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Article

Quantifying the Carbon Sequestration Costs for *Pinus elliottii* Afforestation Project of China Greenhouse Gases Voluntary Emission Reduction Program: A Case Study in Jiangxi Province

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Abstract: Afforestation and reforestation (AR) is an important component of China's Greenhouse Gases (GHG) Voluntary Emission Reduction Program, acting as a valuable nationwide carbon sink. Although a number of studies have explored the costs of creating a carbon sink, such an assessment is lacking for China's GHG Voluntary Emissions Reduction Program. This study develops an economic carbon sink costs measurement model for the *Pinus elliottii* afforestation project, based on the land opportunity cost method, which incorporates carbon sink transaction costs and leakage costs. From this, an empirical analysis on the carbon sink costs and its sensitivity factors was conducted. The results show that, firstly, the carbon sequestration costs of afforestation projects are generally high, ranging from 44.2 Yuan/tCO₂e to 425.4 Yuan/tCO₂e with and without considering the benefits of wood, respectively. This is higher than the current average carbon sink price of 20 Yuan/tCO₂e. Secondly, forestry carbon sink transaction costs have a positive impact on carbon sequestration costs, but the impact is weak. Thirdly, carbon sequestration costs are negatively affected by timber prices but positively influenced by increasing labor prices and discount rate, which is not conducive to the development of carbon sink afforestation projects. In order to strengthen role of forestry in combating climate change, the study holds that the government departments should take measures to reduce carbon sink transaction costs, establish and improve the forestry carbon sink compensation mechanism in the future, and encourage wood-processing companies to make technological innovations to produce and sell durable wood products. The project owners can explore multiple operating models to increase their revenue, including market and non-market benefits, when the carbon sink afforestation project has been launched according to relevant methodologies.

Keywords: afforestation project; forestry carbon sink; land opportunity cost; carbon sink costs; China GHG Voluntary Emission Reduction Program

1. Introduction

Carbon dioxide (CO₂) is one of the main greenhouse gases (GHG) in the atmosphere, and the increase in the atmospheric CO₂ levels is an important factor in global climate change [1]. Since the beginning of the 21st century, the concentration of GHG in the atmosphere has been continuously increasing at a level of about 1.8 parts per million (ppm) per year, due to the consumption of fossil fuels

such as coal, oil and natural gas, and the widespread destruction of forest vegetation [2,3]. The current CO₂ content in the atmosphere has reached 380 ppm from 280 ppm since 1750, which will lead to a rise in global average temperatures [4]. This will result in adversely affect, such as sea level rise, world agriculture and ecosystem change, intensify other natural disasters, and even cause serious negative impacts on human survival and the economy [3,5,6]. Therefore, urgent global action is essential reduce emissions and increase carbon absorption.

Afforestation and reforestation (AR) have become key strategies to enhance terrestrial carbon sequestrations and mitigate CO₂ concentrations in the atmosphere [7–9]. Compared with industrial emission reduction, afforestation to increase carbon absorption has the obvious advantages of lower economic costs and great potential [9–12]. At the same time, afforestation to enhance carbon sequestration is also conducive to promoting the sustainable development of a local forestry industry, and providing new employment opportunities and carbon sink income for local residents [9,12]. Therefore, AR are recognized in the international political and legal frameworks to address global climate change, and integrated in the Clean Development Mechanisms (CDM) and Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanisms developed by the Kyoto Protocol and Copenhagen Agreement, respectively [13].

To take full advantage of forestry to combat climate change, the Chinese government has incorporated afforestation activities into the domestic emission trading schemes (ETs) [14,15]. The pilot ETS in China are dominated by quota trading under total amount (total amount control refers to the environmental management method system with the control of the total amount of pollutants discharged by pollutant discharge units in a certain area in a certain period of time), wherein private enterprises develop their own qualifying China Emission Reduction Projects (CCER) under China's GHG Voluntary Emission Reduction Program. These projects often include AR activities designed to offset carbon emissions by planting sufficient trees to offset the emissions. Thus, this mechanism can include additional financial support for carbon sequestration afforestation project [16,17]. However, the implementation of carbon sink afforestation projects is often closely related to other forms of woodland utilization, because of the technical requirements of planting and maintenance. This results in a certain woodland use opportunity cost [18,19]. Successful implementation of carbon sequestration trading involves multiple stages of filing before trading of certified emissions reductions (CERs) can commence [14]. The above procedures generate large carbon sequestration transaction costs [20–22]. These higher costs can act as barriers to the development of afforestation projects for carbon sink, potentially diminishing the role of forestry in combating climate change. Therefore, scientifically measuring the carbon sink costs of afforestation project in particular regions and identifying low-cost scenarios have important practical and policy value for furthering the development and investment in carbon sink afforestation projects and forestry action plans formulation to deal with climate change of government department.

Carbon sequestration costs, an important driver in the implementation of carbon sequestration afforestation projects, have become an important topic in global research [23,24]. In terms of carbon sequestration cost measurement, a number of different methods for assessing carbon sequestration costs have been developed: the bottom-up model, the sectoral model and the econometrical model have been formed [25,26]. Among them, the bottom-up model is a kind of static calculation model, which estimates the land opportunity cost using land rent, land price or lost crop prices [26]. This model has been used to explore the carbon sequestration costs for the CDM reforestation project in Mexico [27], South Korea [28], United States [29], Latin America [30], United Kingdom [31], Canada [32] and other countries or regions [33–35], and gives the conditions and the regions suitable for the implementation of afforestation projects in both CDM and REDD+ mechanisms. Considering that there is a difference between fixing a certain amount of CO₂ now and fixing the same amount of CO₂ in the future in terms of value and the environmental effects, many scholars believe that it is essential to discount the carbon sinks when calculating the carbon sink costs using the bottom-up model [18,24,35]. The sectoral and

econometrical models from a larger scale macro perspective have been applied in some developed countries [23,24,32,36].

In terms of factors affecting the carbon sequestration costs, Galik believe that the proportion of transaction costs to the overall implementation costs is generally less than 25% [21]. Pearson pointed out that the estimated value of carbon sequestration costs is 30% lower than the actual value because the transaction costs is not considered [22]. Phan found that the factors affecting the unit carbon sequestration costs of avoiding deforestation mainly include the project area size, carbon sink measurement method, operating period, transaction costs, land-use methods, and the proportion of agriculture in GDP [26]. In addition, further studies into the impact of afforestation area on the carbon sequestration cost [34], provide both a theoretical basis for scientific understanding the costs of carbon sequestration, and guidance for different countries to deal with climate change through AR.

However, there is still a need for further research on the carbon sequestration costs. Firstly, quantitative research on the sensitivity of carbon sink costs to changes in carbon trading markets and forestry production environments is relatively scarce and small scale [14,18]. This will not reveal the impact of changes in economic and technological parameters on carbon sequestration costs. Secondly, in terms of the carbon sequestration measurement model, previous authors have not considered restrictions on changing forested land, and ignored the carbon sink transaction cost and carbon leakage cost [30,37]. In view of this, we tried to address these research gaps, using a *P. elliottii* afforestation project for a carbon sink under the China GHG Voluntary Emission Reduction Program as a case study, as they are both large scale and affected by restrictions on forest land-use change. Meanwhile, the project in Jiangxi province is an earlier afforestation project for carbon sequestration in China ETSs and has been registered at the National Development and Reform Commission (NDRC). Therefore, this case study is very typical and representative, the data is also accessible for the analysis. The main objectives of this study were (1) to build and practical improve a carbon sequestration cost measurement model under the condition of implementing carbon sequestration afforestation project from the perspective of economics, which is suitable for China's socio-economic environment; (2) to estimate the carbon sequestration costs for the *Pinus elliottii* afforestation project with the existing conditions; and (3) to explore the sensitivity of carbon sequestration costs to changes in exogenous risk factors.

2. Materials and Methods

To evaluate the impacts of different costs on the overall costs of carbon sequestration, this study takes a modeling approach. Here the forest land net present value under the implementation scenario of afforestation carbon sequestration project is represented by the expected value of the land model, while the income under other probable woodland use scenarios is represented by the annual average land rent. By summing the discounted value of woodland rent, the level of woodland rent under the condition of an indefinite period is obtained, which represents the land opportunity cost. From this, the economic model of carbon sequestration costs measurement is derived from the critical economic conditions of the carbon sequestration forest project implemented.

2.1. Model Selection

2.1.1. Woodland Net Present Value Model

The woodland net present value model (NPV) can be expressed as the sum of the net present value of timber and non-timber values under the condition of infinite rotation on a piece of woodland. Non-timber values represent the value of woodland non-timber products, such as forest recreational value, water and soil conservation, carbon sink, biodiversity maintenance, and some dried and fresh fruits [36,38]. Considering that the research goal of exploring the costs of carbon sink and other forest ecological services cannot be traded to obtain economic benefits, the focal non-timber value in this study is only the value of carbon sinks [18,38]. Thus, the profit flow ($\pi(P_c)$) per unit area ($(\text{hm})^2$) of a

carbon sequestration afforestation project is expressed by the difference between the benefits and costs of the afforestation project, as follows:

$$\pi(P_c) = TRh_t + TRc_t - C_{wt} - C_{ct} \quad (1)$$

In Formula (1), TRh_t is the timber revenue per unit area ($(\text{hm})^2$) of the afforestation project in year t , which is equal to the product of timber price P (850 Yuan/ m^3) and the volume of per plants and the planting density of *P. elliotii* per unit area $N_{TREE_PROJ,t}$ and the timber output rate δ (0.75). Among them, the timber price and the timber output rate is assumed to be fixed for a long time to come, mainly because these two parameters in the future cannot be predicted accurately. For the convenience of analysis, we refer to related research and use it as a constant [18]. TRc_t is the annual carbon sequestration revenue per unit area ($(\text{hm})^2$) of afforestation project in year t , which is equal to the product of annual net carbon sequestration per unit area $\Delta C_{AR_CHINA,t}$ and carbon price P_c ; C_{wt} is management and protection costs of afforestation project per unit area ($(\text{hm})^2$) in year t , C_{ct} is the carbon sink transaction costs per unit area ($(\text{hm})^2$) in year t .

The net present value of the forest land is closely related to the rotation period. When the forest is in the optimal rotation period, the value of the forest land is the largest. At this time, the woodland NPV is also called the “forest land price”. According to Formula (1), referring to the Faustmann–Hartman model [38], a classic model in the field of forestry economics and widely used in land value evaluation and rotation period determination, the woodland NPV model under the condition of infinite rotation can be expressed as:

$$NPV^\infty = \frac{TRh_t \times e^{-rT} - \sum_{t=1}^T (C_{wt} \times e^{-rt})}{1 - e^{-rT}} + \frac{\sum_{t=1}^T (TRc_t \times e^{-rt}) - \sum_{t=1}^T (C_{ct} \times e^{-rt})}{1 - e^{-rT}} \quad (2)$$

In Formula (2), NPV^∞ is the woodland NPV model under the condition of infinite rotation per unit area ($(\text{hm})^2$); r is the discount rate, the value of 5% is the average long-term deposit interest rate from the banks in china [18]; T is the rotation period. In order to express Formula (2) as a function of carbon price P_c , the model can be further converted into:

$$NPV^\infty = \frac{TRh_t \times e^{-rT} - \sum_{t=1}^T (C_{wt} + C_{ct}) \times e^{-rt}}{1 - e^{-rT}} + \frac{\sum_{t=1}^T (TRc_t \times e^{-rt})}{1 - e^{-rT}} \quad (3)$$

Formula (3) is divided into two parts: the left of the plus sign represents the indefinite discounted value of the timber profits minus the costs of afforestation and forestry carbon sink transaction. The model is as follows:

$$V_w = \frac{TRh_t \times e^{-rT} - \sum_{t=1}^T (C_{wt} + C_{ct}) \times e^{-rt}}{1 - e^{-rT}} = \frac{P \times Q(t) \times N_{TREE_PROJ,t} \times \delta \times e^{-rT} - \sum_{t=1}^T (C_{wt} + C_{ct}) \times e^{-rt}}{1 - e^{-rT}} \quad (4)$$

The second part represents the discounted value of carbon sequestration income obtained through carbon sink trading, $V_c = \theta \times P_c$, ordering:

$$\theta = \frac{\sum_{t=1}^T \Delta C_{AR_CHINA,t} \times e^{-rt}}{1 - e^{-rT}} \quad (5)$$

Formula (5), $\sum_{t=1}^T \Delta C_{AR_CHINA,t}$ is the sum of carbon sequestration per unit area ($(\text{hm})^2$) of *P. elliotii* afforestation project in a rotation period. Thus, the woodland NPV under the condition of infinite

rotation can be expressed as an implicit function of carbon price P_c . Formula (2) can be expressed as follows:

$$NPV^\infty = V_w + \theta P_c \quad (6)$$

2.1.2. Carbon Sink Accounting Model in a Rotation Period

Forest such as *P. elliottii* contains six carbon pools: aboveground biomass, underground biomass, dead wood, litter, soil organic carbon and harvested wood products (HWP) [8,37]. Compared with barren mountain and wasteland, the carbon storage of dead trees, litter and soil organic carbon pool after afforestation will not be reduced, so it can be conservatively ignored [39,40]. At the same time, previous studies have assumed that all the carbon sequestration after harvesting is fixed in HWP, neglecting the possible carbon leakage from HWP in the future. This may lead to the overestimation of carbon sequestrations and inaccurate measurement results of carbon sequestration costs [18,37]. In this paper, we attempt to further consider the problem of carbon leakage from HWP on the basis of the existing hypothesis. Therefore, the sum carbon sequestration of *P. elliottii* in a rotation period ($\sum_{t=1}^T \Delta C_{AR_CHINA,t}$) is equal to the difference between the carbon sinks in the biomass carbon pool and the carbon leaks in the HWP carbon pool (in Formula (11)). The specific calculation process of carbon sinks in a rotation period is as follows:

$$Q(t) = 0.2023 \times (1 - e^{-0.01t})^{3.991} \quad (7)$$

$$B_{TREE_PROJ,t} = Q(t) \times D \times BEF \times (1 + R) \times N_{TREE_PROJ,t} \quad (8)$$

$$C_{TREE_PROJ,t} = \frac{44}{12} \times B_{TREE_PROJ,t} \times CF_B \quad (9)$$

$$\Delta C_{TREE_PROJ,t} = \frac{C_{TREE_PROJ,t_2} - C_{TREE_PROJ,t_1}}{t_2 - t_1} \quad (10)$$

$$\sum_{t=1}^T \Delta C_{AR_CHINA,t} = \sum_{t=1}^T \Delta C_{TREE_PROJ,t} - (1 - a) \times cR \quad (11)$$

In Formula (7), $Q(t)$ is the volume (m^3) per plant of *P. elliottii* in year t . Due to the differences in site conditions and management levels, different growth conditions of *P. elliottii* will result. Thus, the growth model which is more suitable for the ecological conditions of the project area should be selected when calculating the volume. However, the volume growth equation of *P. elliottii* in the project area was not found. According to the technical requirements of volume growth measurement of "Methodologies for A/R project activities in china (AR-CM-001-V01)", the existing and published volume growth equation similar to the local ecological conditions can be selected [41]. Therefore, this study mainly selects biomass equations in Yueyang City, Hunan Province that are similar to the natural conditions in the study area [42]. In fact, Yueyang city ($28^\circ 25' 33'' \sim 29^\circ 51' 00''$ N, $112^\circ 18' 31'' \sim 114^\circ 9' 6''$ E) is located in the East Asian monsoon climate region, belonging to the humid continental monsoon climate. The annual average temperature in Yueyang city is $17^\circ C$, with the annual precipitation of about 1300 mm, and the frost-free period is about 270 days; while Jiangxi province ($24^\circ 29' 14'' \sim 30^\circ 04' 41''$ N, $113^\circ 34' 36'' \sim 118^\circ 28' 58''$ E) belongs to the warm and humid monsoon climate in the middle subtropical zone. The annual average temperature is $11.6 \sim 19.6^\circ C$, with average precipitation of about 1635 mm in the Province, and the frost-free period lasts 240~307 days. The precipitation, temperature and frost-free period in Yueyang City are basically the same as the average level of Jiangxi Province. Thus, the ecological conditions such as water and heat in the two places have certain similarity.

In Formula (8), $B_{TREE_PROJ,t}$ is the aboveground biomass per unit area ($t/(hm^2)$) of *P. elliottii* in year t ; D represents the basic wood density of *P. elliottii* ($t.d.m/m^3$), the value is 0.424; BEF represents the biomass expansion factor (BEF) of *P. elliottii*, the value is 1.614; R is the ratio of underground biomass to aboveground biomass of *P. elliottii*, which is used to convert the trunk biomass to the whole forest

biomass, the value is 0.264; The above parameters are derived from “Methodologies for A/R CCER project activities (AR-CM-001-V01)” [41]; $N_{TREE_PROJ,t}$ is the planting density of *P. elliottii* per unit area (plant/(hm)²). We assume that the above parameters (D,BEF,R) are all constants, because their changes over time cannot be accurately predicted with existing technologies.

In Formulas (9) and (10), $C_{TREE_PROJ,t}$ is the annual carbon stock of forest biomass per unit area in year t (tCO₂e/(hm)²); $\Delta C_{TREE_PROJ,t}$ is the annual carbon stock change of *P. elliottii* biomass per unit area in year t (tCO₂e/(hm)²); CF_B is the carbon content in the biomass of *P. elliottii*, the value is 0.521 (The data comes from the “list of greenhouse gases in land use change and forestry” in the second National Information Circular of the people’s Republic of China on climate change); 44/12 is the molecular weight ratio of CO₂ to C; t_1 and t_2 are the t_1 year and the t_2 year after the start of the project, and $t_1 \leq t \leq t_2$.

In Formula (11), cR is the carbon sinks per unit area ((hm)²) at the end of a rotation period, which is equal to the sum of the $\Delta C_{TREE_PROJ,t}$ in a rotation period. a is the proportion of carbon sinks in wood products for a long time; when $a = 0$, all carbon sink in wood products will be released into the atmosphere instantly through combustion or other methods during harvesting; when $a = 1$, all the carbon transferred after harvesting is stored in the wood products forever, and it is not released. Therefore, it is extremely important to determine the parameter a scientifically. In general, a is a function of the rate of decay of HWP. The carbon release rate caused by the decay of HWP is an exponential equation about time t [37], then the carbon sink in HWP is expressed as follows:

$$W(t) = \beta \times cR \times e^{-v_1(t-T)} + (1 - \beta) \times cR \times e^{-v_2(t-T)} \quad (12)$$

In Formula (12), it is assumed that the carbon content cR of the wood after harvesting is stored only in the following two parts of wood products: one part is stored in long-term durable solid wood products, such as building materials, furniture and sawn wood; this part of the carbon release rate is slow. The other part is stored in short-term products, such as packaging materials; this part of the carbon release rate is faster [37]. $t - T$ is the time after the tree is harvested, v_1 is the decay rate of long-lasting wood products. With reference to the study of Sohngen, v_1 of *P. elliottii* is taken as 0.79% per year [37]; v_2 is the rate of decay of short-term wood products, the v_2 of *P. elliottii* is taken as 1.03% per year [37]; β is the proportion of long-term durable goods in wood products, with a value of 50% [30].

$W(t)'$, the derivative of the tree age t from the Formula (12), representing the carbon release rate of wood products, is expressed as follows:

$$W(t)' = -\beta \times cR \times v_1 \times e^{-v_1(t-T)} - (1 - \beta) \times cR \times v_2 \times e^{-v_2(t-T)} \quad (13)$$

Thus, taking into account the carbon leakage from HWP, the accumulated discounted value of carbon sink in a rotation period can also be expressed as:

$$\sum_{t=1}^T \Delta C_{AR_CHINA,t} \times e^{-rt} = cR \times e^{-rT} - \int_{t=T}^{\infty} (W(t)' \times e^{-rt}) dt \quad (14)$$

Substituting Formula (13) into Formula (14) and solving it, we obtain:

$$\sum_{t=1}^T \Delta C_{AR_CHINA,t} \times e^{-rt} = \left[1 - \frac{v_1 \beta}{v_1 + r} - \frac{v_2 (1 - \beta)}{v_2 + r} \right] \times cR \times e^{-rT} \quad (15)$$

According to Formula (11), taking into account the carbon leakage from HWP, the accumulated discounted value of carbon sinks in a rotation period also can be expressed as:

$$\sum_{t=1}^T \Delta C_{AR_CHINA,t} \times e^{-rt} = a \times cR \times e^{-rT} \quad (16)$$

Thus, according to Formulas (15) and (16), the proportion of carbon sink in the HWP for a long time (a) is:

$$a = 1 - \frac{v_1 \beta}{v_1 + r} - \frac{v_2(1 - \beta)}{v_2 + r} \quad (17)$$

2.1.3. Land Opportunity Cost Accounting Model

The land implementing the carbon sink afforestation project must meet the requirements for land eligibility stipulated in the “Methodologies for A/R CCER project activities (AR-CM-001-V01)” [41]. In particular, the land must have been forest-free from 2005 to the implementation of the proposed project. In addition to the implementation of carbon sink afforestation projects, economic forests (oil tea, fruit industry, Chinese medicinal materials, etc.), animal husbandry industries (pigs, chickens, ducks, cattle, sheep, etc.), conventional timber forests (wet pine, fir, bamboo forest) can be developed on the barren mountain and wasteland suitable for forest. Because of these alternative uses, the above forestry development scenario has an opportunity cost associated with implementing the carbon sequestration afforestation project.

Referring to the existing research [18,27], this paper mainly uses the bottom-up model to measure land opportunity cost by using woodland rent index. This is mainly because, according to article 4 of China’s land law, woodland in China cannot be sold and the use of forest land can be changed at will. In addition, with the reform of collective forest tenure, forest land can be leased, and the rental price has gradually formed. Thus, the annual rent index of forest land reflecting the income of other uses of forest land, can be used to measure the opportunity cost of carbon sink afforestation project implementation. The model is as follows:

$$A = \sum_{t=1}^{\infty} \frac{a_t}{(1+r)^{(t-1)}} = a_t/r \quad (18)$$

In Formula (18), A is the net present value of land rents in unlimited period; a_t refers to land rents per year, this paper assumed that the level of land rent per year remains unchanged; r is the discount rate.

2.1.4. Carbon Sink Cost Measurement Model

Whether or not the forest land in a region is used for a carbon sequestration afforestation project, the woodland net present value under the implementation scenario of an afforestation carbon sequestration project needs to be compared with the value of land opportunity cost. The carbon sink afforestation projects will only be implemented when the NPV^{∞} is greater than or equal to A . Thus, when $NPV^{\infty} = A$, carbon sink afforestation projects are implemented and the implicit function with the lowest costs of carbon sequestration can be deduced. The measurement model is as follows:

$$P_c = \frac{A(1 - e^{-rT}) - [P \times Q(t) \times N_{TREE_TROI,t} \times \delta \times e^{-rT} - \sum_{t=1}^T (C_{wt} + C_{ct}) \times e^{-rt}]}{\sum_{t=1}^T (\Delta C_{TREE_PROJ,i} \times e^{-rt}) - (1 - a) \times cR \times e^{-rT}} \quad (19)$$

In Formula (19), P_c is the carbon sequestration costs for the afforestation project (Yuan/tCO₂e); A is the land opportunity cost for the implementation of carbon sequestration project.

From an economic perspective, carbon sink afforestation projects generally only occur in the conditions where the carbon market price exceeds the project cost P_c . According to Formula (19), it can be known that the analytical expression of carbon sequestration costs can be written as an implicit

function of multiple parameter variables. Thus, policies to promote the implementation of carbon sink afforestation projects should be formulated based on specific carbon trading conditions, the forestry industry environment, and specific project characteristics.

2.2. Data Sources

2.2.1. Afforestation Cost

Here, a *P. elliottii* carbon sink afforestation project in Jiangxi province of China was used as a case study (<http://cdm.ccchina.org.cn/archiver/cdmcn/UpFile/Files/Default/20141118094528711855.pdf>). The start year of afforestation project is 2009, and the planting density of *P. elliottii* is 1800 plants individual/(hm)². The project area covers 13 counties and cities in Jiangxi province, with a total area of 17,257.2 (hm)², and the accounting period of the project is 20 years. *P. elliottii* is a common tree species in southern collective forest area of China. The project in Jiangxi province is an earlier carbon sequestration afforestation project of the China GHG Voluntary Emission Reduction Program, which has been registered in the National Development and Reform Commission (NDRC). In addition, the CCERs of this project have been issued in 2016. Therefore, this case study is both typical enough to be representative, has accessible data for the analysis.

The research team conducted a field face to face survey on the afforestation enterprise of this project in August 2019 in order to obtain the relevant cost data per unit area (per (hm)²) of *P. elliottii* (Table 1). We asked the management personnel of afforestation carbon sequestration project in detail and collected the costs of *P. elliottii* afforestation project. In addition, to ensure the accuracy and validity of the research data, we also collected the afforestation design of this project through local forestry departments and asked about the development of the forest land leasing market in the project implementation area.

Table 1. The costs of the *P. elliottii* afforestation project for carbon sink per unit area (hm)².

Item	Unit	Quantity	Unit Price/Yuan	Total Amount/Yuan
Afforestation spending				
Qingshan employment ⁽¹⁾	Day/(hm) ²	22.5	140	3150
Land preparation employment ⁽²⁾	Day/(hm) ²	18	140	2520
Planting employment ⁽³⁾	Day/(hm) ²	12	140	1680
Expanding the hole and cultivating the stump employment ⁽⁴⁾	Day/(hm) ²	7.5	140	1050
Seedling costs	Plants/(hm) ²	1800	0.4	720
Total expenditure on tending in the first three years (5 times in total)				
Remove miscellaneous employment ⁽⁵⁾	Day/(hm) ²	75	140	10,500
Fertilization employment	Day/(hm) ²	30	140	4200
Intermediate cuttings employment	Day/(hm) ²	22.5	140	3150
Fertilizer costs	kg/(hm) ²	1650	3	4950
Annual investment in fire prevention, disease prevention and theft prevention of forestry	Yuan/(hm) ²	1	1500	1500
Investment in afforestation infrastructure construction	Yuan/(hm) ²	1	1500	1500
Timber harvesting and transportation costs	m ³	—	170	—

Notes: ⁽¹⁾ Qingshan means to cut down all weeds, trees and shrubs (except for the protected tree species stipulated by the state). ⁽²⁾ Land preparation is mainly to dig holes. The standard of digging holes for *Pinus elliottii* is 40 cm × 40 cm × 30 cm, that is, 40 cm square and 30 cm deep. ⁽³⁾ Planting mainly refers to transporting seedlings to forestland and planting in time. ⁽⁴⁾ Expanding the hole and cultivating the stump refers to the removal of weeds and miscellaneous irrigation within 1 m range centered on the seedlings, and then the topsoil is dug to the edge of the planted trees, crushed, cultivated into steamed bread shape, and the shape of water storage ditch is excavated above to prevent the loss of water and fertilizer. ⁽⁵⁾ Remove miscellaneous refers to the removal of all shrubs and weeds on the forest land in the tending stage.

2.2.2. Land Rent

Forest land rent varies according to the condition of the site. Generally, if forest land is suitable for intensive forestry activities, such as economic forests, animal husbandry, the annual land rent is generally higher, at 750–1200 yuan/(hm)². If the land is suitable for the development of other conventional timber forest, the annual rent of the land is generally low, at 150–450 yuan/(hm)². Considering that the forest land conditions in the project implementation area are relatively good and the definition of opportunity cost, the average woodland rents of 975 yuan/(hm)² is used to characterize the land opportunity cost of carbon sink afforestation project implementation.

2.2.3. Carbon Sequestration Transaction Cost

Regarding carbon sink transaction costs, the Williamson transaction cost classification was used. The carbon sinks transaction costs was divided and measured based on various costs incurred in the implementation process of afforestation project [20–22]. Specifically, following the implementation procedure of the CDM-AR projects, the transaction cost are subdivided into pre-implementation cost (costs incurred during project development, project design documents (PDD), host country approval and project effectiveness assessments), implementation cost (costs incurred due to project monitoring, emission reduction certification and other procedures), trade costs (costs incurred in the registration of the executive committee, broker matching and other procedures), and other transaction costs (such as adaptive funds, baseline monitoring costs, baseline confirmation costs).

There are notable differences in the specific structure and level of transaction costs at each program stage, notably, the host country approval cost and international trade cost in the early stage will no longer exist in Chinese ETSs. Among the afforestation projects of China GHG Voluntary Emission Reduction Program, the proportion of search costs, baseline monitoring costs and baseline confirmation costs in carbon sink transaction costs is low, and there are large differences between different projects. By contrast, the PDD cost, monitoring cost and certification cost are fixed, and their proportions in carbon sink transaction costs are relatively high. Therefore, the carbon sink transaction costs indicators in this study mostly consist of the one-time development costs and the continuous issuing costs at different stages of project operation, as shown in Table 2. The carbon sink transaction costs per unit area can be obtained by dividing the carbon sink transaction costs of the whole project by the total area of the project.

Table 2. The carbon sink transaction costs of afforestation project for carbon sink.

Cost Structure	Type	Project Preparation Stage		Project Filing Stage		Project Emission Reduction Issuance Phase	
		The Unit Price	Frequency	The Unit Price	Frequency	The Unit Price	Frequency
One-time development cost (10 ⁴ yuan)	Write project design documents (PDD)	10–30 (20)	1	—	—	—	—
	Project approval cost	—	—	10–20 (15)	1	—	—
Continuous issuing cost (10 ⁴ yuan)	Monitoring cost	—	—	—	—	10–20 (15)	3
	Certified cost	—	—	—	—	5–15 (10)	3

Note: The data coming from “Environmental compensation marketization mechanism construction based on forestry carbon sink” provided by Beijing Environmental Exchange; the median value of the corresponding cost in parentheses.

3. Results

3.1. The Carbon Sequestration Cost of the *P. elliottii* Afforestation Project in Different Rotation Periods

Using the Formula (19) and the parameter dates in Tables 1 and 2, the carbon sequestration costs of the *P. elliottii* afforestation project can be calculated by simulation under different rotation conditions. In order to explore the impact of timber revenue and its changes on carbon sink costs, this paper also

presents carbon sink costs without considering timber income. The results are shown in Figure 1, which shows that:

- (1) During the project operation, as the rotation period increases, the carbon sequestration costs of the *P. elliotii* afforestation project showed a downward trend. When the value of wood is considered, the costs reach the lowest at the best rotation of the 20th year, and the carbon sink costs is 44.2 yuan/tCO₂e. When the value of timber is not considered, the carbon sequestration costs decreased from 825.4 yuan/tCO₂e in the 10th year to 425.4 yuan/tCO₂e in the 20th year, a decrease of 48.4%.
- (2) The effect of wood income on overall carbon sequestration costs is very significant. To be specific, carbon sequestration costs were 44.2 tCO₂e in the 20th year when the timber benefits are considered, while the costs was as high as 425.4 yuan/tCO₂e when the timber benefits is not considered, which is 8.62 times higher than the former. This demonstrates the substantial negative impact of wood income on carbon sequestration costs. This also implies that carbon sink costs may be lower if multiple benefits of the afforestation project are considered.

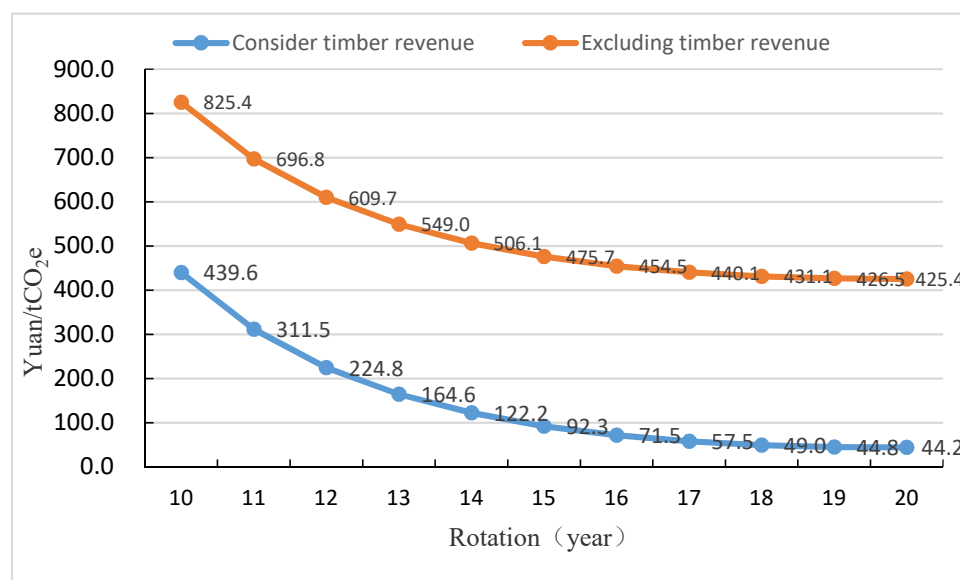


Figure 1. The carbon sink cost under different rotation periods.

3.2. Sensitivity Analysis of Carbon Sink Costs under Different Conditions

The environmental variable parameters of the carbon trading market may change significantly in the future, with the acceleration of China's carbon market construction. At the same time, there are some differences in the forestry production environment between different regions; even in the same region, the differences in forestry production environment at different times are more obvious. Thus, policymakers are primarily concerned about how optimal policies should be formulated and adjusted when different technical and economic parameters. Therefore, it is necessary to further explore the impact of changes in exogenous technical and economic parameters, such as labor price, timber price, carbon sink transaction cost, discount rate, on the carbon sequestration costs as modelled.

3.2.1. The Sensitivity of Carbon Sink Costs to Changes of Carbon Sink Transaction Costs

Figure 2 shows the carbon sequestration costs of *P. elliotii* afforestation projects under different carbon sink transaction costs. It can be seen from Figure 2 that with the increase of carbon sink transaction costs, the carbon sink costs will also increase with and without considering the timber benefits scenario. The carbon sequestration costs are positively related to forestry carbon sink transaction costs. Specifically, when the carbon sink transaction costs increase by 50% from the original level, the carbon sequestration costs will rise to 47.7 yuan/tCO₂e (including timber) and 428.9 yuan/tCO₂e (excluding timber), an increase of 7.92% and 0.82%, respectively. When the carbon sink transaction costs drop by 30% from the original level, the carbon sink cost will drop to 42.1 yuan/tCO₂e (including timber) and 423.3 Yuan tCO₂e (excluding timber), a decrease of 4.75% and 0.49%, respectively. This shows that the carbon sink transaction costs have a weak impact on the carbon sequestration costs.

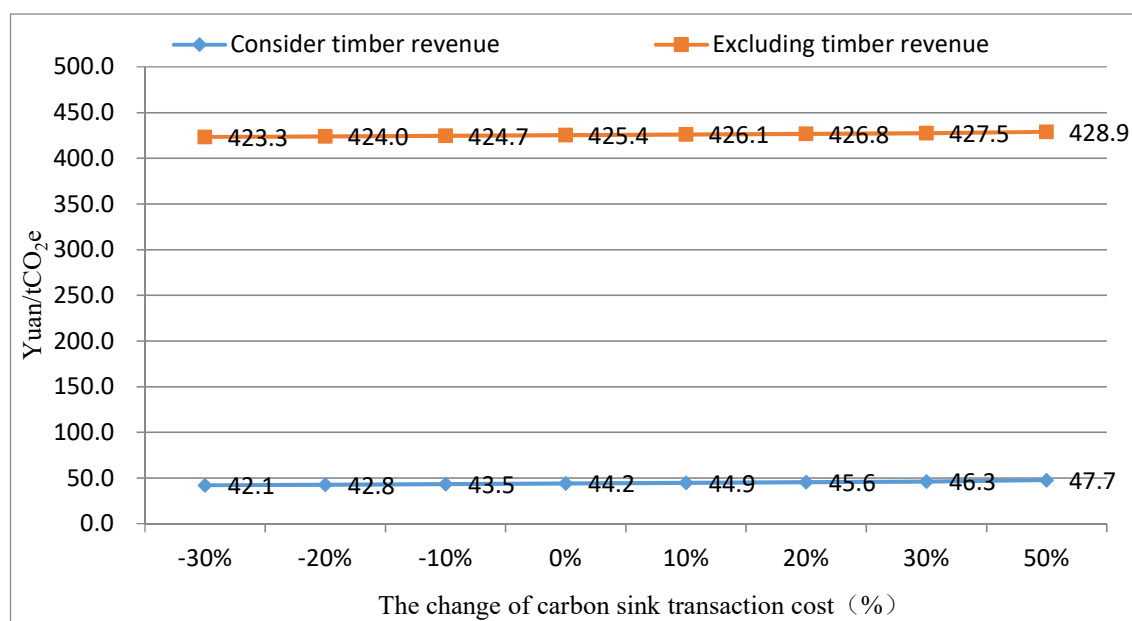


Figure 2. The carbon sink cost under different carbon sequestration transaction costs.

3.2.2. The Sensitivity of Carbon Sink Costs to Changes of Labor Prices

Figure 3 shows the changes in carbon sequestration costs of *P. elliotii* afforestation project under different labor price conditions. It can be seen from Figure 3 that with the increase of labor prices, carbon sequestration costs will increase with and without considering the benefits of wood. The carbon sequestration costs and labor prices are significantly positively correlated. Specifically, when labor prices rose 50% from the original level, the carbon costs will be rise to 154.8 yuan/tCO₂e (including timber) and 536.0 yuan/tCO₂e (excluding timber), an increase of 250.0% and 26.0%, respectively. When the labor price fell 30% form original levels, carbon sink costs will be drop to −22.1 yuan/tCO₂e (including timber) and 359.1 yuan/tCO₂e (excluding timber), a decrease of 150.0% and 15.6%, respectively. Subsequently, afforestation activities will definitely be implemented from the perspective of economics when the labor price falls and the value of wood is considered. However, the value of China's labor force is continuing to rise.

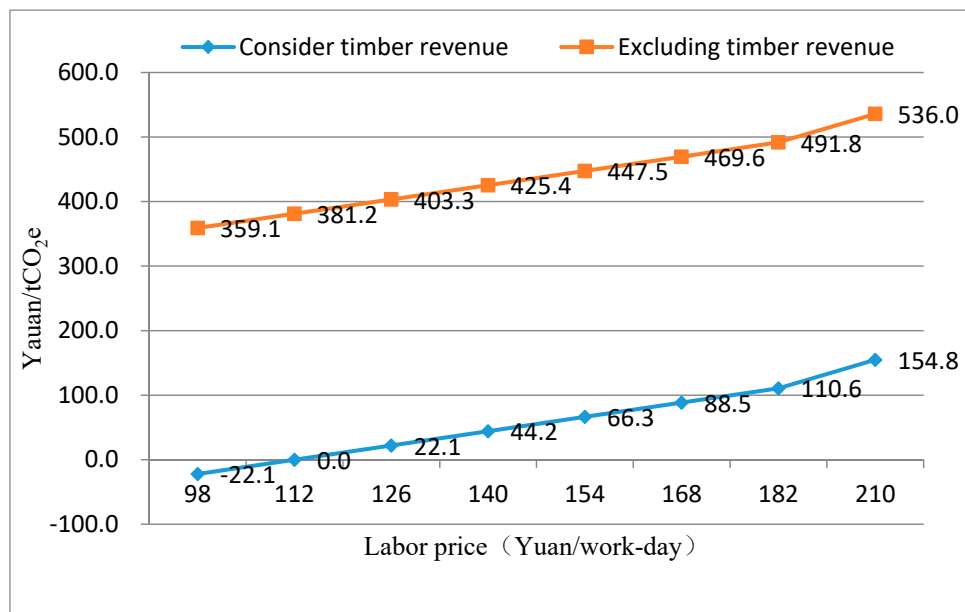


Figure 3. The carbon sink cost under different labor prices.

3.2.3. The Sensitivity of Carbon Sink Costs to Changes of Discount Rates

This section conducts a sensitivity analysis on the impact of changes in discount rates on the carbon sequestration costs of *P. elliotii* afforestation projects, as shown in Figure 4. It can be seen from Figure 4 that as the discount rate rises, carbon sequestration costs will increase. The carbon sequestration costs and the discount rate show a significant positive correlation. Specifically, when the discount rate increases from 5% to 10%, the carbon sequestration costs will increase from the original level to 559.8 yuan/tCO₂e (including timber) and 904.9 yuan/tCO₂e (excluding timber), increasing by 1165.9% and 112.7% respectively. However, when the discount rate is reduced from 5% to 3%, the carbon sequestration costs will be reduced from the original level to −92.7 Yuan/tCO₂e (including timber) and 325.5 yuan/tCO₂e (excluding timber), decreasing by 309.5% and 23.5% respectively. This result shows that afforestation is economically feasible when the discount rate is low.

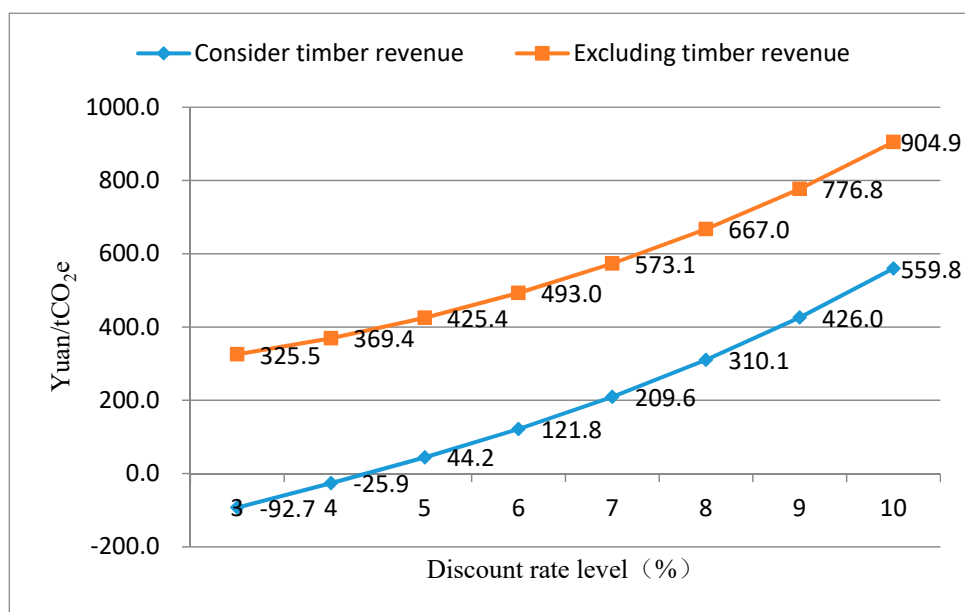


Figure 4. The carbon sequestration cost under different discount rate.

3.2.4. The Sensitivity of Carbon Sink Costs to Changes of Timber Prices

The benefits of wood have a significant impact on the carbon sink costs. This section further will explore the sensitivity of the carbon sink costs to the changes in wood price when the timber benefits is to be considered. Figure 5 shows the carbon sequestration costs under different timber prices, highlighting that as timber price rises, carbon sequestration costs will decrease accordingly. The carbon sequestration costs and timber prices will show a significant negative correlation. Specifically, when the timber price increases by 50%, carbon sink costs will be dropped to -194.0 yuan/tCO₂e, a fall of 538.7%. The results show that ordinary forestation is economically viable when timber prices are high. This also shows that higher timber prices have a positive incentive effect on afforestation activities. This implies that if the comprehensive benefits of carbon sink afforestation projects are fully considered, the carbon sink costs may be significantly reduced.

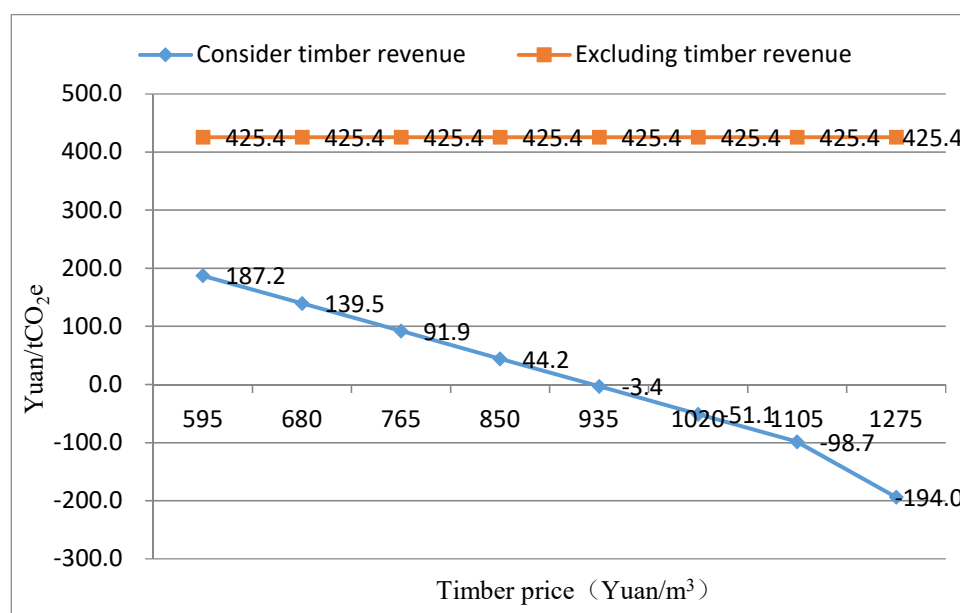


Figure 5. The carbon sequestration cost under different wood prices.

4. Discussion

The results of the carbon sink costs in this study are within the range (3~280 \$/t) of global forest carbon sink costs [43]. This shows that the research results are reasonable and reliable. The cost (44.2 Yuan/tCO₂e) of this study when considering the benefits of wood is higher than the carbon sink cost of *P. elliptica* of 21.86 yuan/tCO₂e in Zhejiang province [18]. This is mainly because the carbon sink costs are not only affected by immediate factors such as tree species growth model, timber income, afforestation cost etc. but also by market factors such as labor price. Due to the underestimation of labor prices in Zhejiang province, the carbon sinks cost of *P. elliptica* is relatively low. Meanwhile, the higher carbon sink cost of the afforestation project in Jiangxi province is also due to the significant inputs (see Table 1) to meet its strict technical requirements on afforestation, forest management and reducing carbon leakage. However, the cost is lower than both China's average carbon sink cost of 1152.8 yuan/tCO₂e and the average carbon sink cost of Jiangxi province of 793.1 yuan/tCO₂e [44]. This is mainly because using agricultural output value as the opportunity cost of forest land utilization may lead to a higher opportunity cost of forest land and then the higher carbon sink costs. However, this is an unrealistic opportunity cost as the use of forest land in China cannot be changed. Therefore, the findings presented here are a more accurate estimate of the true costs experienced by CDM-AR and CCER-AR projects.

Under the current market and technical conditions, the carbon sink costs of the afforestation project is high, and obviously even exceeds the average price of the carbon sink. According to the

actual situation of the nine pilot ETSs in China, the current price of forestry carbon sinks in China is between 14~90 Yuan/tCO₂e [18,45,46]. Although there is a possibility for project owners to engage in afforestation projects for carbon sequestration, project owner may still choose to maintain the original non-carbon sequestration production, because the average carbon price (20 yuan/tCO₂e) is lower than the carbon sequestration costs of *P. elliotii* afforestation projects [46]. This shows that China's ETSs cannot effectively promote the implementation of carbon sink afforestation projects. Therefore, from the perspective of promoting the development of afforestation projects, there is still room for further improvement of China's pilot ETSs in the future. Furthermore, this study only considers that one-time development costs and continuous issuing costs are captured. However, forestry carbon transaction costs also include the costs of information for buyers and sellers of forest carbon sinks, and the determination of the buyer and seller costs of transaction contracts, risk management costs, etc., [20–22]. Considering the above costs, the carbon sink costs will be significantly increased, which will have an adverse impact on the implementation of carbon sinks afforestation projects, and is not conducive to the role of forestry in combating climate change.

The limitations of this study are mainly reflected in the case study. But it is worth noting that, this does not affect the overall reliability of the research results. Although China has had nine pilot ETSs since 2011 and a nationwide unified carbon market was established in 2017, the development of forestry carbon sink projects is relatively lagging. Therefore, a large sample survey is not feasible. However, this does not affect the reliability of this study. First, *P. elliotii* is a common tree species in the southern collective forest area of China. The *P. elliotii* carbon sink afforestation project in Jiangxi province is an earlier project belonging to the China GHG Voluntary Emission Reduction Program. The CCERs of this project have been issued in 2016 year and, therefore, this case study is representative. Second, the variable parameters data of carbon sink transaction costs are mainly selected and determined according to the current average state of the carbon trading market in China. At the same time, the variable parameters of the forestry production environment were mainly determined according to the current average level of the actual investigation in Jiangxi province. This will give the research results certain universal significance. Finally, based on typical cases and the reliable survey data, this study not only explores carbon sink costs under current market and technical conditions, but also further explores the sensitivity of carbon sink costs under different economic and technological parameters. These findings and the methodologies underpinning them, can therefore provide decision-making references to promote the development of afforestation projects in China, and then to achieve the goal of increasing forest carbon sinks in its unique land-use policy system.

Beyond this case study, more research on the costs and benefits of carbon sinks using different species in different countries is essential to facilitate more effective implementation of carbon sequestration projects. Firstly, the key indicators that affect the cost of sequestration, such as afforestation costs, carbon sink transaction costs, lease cost, and land-use opportunity costs, have been considered in this study. However, there are still many factors that affect carbon sink costs, such as site conditions, stand structure, operating methods, related policy factors, landowner's wishes, etc., [35,46]. Thus, considering the difference of the above factors of different tree species in different areas, the carbon sink costs still need further study. Secondly, this study considered only the marketable benefits of the project, such as the value of timber and carbon sink but excluded positive externalities [47,48]. For example, the value of ecological and environmental functions produced by forest ecosystems, such as pollination services to high-value pollinated crops, many of which are grown in abundance in China [49,50]. Further research is needed in the future to address the question: how do we choose scientific methods to quantify the benefits of other ecological services and incorporate them into the model for measuring the forestry carbon sink costs? Meanwhile, other market products can also be incorporated. For example, the project owner in this study also collected turpentine from middle-aged *P. elliotii* forests. This will indirectly reduce the net cost of carbon sinks. Therefore, future research on the multiple benefits of carbon sink projects still needs to be strengthened. Thirdly, the timber output rate (δ), wood density (D), biomass expansion factor (BEF) and above-ground biomass ratio (R) are

assumed to be constant in this study. With the cutting and renewal of wood, the above parameters may change infinitely due to changes in land productivity. However, the related basic research is still relatively limited. Therefore, future research still needs to be further strengthened to address the question: how do we quantify the changes of the above factors over time and incorporate them into the model for measuring carbon sink costs? Last, but not least, the forest project implemented with critical economic conditions indicates that carbon sequestration program in Jiangxi province was a one-time event that occurred in a certain year (2009). It is possible that the program would be a procedure that took a longer time, producing a distribution of stand ages and corresponding flows of expenses and revenues. Such a longer-term AR program possibly would create an economic system that might differ from the single stand discussed in the paper. However, this paper does not discuss the carbon sequestration costs in the case of multi-year afforestation, which is also an issue to be further studied in the future.

5. Conclusions

This study demonstrates that the carbon sequestration costs of *P. elliottii* afforestation projects are generally high and that the effect of the benefits of wood on carbon sequestration costs are extremely significant. Without considering the benefits of wood, the carbon sequestration costs are 8.62 times higher than the scenarios where wood benefits are considered. This shows that failing to consider the multiple benefits of afforestation activities can greatly over-estimate carbon sink costs. However, the carbon sequestration costs are higher than the current average price of 20 Yuan/tCO₂e, indicating that the high carbon sequestration costs remains an important factor restricting the development of afforestation project. Secondly, forestry carbon sink transaction costs have a positive impact on carbon sequestration costs for *P. elliottii* afforestation projects. With the increase of forestry carbon sink transaction costs, the costs will also increase. Thirdly, the timber prices have a significant negative impact on the carbon sequestration costs, while the increasing labor price and discount rate will cause costs to rise substantially. In the context of the rise of the above factors, the implementation of the carbon sequestration afforestation project is not economically feasible.

Based on the above analysis results, to reduce carbon sequestration costs and achieve the full potential of forestry in combating climate change, the study holds that: firstly, relevant departments should take measures to reduce forestry carbon sink transaction costs. Secondly, it is necessary for governments to establish and improve the forestry carbon sink compensation mechanism in the future. While China has established ETSs that include forestry activities, the carbon gains provided by the ETSs cannot effectively cover the carbon sink costs in many regions or scenarios. Furthermore, labor prices and discount rate, carbon sequestration cost for afforestation project are likely to continue rising leading to the real risk of carbon sink afforestation projects being abandoned. Therefore, it is necessary to continue to establish and improve the forestry carbon sink compensation mechanism in the future [46,51]. Thirdly, the government should also encourage wood processing companies to make technological innovations to produce and sell durable wood products. On the one hand, the carbon release rate of durable HWP is relatively slow. On the other hand, the processing and utilization of durable HWP can also replace energy-intensive materials, such as steel and cement, to produce alternative emission reduction effects [8,37,52]. This not only plays a very important role in the global carbon balance, but also reduces the carbon sink costs of the afforestation projects. Therefore, wood-processing companies should also be encouraged to carry out technological innovations to produce and sell durable wood products in the future. Finally, projects can explore multiple operating models of carbon sink forests, including market and non-market benefits, to increase their revenue. This would reduce the net costs of carbon sinks to a certain extent, which is one of the reasons that the afforestation project of Jiangxi province can be launched earlier in China.

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