act in 2008, pledging to reach carbon neutrality by 2050. Meanwhile, Germany, France, Italy, Canada, Hungary, and Portugal promised net-zero carbon emissions by 2050. In all, more than 130 countries or regions have published carbon-neutral targets, signifying the world's carbon-neutral era.

1.2. Forest Carbon Sinks as an Important Means of Achieving Carbon Neutrality

To achieve carbon neutrality, countries need to pursue two key goals: the first is to minimize carbon emissions through energy restructuring, industrial restructuring, and clean technological progress, and the second is to maximize carbon absorption and fixation through the development of ecosystems represented by forests and grasslands [4]. Countries should pursue these two paths concurrently and should not ignore one for the other. All countries can make use of developing forest carbon sinks. As long as there is suitable open space on the land, trees can be planted, bringing multiple benefits including carbon sequestration. In the early stages of forestry, it was mainly used for building with lumber. Later, there was recognition of the carbon sink benefits, as well as ecological and environmental benefits. As such, in recent years, forests have been given a prominent role in addressing climate change.

While China is actively adapting its economic development to the requirements of low carbonization, it should strengthen the use of a carbon sinks model that includes forest carbon sinks [5]. As is well known, China has been emphasizing the development of forests and other resources to achieve sustainable development since the late 1970s. Starting on 1 July 2020, the newly revised Forest Law of China has been implemented, specifying that March 12 every year is Arbor Day. More importantly, China actively promotes the development of forest carbon sinks as the main action to address climate change. As early as 2009, China formulated the Forestry Action Plan to Combat Climate Change, and since then, the emphasis on forest carbon sinks has been continuously increasing.

1.3. Research on the Role of Forest Carbon Sinks in China's Carbon Neutrality Process Needs to Be Strengthened

Academic research on China has mainly focused on the goals of reducing carbon emissions and achieving a carbon peak by mitigating carbon emissions [6], while the research on forest carbon sinks and their effect on carbon neutrality has not received the same level of attention. There is some literature on the subject, but its emphasis is on estimating China's forest carbon sinks or sequestration capacity, but not the growth trend in the future with the change of ecological civilization construction and investment to the end of this century. For example, Zhao et al. [7] analyzed the relative contributions of forest areal expansion and growth to China's forest stand biomass carbon sequestration from 1977 to 2018, but they did not study the contribution of carbon fixation to carbon neutrality. Zhao et al. [8] studied the spatial spillover of forest carbon sinks in the process of carbon neutrality in China but did not conduct long-term prediction and analysis for China's forest carbon sink. Ge et al. [9] constructed a forest carbon sink cost estimation model based on the afforestation cost method and found that the regional distribution of carbon sink costs varied greatly and that Southwest China had low forest carbon sink cost and was suitable for afforestation to create carbon sinks, but they did not consider the impact of forest investment and forest stock on forest carbon sinks. Although Xu et al. [10] analyzed the impact of GDP and urbanization factors driving the growth of forest carbon sinks and Ke et al. [11] considered the impact of carbon prices on forest carbon sinks in the long-term change process of forest carbon sink in China to 2060, they still did not focus on the direct driving effect of forest investment and forest volume.

1.4. The Goal and Innovation of This Article

Therefore, in order to fill the research gap, we find the relationship among the influencing factors, including forest volume, forestry investment and forest carbon sinks in China, based on the accounting of the annual amount of forest carbon sink, and use scenario analysis to focus on the change trend of forest carbon sinks in the long term to 2100, and its role in China's carbon neutrality process. Finally, based on the results of our statistical model, we discuss the results and consideration points of the scenarios and policy implications and recommendations with a view to improve forest management and make forest carbon sinks a more effective tool for achieving carbon neutrality. These are the study's main objectives.

The novelty of our article contributes to the study of China's forest carbon sink capacity in three aspects. First, we model and employ various analytical methods with small errors to depict multiple possible scenarios of China's forest carbon sink capacity up to the year 2100, providing a more comprehensive and forward-looking approach compared to existing research that mainly focuses on 2050 or 2060 [11–13]. Second, while many academic studies estimate China's forest carbon, there is a lack of long-term tracking research on forest carbon sinks within the context of China's goal of achieving carbon neutrality [7,14]. Therefore, we compare China's carbon emissions trend with its forest carbon sinks capacity to evaluate the latter's role in achieving the carbon neutrality target. Finally, we analyze the main factors behind the long-term changes in forest carbon sinks, and investigate the long-term effects of forest volume and forestry investment on forest carbon sinks capacity up to 2100.

Our research makes the following policy contributions. It can assist in the objective quantification and evaluation of forest carbon sinks in promoting China's carbon-neutrality goal, and attract more enterprises, governments, and individuals to participate in the process of China's forest construction and development. Further, it can raise awareness of the key functions of forest ecology. Forest construction and development is closely connected to the process of China's ecological civilization construction, and forest carbon sinks have a direct impact on the degree of China's ecological civilization construction. In addition, forest carbon sinks will put forward higher requirements and more urgent demands for China to accelerate the promotion of a national carbon market.

2. Literature Review

Against the background of global climate change, carbon sinks, sequestration of forest vegetation, and green roofs are receiving increasing attention [15–17]. The international study of forest carbon sinks can be traced back to the middle and late 1960s [18]. Then, in 1972, UNESCO carried out pioneering research on forest carbon sinks through the Man and the Biosphere Programme. Subsequently, representative countries and continents such as the United States, Europe, and Canada carried out global carbon cycle and regional forest ecological balance research, and further explored the role of forest carbon sinks [19].

More recently, United Nations organizations such as the Food and Agriculture Organization and the Special Committee on Climate Change have carried out research on the measurement of forest carbon sinks. This research provides a scientific methodology and a substantial database for quantitative analysis of the role of forests in addressing climate change. In particular, their study of forest carbon sinks provides a basic framework for estimating forest carbon sinks and carbon sequestration capacities.

Meanwhile, many scholars have conducted in-depth research on forest carbon sinks in different countries, focusing on estimating their size and concluding that forests have an indispensable long-run role in addressing climate change. For instance, Wernick and Kauppi [20] advocated effective long-run management of forests and forest carbon sinks, rather than focusing on their short-term effects, and that this management can be a relatively inexpensive means of combating climate change [21]. However, there is a conflict between forest carbon sinks and the economic benefits derived from deforestation, requiring an optimal balance between the two objectives [22]. Increasing forest carbon sinks reduces the benefits from using forest products.

Most scholars have focused on estimating forest carbon sinks. For example, Magerl et al. [23] analyzed the transformation from deforestation to restoration in the United States from 1870 to 2012, which has helped to promote forest carbon sinks in the United States. Bull and Thompson [24] analyzed the feasibility of incorporating forest carbon sinks into the carbon emissions trading framework in the United States and Australia, and specifically the interaction between institutions and participants involved in forest carbon sinks trading, thus providing market conditions for the pricing of forest carbon sinks. Cong et al. [25] evaluated the carbon sink of Japan's Fukuoka Premium and its achievement of the net-zero emission target and found that it would not achieve its target by 2050 without additional efforts in emissions reduction and absorption, providing case support for the development of national forest carbon sinks. Gren et al. [26] found that the supply of forest carbon sinks in the EU increases if marginal emission reduction costs in the non-trade sector are relatively low. Raw et al. [27] believe that blue carbon ecosystems (mangroves, salt marshes, and seaweed) can help mitigate climate change by effectively storing carbon dioxide in the atmosphere. They analyzed South Africa's total carbon storage, anthropogenic carbon dioxide emissions, and restoration to enhance the carbon sequestration potential of blue carbon ecosystems.

Although China's research on forest carbon sinks is more recent than other international research, there are a number of influential studies. Fang et al. [28] began the study of carbon sinks in China, and in 2000, his research team examined forest carbon sinks from the perspective of global ecology [29]. Li et al. [30] shifted the perspective to the role of forest carbon sinks in coping with global climate change and suggested that forest carbon sinks should be included in international negotiations on global climate change. Zhang et al. [31] constructed a regression model for forest carbon sink assessment in China and calculated the optimal annual harvest. To minimize the loss of carbon storage consumed by Chinese forests due to economic development, they found the annual harvest should be 426 million cubic meters. The research to date has focused on estimating and analyzing forest carbon sinks but has not yet addressed the impact on carbon neutrality.

The Chinese national government has not published annual data on forest carbon sinks. As a result, scientific estimation of forest carbon sinks has become an important area of research. Different regions of the world, mostly for reasons of data quality and availability, have used different techniques to measure forest resources and carbon sinks. This variability presents some difficulties in comparing results across countries [32]. The result is that the various methods may arrive at different estimates of the magnitude of forest carbon sinks. Therefore, in most studies of forest carbon sink estimation, one core task is to choose the estimation method, which we will do in the next section of the paper.

Forest carbon sink estimation methods fall broadly into two classes. The first method estimates forest carbon storage through physical measures such as the average biomass, stock volume, forest soil carbon determination, and biomass inventory. The second class of methods employ micrometeorology, which measures carbon storage by tracking carbon dioxide flux. It includes the methods of vortex correlation, vortex accumulation, vorticity covariance, and relaxation vortex [33–35]. The biomass method tends to overestimate the size of carbon sinks and so more modern methods have taken its place [28].

Forests vary by site conditions, age, tree species, and forest management practices. All of these factors influence the carbon sequestration capacity of forests. There is considerable variation in the quality of data available to estimate forest resources across countries. Countries in Europe and North America typically have detailed, accurate, and high-resolution data at the national scale, which allows the use of more reliable models for estimating forest carbon storage [36,37]. The highest-level simulation models for estimating forest carbon storage tend to be at the forest stand level because that is where the most accurate and detailed information can be found. Simulation models such as STANDCARB consider stand-level features (tree species, soil texture, age, and density) and forest management practices (fire management, harvest etc.) [38].

For country-level studies such as ours, such approaches are often not practicable; in China's case this limitation is mainly because of the difficulty of obtaining detailed country-level data. For the rest of the world, data quality is highly variable; studies in most countries rely on national forest inventory reports that only provide volume-based information. In most cases, this limited data restricts those studies to using volume-based methods to convert forest volumes to biomass, and then convert those results to carbon estimates [32]. With a few exceptions (see, Wang et al. [39]), forest carbon storage in China has been estimated using volume-based methods because the national-level forestry inventories only provide volume-based information.

The forest volume estimation method is the most common way to convert forest volumes to carbon storage estimates. Many scholars use this method to evaluate the forest carbon sinks in China. For example, using the characteristics of China's forest ecosystem and the national forest resources inventory data, Shi et al. [40] estimated forest carbon sinks between 2009 and 2013. Their results showing that China's forest carbon sequestration would increase each year support the conclusion that national forests have an important role in combating climate change. Based on China's forest resources inventory data from 1988 to 2013 and by improving the forest volume method, Xue et al. [41] focused on estimating forest carbon sinks in 31 mainland provinces and further analyzing the regional differences of the forest carbon sinks and the dynamic evolution trend. Li and Li [42] also used the volume method to estimate the forest carbon sinks of Guizhou Province from 2015 to 2017 and found a trend of growth of forest carbon sinks in the province. However, Shi et al. [40] and Xue et al. [41] have less consideration and analysis of the overall situation of China's carbon sequestration. Studies such as these typically use data from China's national forest inventory, which has been conducted every five years between 1973 and 2018.

Other studies of China have constructed continuous annual data of forest carbon sequestration. They used different estimation methods based on the Integrated Terrestrial Ecosystem C-budget Model (InTEC) developed by Chen et al. [43]. The InTEC model simulates carbon dynamics in a forest ecosystem using a combination of remote sensing and forestry inventory data to obtain information on land cover and leaf area index (LAI), soil texture, climate, forest age, and nitrogen deposition. Wang et al. [39] used the InTEC model to simulate carbon sinks in China from 1901 to 2001. They found that the estimated results for carbon balance in biomass from the model largely agreed with estimates from forest inventories of China's forests.

The estimation and analysis of forest carbon sinks in China is gradually becoming mainstream, which indicates that the method has a wide application value and potential for evaluation of forest carbon sinks capacity. We will make use of the forest volume method to estimate carbon sinks. The reasons are threefold: first, the method is compatible with the forestry inventory data that we have available; second, the method has been widely used in the literature to estimate carbon sinks in China; and third, estimates from simulation models such as InTEC that rely on high resolution data are in agreement with those obtained from volume-based forestry inventories such as China's. The forest volume method sums the carbon storage of forest trees, the carbon storage of understory vegetation, and the carbon storage of forest land. The method fully encompasses the carbon sink function of forests from top to bottom.

To the best of our knowledge, the number of predictive studies on forest carbon sinks and their carbon sinks capacity in China is small and the prediction period is short, only to 2050 or 2060. Moreover, these studies do not take into account the broader context in which China strives to achieve its carbon-neutral targets. For example, Xu et al. [44] predicted the potential of the forest carbon sinks in China up to 2050. Based on the logistic model, they determined that under the condition of natural growth, China's forest biomass carbon pool would increase by 7.23 billion tons of carbon to 13.09 billion tons of carbon in 2050 with an average annual carbon sink of 140 million tons of carbon. Qiu et al. [45] also made a prediction of carbon sequestration potential of forest vegetation in China from 2003 to 2050, and found that the carbon storage, density, and carbon sinks of forest vegetation in China would increase rapidly, and from 2020 to 2050, China's forest vegetation would absorb 22.14% of carbon emissions from fossil fuel combustion. However, they did not consider the impact of China's forest carbon sinks on China's achievement of carbon-neutrality targets, let alone the prediction to 2100, so it may be not enough to support the realization of China's carbon neutralization goal.

Accordingly, we find that the existing literature largely seeks to evaluate the current situation of forest carbon sinks in China. Studies that attempt to perform long-term prediction of forest carbon sinks in China in the context of the goal of achieving carbon neutrality are relatively few. Although some studies predict the change trend of China's forest carbon sink to 2050 or 2060, they only study the forest carbon sink and do not analyze the substantive impact on China's carbon neutrality. As such, there is a lack of research on realizing carbon neutrality goals in China from the perspective of forest carbon sinks.

3. Methodology, Models and Data

3.1. Methodology Procedures

The research proceeds in the following four steps in Figure 1. The first step estimates forest carbon sinks in China and provides a data basis for research. The second step determines the cointegration equation between forest carbon sink, forestry investment, and forest volume on the basis of examining the unit root test and cointegration relationship. The third step sets the growth of forestry investment and forest stock in China for scenarios of routine, accelerated, and strengthened ecological civilization. The fourth step substitutes the scenario values from the third step into the cointegration equation determined in the second step to obtain the trend of changes in China's forest carbon sinks under different scenarios.

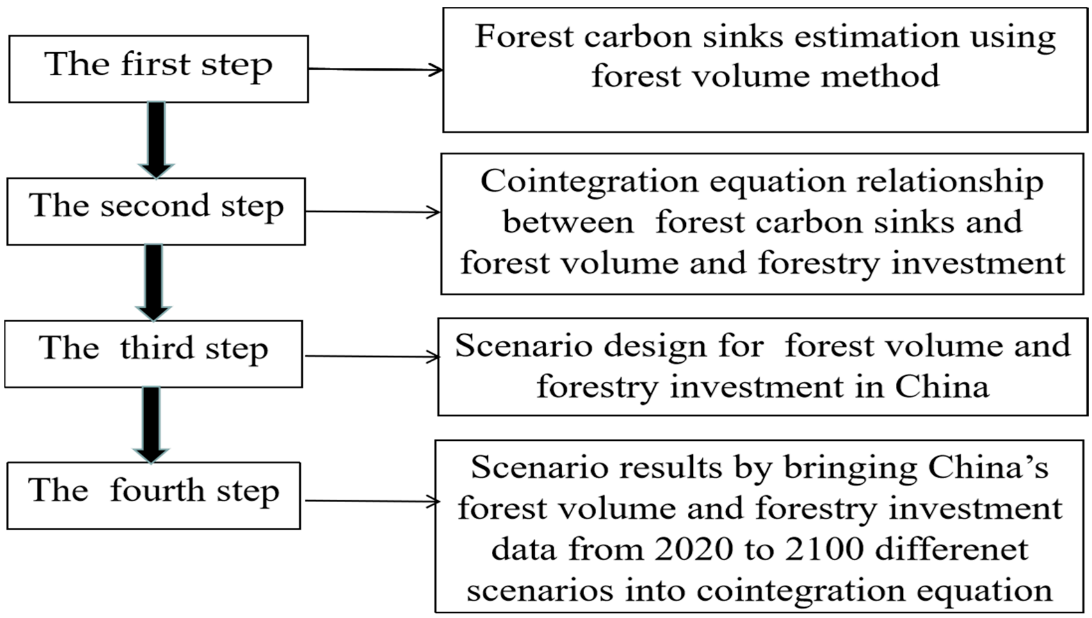

Figure 1. Methodology procedures.

3.2. Forest Carbon Sinks Estimation Method

Using data from nine forestry inventories of China conducted between 1973 and 2018, we follow Zhang et al. [46] and Li and Li [42] in calculating the forest carbon sinks in China using the widely applied forest volume method.

Under this method: forest carbon storage = carbon storage of forest trees + carbon storage of understory vegetation + carbon storage of forest land.
In turn: forest carbon storage = (forest volume × expansion coefficient × volume coefficient × carbon content rate) + (conversion coefficient of plant carbon sequestration of understory vegetation × forest volume) + (conversion coefficient of forest land carbon sequestration × forest volume) [47].

In equation form with appropriate numerical coefficients:

$$\begin{aligned} C_F &= V_F \times \delta \times \rho + \alpha(V_F \times \delta \times \rho \times \gamma) + \beta(V_F \times \delta \times \rho \times \gamma) \\ &= V_F \times 1.9 \times 0.5 \times 0.5 + 0.195(V_F \times 1.9 \times 0.5 \times 0.5) + 1.244(V_F \times 1.9 \times 0.5 \times 0.5) \\ &= 1.1585 V_F \end{aligned} \quad (1)$$

where:

- C_F represents forest carbon stocks in billions of tons of carbon.
- V_F indicates forest volume in 100 million cubic meters.
- δ is the biomass expansion coefficient.
- ρ is the coefficient of conversion of forest biomass to dry weight.
- γ is the carbon content rate.
- α is the carbon conversion factor of the forest understory.
- β is the carbon conversion factor of forest carbon sequestration.

The coefficients δ, ρ, and γ take on values of 1.90, 0.5, and 0.5 respectively, based on recommendations by the Intergovernmental Panel on Climate Change (IPCC). The conversion factors α and β take on values of 0.195 and 1.244, also based on IPCC recommendations [48]. These values have been used in other papers that estimated China's forest carbon sinks [31,40,42].

3.3. Cointegration Equation Model

3.3.1. Choice of Influencing Factors

There are many factors affecting sequestration capacity, including forest area, forest growth, forest management, and forest ecological construction. However, some factors such as forest management practices and institutional freedom cannot be easily quantified [49]. This is especially true when we consider the constraints that data availability and the given future scenario depiction place on us. Therefore, we choose some important factors that affect forest carbon sinks capacity and focus on the quantitative contribution of influencing factors. Here, we choose forest volume and forestry investment as two major factors affecting forest carbon sinks. By forestry investment we mean all investments in forest development in China. For example, China has successively launched and implemented six key forestry projects, including natural forest protection, returning farmland to forests, controlling wind and sand sources in Beijing and Tianjin, constructing the Yangtze River protective forest system, protecting wildlife and natural reserves, and constructing fast-growing and high-yield forest bases in key areas. In terms of construction content, it covers the main aspects of forestry construction such as forest resource conservation, desertification prevention and control, returning farmland to forests, and wildlife protection, covering over 97% of China's counties and cities in terms of geographical distribution [50]; the planned afforestation task exceeds 1.1 billion acres (4.45 m km^2) and the total investment reaches over 700 billion yuan (more than US$100 billion) (Ahrends, et al., [51] contains the acreage and investment figures).

Other factors, such as forest cover and forest area, ultimately affect the forest carbon sinks level in China through forest volume. Therefore, we focus on forest volume and forestry investment.

Forest volume is a direct factor affecting forest carbon sinks. In general, the larger the forest volume, the greater the forest carbon sequestration capacity. Therefore, the effect of forest volume on forest carbon sinks is positive.

Forestry investment is another important factor. The more investment, the higher the enthusiasm of forest ecological governance, and so the better the effect of forest governance. Therefore, in general, there is a positive relationship between forestry investment and forest carbon sinks.

3.3.2. Cointegration Equation Determination

The data for our explanatory variables—forest volume and forestry investment from 1994 to 2019—was collected from the *China Statistical Yearbook and China Forestry and Grassland Statistical Yearbook.* The dependent variable, Chinese forest carbon sinks, was estimated using the forest volume method (described in Section 3.1). We construct a quantitative relationship between forest volume (X_1), forestry investment (X_2), and forest carbon sinks (Y) to determine the contribution of X_1 and X_2 to Y.

All variables show an increasing trend over time and are likely nonstationary. To spurious (pseudo) regression they must be tested for stationarity. We conducted the Augmented Dickey-Fuller (ADF) unit root test to check for stationarity and the results are in Table 1. As suspected, the original sequences are nonstationary (have unit roots); however, the first order differenced (I(1)) series become stationary.

Table 1. Unit root test results.

Variables	Test Form	ADF Test Value of Original Sequence	Test Form	ADF Test Value of First-Order Difference Sequence	Conclusion
Y	(C, 0, 5)	−0.2995	(0, 0, 5)	−4.7958 ***	I(1)
X_1	(C, 0, 5)	0.9439	(0, 0, 5)	−4.2948 ***	I(1)
X_2	(C, 0, 5)	−0.6812	(C, T, 0)	−1.9644 ***	I(1)

Notes: *** is significant at the level of 1%; (C, T, k) are intercept term, trend term, and lag order, respectively. I(1) denotes first-order difference stationary series.

Since all three time series variables are I(1) series, the cointegration test can be carried out to determine whether there is a long-term equilibrium relationship between X_1, X_2, and Y. We apply the commonly used Johansen cointegration method to test the cointegration relationship variables [1]. The results of the cointegration test are in Table 2.

Table 2. Cointegration test results.

Hypothesis Test Type	E Eigenvalues	Trace Statistic	Trace Statistics Threshold (5%)
None **	0.6635	37.1468	29.7971
At most 1	0.3212	11.0093	15.4947
At most 2	0.0688	1.7119	3.8415

Note: ** is significant at the level of 5%.

From Table 2, we can see that the trace test and maximum eigenvalue test reject the original hypothesis at the 5% confidence level, which means that there is one cointegration relationship between X_1, X_2 and Y.

Next, we can regress Y on X_1 and X_2. The estimated equation is:

$$Y = -0.231032 + 0.010771X_1 + 0.000128X_2 \quad (2)$$

In this equation, both X_1 and X_2 regression coefficients were significant at the 5% level, but the intercept term was not statistically significant. Therefore, we re-estimate the relationship without an intercept. The new equation is

$$Y = 0.008893X_1 + 0.000149X_2 \quad (3)$$

The coefficients of X_1 and X_2 are now significant at the 1% level, and the signs meet the theoretical expectations. The adjusted R^2 is 0.96, indicating a close fit between X_1, X_2, and Y. From these results we can conclude that the fitted regression model can be used to quantify the contribution of forest volume and forestry investment to forest carbon sinks in China and to conduct long term prediction of the forest carbon sinks.

As a check on the predictive accuracy of the model, we perform within-sample prediction. We substitute the forest volume and forestry investment values from 2015 to 2019 into the estimated equation and then compare the results with the actual forest carbon sinks values for those years. The errors for the predicted forest carbon sinks values are 2.14%, 1.23%, −0.98%, 1.03%, and −1.02%, respectively, i.e., the error between the prediction value and the actual value is within 2.5%. Based on this key performance indicator, the cointegration Equation (3) we constructed has high predictive performance and can complete the long-term prediction task of forest carbon sinks in China.

3.4. Scenario Design

Next, we use scenario analysis combined with the prediction from Equation (3) to investigate the long-term evolution of forest carbon sinks in China from 2020 to 2100. In May 2023, the Ministry of Natural Resources, the National Development and Reform Commission, the Ministry of Finance and the National Forestry and Grass Administration jointly issued the Implementation Plan for Strengthening and Improving the Capacity of Ecosystem Carbon Sink, which means that China is paying more attention to ecological carbon sinks and their role in the carbon neutrality process. Therefore, China's ecological carbon sinks will not deteriorate and so we only present scenarios with positive growth in carbon sinks. We begin by defining three scenarios whose settings are simply combinations of values of the factors X_1 and X_2. The three scenarios which we call the routine, accelerated, and strengthened ecological civilization were derived from the provisions of the national autonomous contribution to climate change as well as resolutions made at the 2012 National Congress of the Party. For each scenario, we then use the fitted equation to make long-term predictions.

Because China attaches great importance to the construction of ecological civilization, we assume that the efforts of China's ecological civilization construction will gradually increase under the scenarios of routine, accelerated, and strengthened ecological civilization. China has placed the construction of a sustainable ecological civilization at the height of its national strategy. This strategy requires China to prioritize the creation of ecological civilization as part of its future development plans. Factors such as forestry investment and forest growth and volume are levers that the government can affect to try to achieve this goal. We will allow China's forest volume and forestry investment to vary and then use the regression equation to predict the forest carbon sinks for each scenario.

Following the provisions of the national autonomous contribution to climate change, China's forest volume should be 4.5 billion cubic meters higher in 2030 than it was in 2005. The national forest management plan (2016–2050) proposed that the forest volume in China would be over 23 billion cubic meters by 2050. Accordingly, from 2020 to 2050, China's forest volume needs to increase by at least 180 million cubic meters per year. Therefore, we assume that forest volume increases by 180 million cubic meters per year from 2020 to 2100 in the routine ecological civilization scenario.

Because the accelerated ecological scenario has a higher annual forest volume than the routine ecological civilization scenario, and the strengthened ecological scenario has a higher annual forest volume than the accelerated ecological scenario, we assume that China's annual forest volume is assumed to be 1% and 2% more under these scenarios than under the routine ecological civilization scenario. As such, more than 23 billion cubic meters of forest will be attained in China by 2050 in all three scenarios, reaching 23.3, 23.5, and 23.7 billion cubic meters, respectively, and more than 32 billion cubic meters of forest in China will be attained by 2100 in all three scenarios, reaching 32.3, 32.6, and 33 billion cubic meters, respectively.

In 2012, the 18th National Congress of the Party made a general plan for the construction of ecological civilization; for the first time, "Beautiful China" was regarded as the grand goal of ecological civilization construction. Since then, China's ecological civilization has entered a new era, with the scale of ecological investment rapidly expanding and the forestry investment growth rate reaching 3.5% from 2012 to 2019. Therefore, we assume in the routine ecological civilization scenario, the growth rate will be set at 3.5% by 2020 and will increase by 0.5 percentage points every five years until the goal of Beautiful China is achieved by 2050. Since the construction of a beautiful China is expected to be achieved by 2050 according to "the 14th Five Year Plan for National Economic and Social Development of the People's Republic of China and the Outline of the Long-Range Goals for 2035", assuming the goal will have been achieved by 2050, China's environmental pollution problem will have been fundamentally solved. Meanwhile, China will have achieved its carbon peak target and will be in the phase of carbon emissions decreasing, accomplishing a win–win between economic development and carbon emissions. Beyond this point China can afford to moderately reduce forestry investment since after attaining the goal of "a beautiful China", there is diminishing space for forestry investment resulting in a relatively slow decrease in forestry investment while continuing to maintain the ecological environment. Therefore, we assume that the forestry investment growth rate is reduced by 0.5 percentage points every 5 years beginning in 2050 until 2100 in order to maintain a good forest ecological level. If the designed forest investment decreases too quickly, such as 1% or even higher every five years, it may damage the existing forest ecological level and be unfavorable for continuing to play the role of forest carbon sink.

In turn, since China's ecological investment in the routine, accelerated, and strengthened ecological civilization scenarios increase, we assume that China's annual forestry investment growth rate is 0.5 and 1 percentage point higher in the accelerated and strengthened ecological civilization scenarios than in the routine ecological civilization scenario.

So, under the routine, accelerated, and strengthened ecological civilization scenarios, shown in Table 3, China's forestry investment will reach 2.2 trillion, 2.5 trillion, and 2.9 trillion yuan by 2050, and China's forestry investment will reach 13.6 trillion, 20.1 trillion and 29.5 trillion yuan under the three scenarios by 2100.

Table 3. Ecological civilization scenarios.

	Routine	Accelerated	Strengthened
Forest Volume per Year (X_1)	180 million m^3	181.8 million m^3	183.6 million m^3
Forestry Investment Avg. Growth (X_2)	5.4%	5.9%	6.4%
Total Forest Volume by 2050	23.3 billion m^3	23.5 billion m^3	23.7 billion m^3
Total Forest Volume by 2100	32.3 billion m^3	32.6 billion m^3	33 billion m^3
Total Forestry Investment by 2050	2.2 trillion (CN¥)	2.5 trillion (CN¥)	2.9 trillion (CN¥)

4. Results

4.1. Historical Assessment of Carbon Sequestration Capacity by Forest Carbon Sinks in China

Since the founding of the People's Republic of China, nine national forest resource inventories have been performed. The first was from 1973 to 1976. Beginning in 1977, the forest resources inventory has been conducted every five years, and the ninth was from 2014 to 2018. As a result, we have one value for the forest volume for each five-year period, i.e., the data on forest volume remains essentially the same for each five-year interval.

With forest volume, we can calculate China's forest carbon reserves every five years according to Equation (1), and then use the difference between the forest carbon reserves in two periods to obtain the carbon sinks capacity of China's forest carbon reserves during this forest resource inventory period. In this way, we can get the annual data of forest carbon sink levels in China. From 1973 to 2018, China's forest carbon sinks capacity averaged 280 million tons of carbon per year, equivalent to 1.03 billion tons of carbon dioxide sequestration per year (one ton of carbon equals 3.67 tons of carbon dioxide).

4.2. Future Characteristics of China's Forest Carbon by Carbon Sinks Sequestration Capacity

By bringing China's forest volume and forestry investment data from 2020 to 2100 in the routine, accelerated, and strengthened ecological civilization scenarios into Equation (3), we can get the forest carbon sink level from 2020 to 2100, and we can then calculate the growth rate of the forest carbon sinks in corresponding scenarios, as shown in Figure 2.

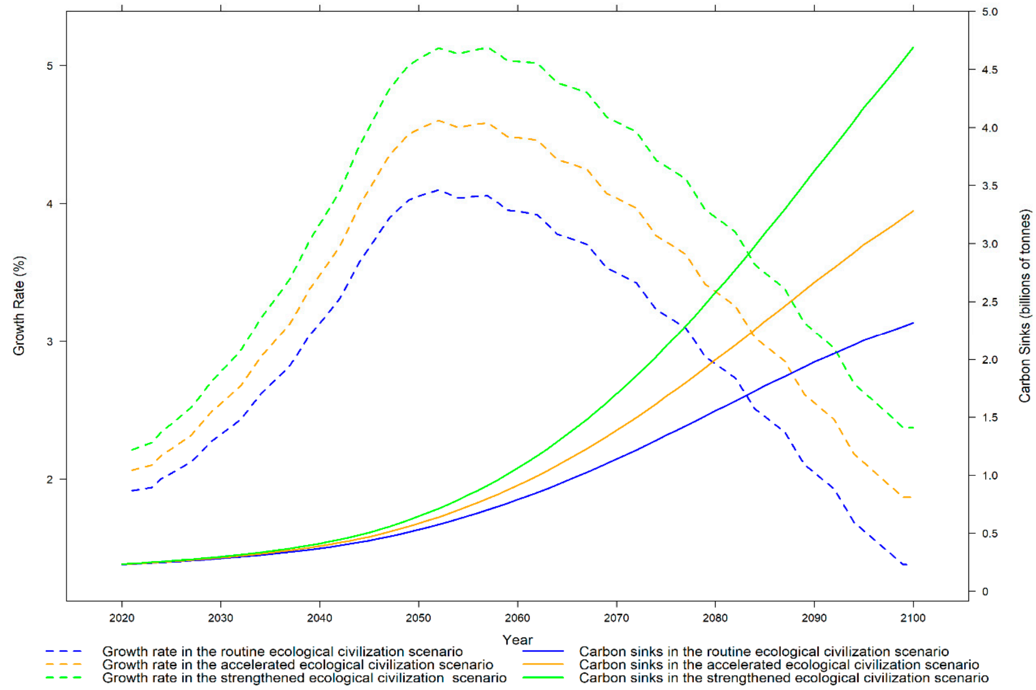

Figure 2. Forest carbon sinks and their growth rates in China under different scenarios (in billion tons of carbon and %).

According to Figure 2, under the routine, accelerated, and strengthened ecological civilization scenarios, the level of the forest carbon sinks in China is not obvious from 2020 to 2050. Beyond 2050, the difference becomes apparent. We found the following results.

4.2.1. Growth Trend and Characteristics of Forest Carbon Sinks in China

The level of forest carbon sinks in China will increase under the different scenarios, and the differences between scenarios will widen over time. For example, the forest carbon sink levels in China will be 0.230, 0.231, and 0.233 billion tons of carbon in the routine, accelerated, and strengthened ecological civilization scenario in 2020. The difference between the accelerated ecological civilization scenario and the routine ecological civilization scenario is about 0.001 billion tons of carbon and the difference between the strengthened ecological civilization scenario and the accelerated ecological civilization scenario is about 0.002 billion tons of carbon; China's forest carbon sinks will increase to 0.281, 0.289, and 0.296 billion tons of carbon by 2030 in the three scenarios and the difference between the accelerated ecological civilization scenario and the routine ecological civilization scenario or between the strengthened ecological civilization scenario and the accelerated ecological civilization scenario will increase to about 0.007 billion tons of carbon.

By 2050, China's forest carbon sink levels will grow to 0.531, 0.584, and 0.645 billion tons of carbon in the three scenarios and the difference between the accelerated ecological civilization scenario and the routine ecological civilization scenario or between the strengthened ecological civilization scenario and the accelerated ecological civilization scenario will be greater than 0.05 billion tons of carbon. By 2100, China's forest carbon sinks levels will rise to 2.32, 3.28, and 4.69 billion tons of carbon in the three scenarios and the difference between the accelerated ecological civilization scenario and the routine ecological civilization scenario or between the strengthened ecological civilization scenario and the accelerated ecological civilization scenario will be more than 0.9 billion tons of carbon. These changes reflect that the level of the forest carbon sinks in China will greatly increase in the process of ecological civilization construction. Furthermore, with the accumulation of ecological construction under different scenarios, the difference in forest carbon sink levels will increase in all scenarios. Under the scenario of strengthened ecological civilization, China's forest carbon sinks will be the highest, followed by the accelerated ecological civilization scenario, and lowest under the routine ecological civilization scenario.

4.2.2. Characteristics of Forest Carbon Sinks Growth

For each of the three scenarios, China's forest carbon sinks growth rate shows a rising trend that peaks around 2050 and then subsequently declines. To achieve the basic goal of environmental governance with a fundamentally improved ecological environment by 2035 along with the more ambitious goal of environmental governance by 2050, each of our scenarios assumes that China will continue to strengthen ecological investment including forestry investment. Once those goals are achieved in 2050, the growth rate of forestry investment will taper off. Therefore, the growth rate of the forest carbon sinks in China can be assumed to initially increase and then decrease in all three scenarios.

As seen in Figure 2 the growth rates of forest carbon sinks are 2021 is 1.92%, 2.07%, and 2.21% under the routine, accelerated, and strengthened ecological civilization scenarios, and by 2050, the growth rates increase to the highest rates—4.19%, 4.68%, and 5.20%—under the three scenarios, but by 2100 the growth rate falls back to 1.38%, 1.87%, and 2.38%. Because forestry investment is growing fastest under the scenario of strengthened ecological civilization, forest volume is also the largest, leading to the highest average growth rate of forest carbon sinks from 2018 to 2100 (3.83%), followed by the accelerated ecological civilization scenario (3.38%), and then by the routine ecological civilization scenario (2.94%).

In addition, the difference of forest carbon sinks in different scenarios tends to widen over time. If we divide the growth rate of China's forest carbon sinks in the accelerated ecological civilization scenario by the growth rate of the routine ecological civilization scenario (this ratio is recorded as R1) and divide the growth rate of China's forest carbon sink in strengthened ecological civilization by the growth rate under the accelerated ecological civilization scenario (this ratio is recorded as R2), we find that there is an increasing trend in these ratios. R1 increases by 25.7%, from 1.077 in 2021 to 1.3533 in 2100, and R2 increases by 18.6%, from 1.071 in 2021 to 1.2703 in 2100.

4.2.3. Using Forest Carbon Sinks to Achieve Carbon Neutrality

Xu et al. [52] made use of scenario analysis along with data on the carbon emission factors for coal, oil, and gas to determine China's CO_2 emissions peak. In this section we combine their estimates for when China's carbon emissions will peak with our forecast of China's carbon sinks to determine when China will achieve carbon neutrality. By combining forecasts of future carbon emissions generated by energy use with our own forecast for the emissions offset by carbon sinks, we predict that this goal can be achieved by 2060 or before. Note that their scenarios are distinct from ours. They consider how various growth trajectories affect the peak year for carbon emissions. Our scenarios, on the other hand, consider how various forestry investment trajectories affect the future carbon sinks.

The scenarios in Xu et al. [52] are reproduced in Table 4, with their CO_2 emissions converted to carbon emissions by dividing CO_2 emissions by 3.67.

Table 4. Overview of China's carbon peaking.

Scenario	Carbon Peak Year	Carbon Volume (Billions of Tonnes of Carbon)
Low growth	2029	2.75
Benchmark moderate growth	2031	2.94
High growth	2035	3.17

If we extrapolate the predictions under each of their scenarios beyond the peak dates to 2050 and then take the average, we obtain an average carbon emissions value of 0.77 billion tons for 2050. This value represents the overall picture of China's carbon emissions in 2050. Since emissions would have peaked under all three scenarios by the mid-2030s, this picture means that China's total carbon emissions will be less than 0.77 billion tons from 2050 to 2060.

Based on this amount, we can get the approximate year in which the forest carbon sink level in China exceeds 0.77 billion tons of carbon under the routine, accelerated and strengthened ecological civilization scenarios. China's forest carbon sink levels will exceed 0.77 billion tons of carbon in 2060 (0.789 billion tons of carbon), 2057 (0.798 billion tons of carbon), and 2054 (0.797 billion tons of carbon). If we consider the continuous adjustment of energy consumption structure to 2060, carbon emissions must be less than 0.77 billion tons in 2060, 2057, and 2054.

These figures illustrate that under the continuous low-carbon adjustment of energy consumption structure, giving full play to the carbon sequestration effect of forest carbon sinks on carbon emissions, China can achieve carbon neutrality before 2060.

4.2.4. Comparison with Other Studies

This result expands the current analysis of long-term change of forest carbon sinks in China. Compared with Ke et al. [11], the novelty of the results of this article is mainly reflected in the following aspects:

First, the analysis period is long. They analyzed the trend of changes to 2060, while we analyzed the trend of changes to 2100, and this better provides the long-term changes and patterns of forest carbon sinks in China.

Second, different influencing factors are considered. We mainly consider direct factors that affect China's forest carbon sinks, such as forest investment and forest stock, while they mainly consider indirect factors such as carbon prices. However, the Chinese carbon market has not yet formed a reasonable carbon price mechanism, and carbon prices may not be sufficient to reflect the impact of forest carbon sink development.

Third, the long-term prediction results are significantly different. They seriously overestimated the potential of China's forest carbon sequestration. They believe that from 2021 to 2060, China's average annual forest carbon sequestration is 0.170 billion tons of carbon, while our research is roughly 0.150 billion tons of carbon. They did not study the situation after 2060, but our research found that China's average annual carbon sinks showed a significant growth trend from 2060 to 2100, but the growth rate would decrease slightly compared to the average growth rate from 2021 to 2060.

Fourth, they did not consider whether China could achieve carbon neutrality by 2060 through forest carbon sinks. In contrast, our research found that China could achieve carbon neutrality as early as 2054 through the role of forest carbon sinks. It should be noted that the process of carbon neutrality requires carbon reduction through a clean transformation of the energy structure, and also the carbon neutrality effect of forest carbon sinks.

From these differences, it can be seen that this article can clearly identify the important role of forest carbon sinks in carbon neutrality in China, and can also accurately analyze the important impact of forest investment and forest stock on forest carbon sequestration.

5. Discussion, Conclusions and Policy Implications

5.1. Discussion

In our analysis of the factors affecting forest carbon sequestration, forestry investment and forest volume are two important factors. For forests that already exist, forest volume (the amount of biomass) depends on the growth rate of the forest which cannot be directly affected by human intervention. Forestry investment is a variable that can be regulated by the government. Therefore, we should focus mainly on the role of forestry investment in carbon neutrality to facilitate policy analysis.

According to our analysis, with forestry investment contributing to China's carbon neutrality, China should choose the path of strengthened ecological civilization with lower average investment costs and shorter duration. However, there is one caveat to this path; forestry investment must maintain a high growth rate of at least 6.3%, which is higher than for the other two scenarios. The average annual growth rate of forestry investment in China will be 5.4% from 2020 to 2060 under the routine ecological civilization scenario, 5.9% between 2020 and 2057 under the accelerated ecological civilization scenario, and 6.3% from 2020 to 2054 under the strengthened ecological civilization scenario.

Although we have comprehensively characterized and discussed the role of forest carbon sinks in China's carbon neutralization process, we still need to pay attention to the following five points:

First, one concern that arises because of the long-term nature of our forecast is statistical error as a result of future policy variation that is not accounted for in our model. While this concern cannot be eliminated, we took several steps to mitigate this concern, including the use of multiple scenarios to account for different potential policy directions, and the use of out-of-sample validation to set bounds on our forecast's statistical error.

Second, developing forest carbon sinks is an important aspect of achieving China's carbon neutrality goal, but the role of forest carbon sinks cannot be infinitely replicated, and its role is complementary with the transition to clean energy. Therefore, the research in this article provides a basis for objectively assessing the role of forest carbon sinks in achieving the carbon neutrality goal, but this does not mean that forest carbon sinks can replace the fundamental requirement of energy transformation.

Third, developing forest carbon sequestration might primarily achieve results in the long term. As is well known from a Chinese proverb, "It takes ten years to grow trees". Therefore, promoting the development of the forest industry through forestry investment requires patience. Moreover, forest growth must conform to the biological growth cycle, which requires that forestry investment should be continuous and uninterrupted. This need requires high ecological investment represented by forest investment.

Fourth, to protect forests and promote their healthy development, institutionalized means should be emphasized. Incorporating the strategy of developing forest carbon sinks into the forest development system is a key measure to actively develop forest carbon sinks. Institutionalization can maintain the sustainability of developing forest carbon sinks and avoid disruptions. For example, it is possible to provide a strong incentive mechanism for the development of the forest industry and forest carbon sinks through the deep reform of the collective forest tenure system and a legal system for forest carbon sink property rights (ownership, possession, use, revenue, and disposal rights).

Fifth, the impact of carbon prices on forest carbon sinks is not yet clear. The improvement of China's carbon market needs carbon sinks to guide the development of forest carbon sinks, but the impact of carbon price on forest carbon sinks needs to be established in a more developed carbon market environment. Given that China's unified carbon market has just started, the impact of carbon price on the development of forest carbon sinks needs to be observed.

5.2. Conclusions

Scientific estimation and prediction of forest carbon sink levels in China is of great significance for achieving the goal of carbon neutrality. Based on the estimation of forest carbon sink levels in China from 1994 to 2019 using a cointegration test method, we quantified the contribution of forest volume and forestry investment to China's forest carbon sinks. We then developed scenarios of the trend in forest volume and forestry investment to obtain the trajectory of China's forest carbon sink levels to the year 2100. Finally, we analyzed feasible ways to achieve carbon neutrality in China, from which we obtain some key conclusions.

First, the influence of forest volume and forestry investment on forest carbon sinks in China is positive, which accords with theoretical expectations. This finding indicates that increasing forest volume and forestry investment can directly increase the level of the forest carbon sinks in China. Forest volume is a dominant variable under the state of natural forest growth since the regression coefficient showing forest volume's influence on forest carbon sinks is larger than that of forestry investment. However, forestry investment is a critical factor for China's forest management departments to promote the role of forest carbon sinks. Furthermore, forestry investment is easy to implement and adjust by the government and other economic agents that participate in the process of ecological investment.

Second, the level of forest carbon sinks in China is markedly different under different scenarios. Under the strengthened ecological civilization scenario with the highest forest volume and forestry investment, China's forest carbon sinks level is the highest, followed by the accelerated ecological civilization scenario and then by the routine ecological civilization scenario. In addition, the gap in forest carbon sink levels between different scenarios becomes larger with the passage of time. The forest carbon sink levels in China will be 0.281, 0.289, and 0.296 billion tons of carbon in the routine, accelerated, and strengthened ecological civilization scenarios by 2030, the number will be 0.531, 0.584, and 0.645 billion tons of carbon in the corresponding scenarios by 2050, and will be 2.32, 3.28, and 4.69 billion tons of carbon in the corresponding scenarios by 2100.

The growth rate of forest carbon sinks in China, driven by the slow growth rate of forestry investment, will have an inverted-U curve that rises first and then slows under all three scenarios, while the difference in growth rates between different scenarios will widen over time. The reason is that the growth rate of forest volume and forestry investment under the strengthened ecological civilization scenario is higher than that in the accelerated ecological civilization scenario, and the growth rate of forest volume and forestry investment in the accelerated ecological civilization scenario is higher than in the routine ecological civilization scenario.

Third, it is estimated conservatively that China's forest carbon sinks can achieve the national goal of carbon neutrality on or before 2060 based on the large role of renewable energy in carbon emission reduction. China's carbon neutrality can be realized in 2054 under the strengthened ecological civilization scenario. If the carbon-neutral target is achieved by 2054, ahead of schedule, China will need to accumulate 53.3 trillion yuan in forestry investment from 2020 to 2054, with a growth rate of at least 6.3% each year. If China achieves carbon neutrality by 2060, it will need to invest a cumulative 62.6 trillion yuan in forestry from 2020 to 2060. Therefore, China should choose a strengthened zero-carbon development path to achieve carbon neutrality at a total lower investment cost, provided that forestry investment maintains an average annual growth rate of at least 6.3% through 2054.

5.3. Policy Implications

Based on the conclusions in the previous section, we can glean the following policy implications:

First, we should attach great importance to the role of forest carbon sinks in China's goal of carbon neutrality, and vigorously develop forest carbon sinks to achieve net-zero carbon development. Therefore, it is necessary to bring the development of the forest carbon sinks industry into the general program of national ecological civilization, standardize the legitimacy of developing forest carbon sinks by the legal system, and heavily penalize the destruction of forest carbon sinks. Meanwhile, it is necessary to form a pattern of forest farms as carbon sink bases, cultivate forest carbon sink bases by guiding economic agents to participate in afforestation activities, and increase China's forest carbon sinks industry to promote China's carbon neutrality goal as soon as possible and provide conditions for the smooth realization of carbon neutralization.

Second, while continuing to promote a zero-carbon energy structure and optimization and upgrading of industrial structure to promote carbon emission reduction, expanding forestry investment is an important task to achieve carbon neutrality before 2060. By maintaining a large scale and high growth rate of forestry investment, China's carbon neutrality target can be expedited. State investment should expand the scope of forestry investment options, encourage qualified personal capital, private capital, and foreign capital to actively pursue forest construction and conservation, extensively mobilize social forces, and actively invest in forest construction and management. Moreover, regardless of the growth rate of economic development, it must not reduce the growth rate of forestry investment. Recently, China's economic development ushered in the new normal where improving economic growth quality has become an inevitable trend. Forestry investment must not be reduced, because the growth rate (i.e., over 6.3%) of forestry investment should be higher than the economic growth rate (that is less than 6%).

Third, it is necessary to improve the level of forest management [53]. It is critical to improve the scientific level of forest management by integrating modern technical means such as big data and intelligent management into the entire process of forest breeding, sowing, and conserving, with focus on the prevention and control of forest diseases and insect disasters and carrying out early warning and management of forest fires to maintain ecological balance in forest resource areas. Therefore, the Chinese government should have fully modernized and advanced management tools to foster a good environment and conditions for forest growth, and to provide technical support for creating a stable carbon sequestration environment.

Fourth, China should vigorously develop the carbon sinks market, so that forest carbon sinks become an important part of the equation. Forest carbon sinks have become an important trading tool in China's carbon market. Therefore, it is necessary to define the forest industry and carbon sink property rights clearly, and to define the right to use, and the benefits of, forest carbon sinks. The funds brought by the forest carbon sinks can be used for economic and ecological construction in areas rich in forestry resources, thus supporting China's economic development and ecological civilization construction. Therefore, all sectors of society need to attach importance to the forest carbon sinks market [14]. As such, on the basis of the pilot carbon trading market and rollout of the national carbon market, China should strengthen the coverage of the carbon market to include sectors other than electricity including forest carbon sinks trading, so that they can be effectively linked with productive enterprises and provide more efficient carbon-neutral services to allow the continued use of high carbon-emitting but productive enterprises, such as steel, cement, and oil. After joining the carbon market, forest carbon sinks can increase the variety of carbon market transactions, improve their trading efficiency, and reduce market volatility, thus realizing the ecological value of forest products and compensating for the costs of afforestation and forest management.

Fifth, the development of institutionalized forest carbon sequestration should achieve new results. Incorporating the development of forest carbon sinks into the forest legal system and policy arrangements will provide a reliable institutional guarantee for the development of forest carbon sinks. Revising and improving the Forest Protection Law will further strengthen China's collective forest rights reform, the ecological welfare forest certification program, and other major ecological projects. Through implementing and improving these systems, China can enhance the carbon absorption of forests and the ecological effectiveness of forest development.

Finally, China should improve the forest governance system, and establish a new model of national participation in the development of forest carbon sinks. It should improve the work guarantee system for the forest leader system by clarifying the responsibilities of the forest leader, compacting the work responsibilities, and forming a work mechanism that focuses on implementation at all levels. In addition, forest patrols are needed to coordinate and solve problems in a timely manner. In short, China must use the new forest governance system and comprehensively improve the ability of forest management to protect the development of forests and forest carbon sinks.

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Note

[1] The tests were conducted using version 10 of EViews statistical software.

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