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Improving Carbon Sequestration Capacity of Forest Vegetation in China: Afforestation or Forest Management?

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Abstract: Both forest management—especially forest tending—and afforestation help to enhance the carbon sequestration of forest vegetation. However, with limited resources, appropriate measures need to be selected to increase the vegetation carbon sinks based on regional endowments. This study aimed to assess the differences in the effects and costs of afforestation and forest tending on vegetation carbon sequestration and to help select suitable afforestation and forest tending areas. In this paper, we used panel fixed effects models to analyze the effects of afforestation and forest tending on vegetation carbon sequestration and conducted a regional heterogeneity analysis to identify suitable afforestation and tending areas. Our results show that the vegetation carbon sequestration capacity of forest tending is 4.48 times higher than that of afforestation, and there is obvious spatial heterogeneity in the effects of afforestation and forest tending on vegetation carbon sequestration. Specifically, the marginal contribution of afforestation is higher than that of tending in northwest and southwest China, whereas the marginal contribution of tending is greater in other regions. Additionally, the afforestation cost for vegetation carbon sequestration is 44.44 times higher than that of tending. Therefore, the management of existing forests must be enhanced, especially in northeastern, southern, and northern China. Similar to the northwest and southwest regions of China, there is still a need to emphasize the use of suitable space for afforestation.

Keywords: plantation; forest tending; carbon stock; effectiveness; spatial targeting

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1. Introduction

Human-induced climate change has caused widespread adverse impacts on nature and people, beyond natural climate variability [1], and this global warming is driven by excessive greenhouse gas emissions—primarily carbon dioxide (CO_2) [2]. It is well established that climate change trends and related risks depend heavily on mitigation and adaptation actions. Therefore, global warming should be limited to 1.5 °C to achieve a fair and sustainable world [1]. In other words, the amount of CO_2 in the atmosphere must be controlled by reducing emissions and increasing carbon stocks. As the largest carbon pool in terrestrial ecosystems, forests are one of the direct and effective carbon sinks (refers to CO_2) [3], as well as a cost-effective and Nature-based Solution (NbS) for climate change mitigation [4]. Greenhouse gas emissions can be limited by preventing deforestation and forest degradation and sequestering carbon from the atmosphere via afforestation and forest management. Therefore, it is crucial to assess the capacity and cost of carbon sequestration in forest vegetation (this article mainly refers to the above-ground part) for different forest programs while protecting existing forests from destruction.

Afforestation increases regional vegetation carbon sequestration capacity by changing land-use types, and increasing forest vegetation cover and carbon accumulation in terrestrial biomass [5]. However, afforestation space is limited by land resources [6], and there are trade-offs between afforestation and food production [7]. Therefore, the scalability of such a method to achieve long-term global warming limitation goals has been questioned [8].

To increase carbon stocks, improved management of existing forests is required to achieve higher carbon intensity [9].

Forest management can promote forest growth, improve forest quality, and increase forest carbon stock [10,11]. It is mainly used to adjust forest structure, optimize forest density, and improve ventilation and light conditions in forests by promoting tending cutting, regeneration, and other activities. Forest management, such as tending, has reduced the need for land space and has great potential for vegetation carbon sequestration; however, the work is time-consuming, and obvious results are not apparent in the short term. Therefore, afforestation is preferred in practice, since government officials are more interested in what they can achieve over the next few years rather than in the long term [12,13].

Nature-based Solution (NbS), especially forest-based programs, are more cost-effective than alternative CO_2 removal technologies [2,14]. Considerable research has been conducted on the assessment of carbon sequestration costs in forests. It considers the opportunity cost of land, upfront treatment costs, and future benefits including carbon sequestration values [15]. However, the vegetation carbon sequestration levels change during different periods of forest growth. Considering that the total expenditure alone cannot identify the vegetation carbon sequestration effect of forest inputs at different stages, which is not conducive to the selection of afforestation and forest management, there is hence a need to compare the effectiveness between afforestation and forest management.

China has made great strides in afforestation and has achieved remarkable success in area expansion, but the forest quality is disappointing [16]. With a forest coverage rate of 23.04%, China has the largest increase in forest resources worldwide [17]. However, the space suitable for afforestation is presently declining, and the natural conditions in these areas are worsening, making afforestation more difficult and costly. Moreover, China's forest quality and productivity lag largely behind both international levels and its land potential [16], with arbor volume per hectare (ha) accounting for only 84% of the world average [18]. This is mainly due to the long-term neglect of forest management, especially forest tending [11,18]. Thus, based on China's reality, evaluating the effectiveness of its forest measures, including afforestation and forest tending, can help transform its practices to increase vegetation carbon sequestration and provide references for other countries.

Effectiveness refers to the degree of environmental or service changes caused by ecological compensation projects with limited funds and includes environmental effectiveness and cost-effectiveness. We thus compared the effects and costs of afforestation and forest tending on vegetation carbon sequestration. In addition, government financial investment is the main source of funding for ecological forestry construction in China. Such government-led ecological compensation programs are likely to face limited budgets. It is important to select target areas to allocate funds most effectively. Therefore, we further analyzed the spatial differences in the vegetation carbon sequestration effects and costs of different forest measures to help achieve an efficient allocation of resources. Finally, the forest growth cycle is long, and there may be a lagged effect on previous inputs. We also analyzed the lagged effects of different forest measures on vegetation carbon sequestration.

Using econometric models, this study aims to answer the following questions: (1) From the perspective of environmental effectiveness, which measure has greater vegetation carbon sequestration capacity, afforestation or forest tending? (2) From the cost-effectiveness perspective, which measure has the most advantages? (3) Are there regional differences in the effects of the two measures on vegetation carbon sequestration? In other words, which regions are more suitable for afforestation, and which regions are more suitable for forest tending? With answers to these questions, we hope to select more appropriate forest measures for different regions of China to achieve optimal resource allocation and provide a reference for other countries with similar realities to help achieve sustainable forest development.

2. Materials and Methods

2.1. Study Area

This study selected 30 provinces (autonomous regions and municipalities directly under the Central Government, hereinafter collectively referred to as provinces) in China from 2000 to 2019 as the research units. Due to the lack of data on Tibet, Hong Kong, Macau, and Taiwan, these provinces were not considered. China is a vast country with large differences in natural conditions and economic development levels between regions, and dividing the 30 provinces into 5 major forestry zones helps to select more suitable measures, afforestation, or forest tending. The northeast forest region (NER) includes Heilongjiang, Jilin, Liaoning, and Inner Mongolia (IM). The southwest forest region (SWR) involves Sichuan and Yunnan. The southern forest region (SR) includes Anhui, Shanghai, Jiangsu, Zhejiang, Jiangxi, Fujian, Hainan, Guangdong, Guangxi, Guizhou, Chongqing, Hubei, and Hunan. The northwest forest region (NWR) includes Shaanxi, Gansu, Qinghai, Xinjiang, and Ningxia. The northern China forest region (NCR) includes Beijing, Tianjin, Shanxi, Henan, Shandong, and Hebei.

2.2. Variable Measures

A panel fixed-effects model was used to assess the effects of afforestation and forest tending on the direct effects of vegetation carbon sequestration. With other variables held constant, afforestation and forest tending were used as independent variables to study their marginal contributions to vegetation carbon sequestration, and spatial heterogeneity analysis was conducted. On this basis, the marginal contributions and financial inputs were used to calculate the vegetation carbon sequestration costs of afforestation and forest tending.

2.2.1. Dependent Variable

On the one hand, the amount and rate of carbon sequestration by forest vegetation (CSF) are higher than those of soil, especially in the early stage of afforestation [4], and the carbon storage changes in soil after afforestation are more complicated [19]. On the other hand, compared to data from the National Forest Resources Inventory, satellite remote sensing data can reflect forest changes in China in a more timely and continuous manner. Therefore, we selected the carbon sequestration of forest vegetation (CSF) as the dependent variable, calculated by net primary productivity (*NPP*). The specific calculation is shown in Section 2.3.1.

2.2.2. Independent Variables

This study mainly focuses on the effects and costs of vegetation carbon sequestration by two forest measures—afforestation and forest tending. Therefore, we selected afforestation and forest tending as independent variables that can directly increase forest resources.

Afforestation was measured by cumulative afforestation area and adjusted by the survival rate. The carbon sequestration capacity of new plants is closely related to their survival rate, with the potential for biological sequestration decreasing by 48% compared to the non-survival rate when the survival rate is considered [20]. Since it is difficult to obtain more accurate survival data on afforestation in each province of China, we used the average value of the afforestation qualified rate in some years as a proxy for the survival rate in each province. The qualified rate refers to the percentage of the qualified areas meeting the technical standards in the total afforestation area after one year.

Forest tending refers to the general term for various forest measures taken from a closed young forest to a mature forest, which is mainly applicable to young- and middle-aged forests. Thus, young- and middle-aged forest tending areas were used to indicate the forest tending.

2.2.3. Control Variables

In terms of input elements, the "number of forestry employees at the end of the year" was selected as a measure of the forestry labor; forestry capital was measured by the cumulative value of "completed investment in forestry fixed assets." Specifically, the investment amount was adjusted by using the fixed asset investment price index of the base year (2000) as the deflator. Then, we used the perpetual inventory method to estimate the capital stock and obtained the capital depreciation rate data of each province based on the research results [21].

For socio-economic factors, we selected gross domestic product (*GDP*) and regional population as the variables. Following the environmental Kuznets curve, there may be a non-linear relationship between *GDP* and forest vegetation cover [22], so we added the squared term of *GDP* to the model. The increase in population is detrimental to the conservation and accumulation of forest resources. On the one hand, it may lead to a greater demand for forest products. On the other hand, resource constraints exist within a specific spatial range, which inevitably leads to resource competition [11].

Regarding natural factors, average annual precipitation and temperature were selected as control factors. The physiological process of CO_2 uptake by vegetation through photosynthesis must be carried out at a suitable temperature. Therefore, the temperature may have an impact on the amount of *CSF* [23]. Similarly, precipitation also affects vegetation growth, and an appropriate amount of water can increase the survival and growth of vegetation [24]. In addition, the quantity and quality of forest resources are influenced by the conditions of the previous forest [25]. Therefore, we selected *CSF* with a one-period lag to estimate this influence. Descriptive statistics of the variables are presented in Table 1.

Table 1. Descriptive statistics.

Variable Code	Variable Name	Unit	Mean	S.D
CSF	Carbon sequestration of forest vegetation	Tg C	186.49	212.94
affor	Afforestation	10^4 ha	275.75	230.74
tend	Forest tending	10^4 ha	22.39	20.84
labor	Forestry labor	10^4 person	4.43	6.12
fixin	Forestry fixed asset investment	10^8 USD ‡	19.28	38.07
GDP	Gross domestic product	10^9 USD	60.10	33.12
popu	Regional population	10^4 person	4431.83	2708.51
temp	Average annual temperature	°C	12.91	6.04
prec	Average annual precipitation	mm	935.63	518.59

‡ The USD and CNY conversion rate in this study is as of 17 May 2023, and more specifically, CNY/USD = 0.14.

2.3. Methods

2.3.1. Calculation of Carbon Sequestration by Forest Vegetation

Vegetation in the ecosystem absorbs CO_2 from the air, produces organic matter such as glucose, and releases oxygen through photosynthesis. The chemical equation is as follows: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$, which means that 1.62 g of CO_2 could be fixed for each gram of dry matter formed by the vegetation. The *NPP* of vegetation represents the dry organic matter produced by green plants per unit area after deducting the autotrophic respiration. In addition, the carbon content of dry matter accounts for approximately 45% of the total *NPP*. Therefore, the following equation determines vegetation carbon sequestration [26]:

$$CS = (NPP/0.45) \times 1.62, \quad (1)$$

where *CS* represents the amount of carbon sequestered by vegetation (g C/m^2), and *NPP* is the amount of carbon in the dry matter of vegetation (g C/m^2).

To obtain the vegetation carbon sequestration of forests, we extracted forest land data from Chinese land use data. We then obtained the *NPP* in forestland using the raster calculation function in ArcGIS. Finally, based on the area of forestland, we determined the total carbon sequestration by forest vegetation.

$$CSF = (CS \times S)/10^{12}, \quad (2)$$

where *CSF* represents the amount of carbon sequestration by forest vegetation (Tg C/m^2, 1 Tg = 10^{12} g) and *S* is the area of forest land (m^2).

2.3.2. Panel Fixed Effects Model

This study used the panel fixed effects model for two reasons. First, it can partly solve the problem of biased coefficient estimates due to omitted variables and accurately estimate the marginal contribution of afforestation and tending to *CSF*. Second, to ensure the robustness of the estimation results, regional dummy variables can be set to mitigate the inefficiency of estimation due to the subsample regression [27].

$$\begin{aligned} CSF_{it} &= \beta_1 affor_{it} + \beta_2 tend_{it} + \alpha_1 labor_{it} + \alpha_2 fixin_{it} + \alpha_3 GDP_{it} + \alpha_4 {GDP^2}_{it} + \alpha_5 popu_{it} \\ &+ \alpha_6 temp_{it} + \alpha_7 prec_{it} + \alpha_8 CSF\_1_{it-1} + \mu_i + \varepsilon_{it} \end{aligned} \tag{3}$$

In Equation (3), *CSF* is carbon sequestration of forest vegetation, *affor* is afforestation, and *tend* is forest tending. Further, *labor* is forestry labor, *fixin* is forestry fixed asset investment, *GDP* represents the gross domestic product of each province, *popu* indicates the number of people in each province, *temp* is average annual temperature, and *prec* is average annual precipitation. *CSF_1* is *CSF* with a one-period lag. In addition, β is the marginal contribution of forest measures, and α are parameters for variables, i represents the province, t represents the year, μ is the fixed effects, and ε is the error term.

2.3.3. Non-Parametric Kernel Density Estimation

Kernel density estimation is a non-parametric estimation method that uses a kernel function to estimate the probability density function. Although histograms can also estimate the density function, the result is always a discontinuous step function, even for continuous random variables, whereas kernel density estimation yields a smoother density estimate by relaxing the condition. Assume that the probability density function $f(x_0)$ of a continuous random variable x at x_0 with observations of $x_1, x_2, \cdots, x_n$, and the kernel density estimate is:

$$\widehat{f}(x_0) = \frac{1}{nh}\sum_{i=1}^{n} K[(x_i - x_0)/h] \tag{4}$$

where $K(\cdot)$ is the kernel function and h is the bandwidth that determines the smoothness of the estimated density function. The larger the value of h, the smaller the variance of the kernel estimate and the smoother the density function curve. However, if the neighborhood around x_0 is larger, the estimate will be more biased. Thus, when choosing the optimal h, a trade-off between estimator variance and bias must be made to minimize the mean squared error. To obtain an overall measure of the mean squared error for all possible values of x_0, we need to minimize the integrated mean squared error (IMSE). This study used Epanechnikov to minimize the IMSE. We operated in Stata17, which defaults to the optimal bandwidth.

2.3.4. Vegetation Carbon Sequestration Cost Calculation

Detailed data statistics of afforestation and tending funds were only available from 2011 to 2014. The sample size is so small that the estimation results may be unstable if we directly estimate the marginal contribution of afforestation and tending investment to the *CSF*. Therefore, in this study, the vegetation carbon sequestration costs of afforestation and tending were calculated separately based on the relationship between capital investment and vegetation carbon sequestration per unit area, as shown in Equation (5):

$$c_{kj} = I_{kj} / \left(\beta_k \times 10^6\right) \tag{5}$$

where c is the vegetation carbon sequestration cost (USD/t, 1 t = 10^6 g), I is the capital investment per unit area (USD/10^4 ha), and β is the marginal contribution of forest measures to the *CSF* (Equation (3); Tg C/10^4 ha). Here, k represents forest measures and is a binary variable, 1 represents afforestation, 2 represents forest tending, and j is the region.

2.4. Data Collection

The *NPP* data were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) *NPP* product (MOD17A3HGF) (https://lpdaac.usgs.gov/products/mod17a3hgfv006/ (accessed on 5 July 2022)) released by the National Aeronautics and Space Administration (NASA), with a spatial resolution of 500 m. The forest land data were obtained from the annual China land cover dataset produced by Yang and Huang, based on the GEE platform [28], with a spatial resolution of 30 m. Compared with other land use products, its temporal resolution is higher and can be obtained every year of land use change; the data on precipitation and temperature were retrieved from the Resource and Environment Science and Data Centre, Chinese Academy of Sciences (http://www.resdc.cn/ (accessed on 5 July 2022)); the data on afforestation area, forest tending area, forestry labor, forestry fixed asset investment, capital investment of afforestation, and forest tending were obtained from the China Forestry and Grassland Statistical Yearbook. The total afforestation area data and qualified area data were derived from the website of the National Forestry and Grassland Administration (http://www.forestry.gov.cn/ (accessed on 5 July 2022)). The socio-economic data, such as *GDP*, regional population, regional *GDP* index, and fixed asset investment price index, were obtained from the China Statistical Yearbook and the website of the National Bureau of Statistics (http://www.stats.gov.cn/ (accessed on 5 July 2022)).

3. Results

3.1. Spatial and Temporal Evolution of CSF

3.1.1. Temporal Changes

As shown in Figure 1, the *CSF* in China shows a fluctuating upward trend, increasing from 4921.03 Tg C in 2000 to 5821.74 Tg C in 2019, an increase of 18.30%. This is closely related to the successive launch of forestry programs in the new era, especially the Natural Forest Protection Project (NFPP) and the Sloping Land Conversion Program (SLCP), which has undertaken most of the country's forest plantation tasks and achieved remarkable ecological construction results. In addition, the amount of *CSF* in all regions increased to different degrees. Specifically, it increased more than 40% in NWR and NCR, approximately 20% in SWR and SR, and 7.21% in NER. The amount of *CSF* varied among forest regions, with SR consistently ranking first by a wide margin, followed by SWR and SWR in third place, while NWR and NCR were at the bottom of the list.

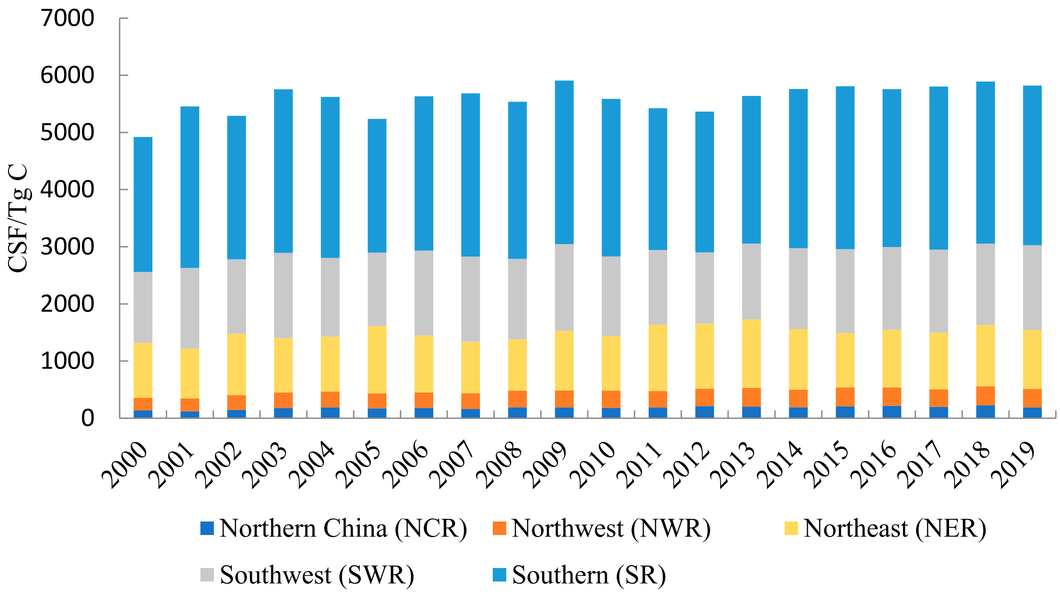

Figure 1. Trends in the amount of carbon sequestration of forest vegetation (*CSF*) in China.

To further explore the temporal evolution of *CSF* in China, 2000, 2005, 2010, 2015, and 2019 were selected for kernel density estimation (see Figure 2).

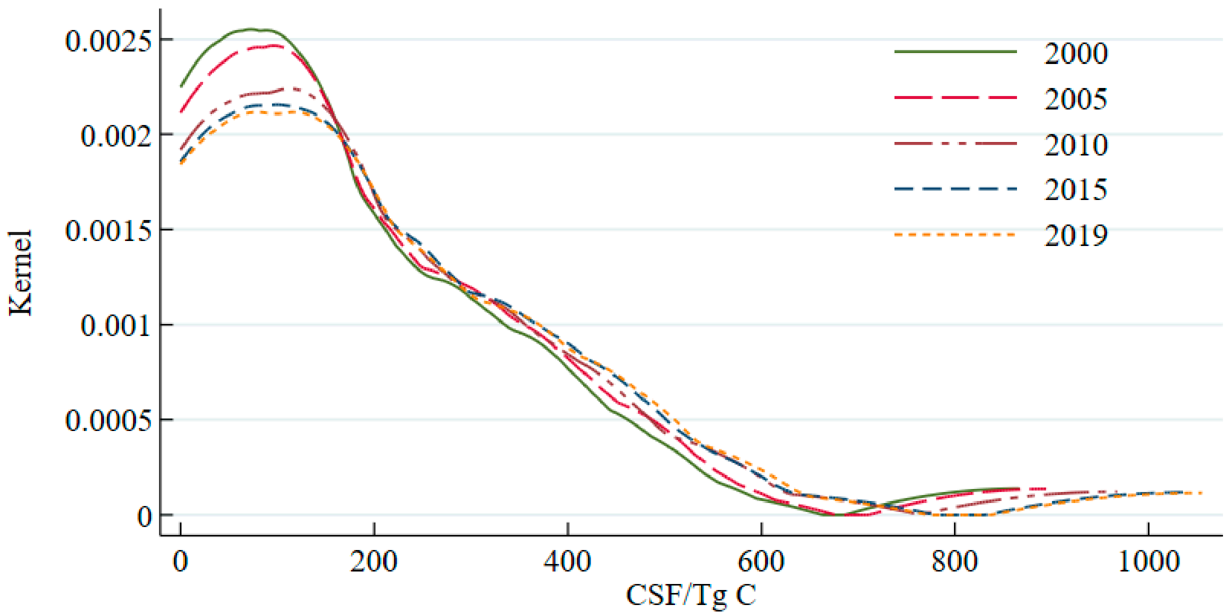

Figure 2. Kernel density estimates of carbon sequestration of forest vegetation (*CSF*) in China.

The density curve of *CSF* in China shows the distribution characteristics of moving from left to right, the peak from high to low, and the right tail elongates yearly (Figure 2). Although the total amount of *CSF* continued to increase over time, the gap in *CSF* between regions also gradually widened, which may be due to the spatial agglomeration of key forestry ecological programs such as the NFPP and SLCP. The implementation of programs led to a continuous increase in the *CSF*, causing its density curve to shift to the right. However, these programs are mainly located in remote mountainous areas, frontier areas, and desertification areas, whereas the *CSF* in developed areas declined due to the dense population. Thus, the spatial differences continue to expand, resulting in a decrease in the peak value of the density curve. It is worth noting that the density curves of the *CSF* in 2015 and 2019 are basically the same, indicating that there is no significant change during this period, which may be caused by the slowdown in the construction of forestry ecological programs.

3.1.2. Spatial Distribution

The natural breakpoint method was used to classify the *CSF* into five adjacent but non-intersecting complete intervals: lower-value area (0, 22.66), low-value area (22.66, 80.81), medium-value area (80.81, 263.56), high-value area (263.56, 482.42), and higher-value area (482.42, $+\infty$), which were visualized using ArcGIS (Figure 3).

As shown in Figure 3, the spatial distribution of the *CSF* is obviously unbalanced, showing a distribution pattern of high in the south and low in the north. Provinces with relatively high *CSF* levels are mainly located in the NER and SWR.

The amount of *CSF* was not large in most provinces in 2000, especially in NWR and NCR. Desertification was more serious in Xinjiang, Qinghai, and Gansu, whereas provinces such as Hebei, Henan, and Shandong were dominated by food production, and municipalities such as Beijing, Shanghai, and Tianjin had small areas, developed economies, and high population density. Consequently, forest cover in these areas was sparse and relatively low, and *CSF* was also low. The high-value areas of *CSF* were mainly found in the SER, NER, and some provinces in the SCR. These areas have a large number of mountain ranges and natural forests and are relatively rich in forest resources. Therefore, vegetation has a clear advantage in terms of its carbon sequestration capacity in general.

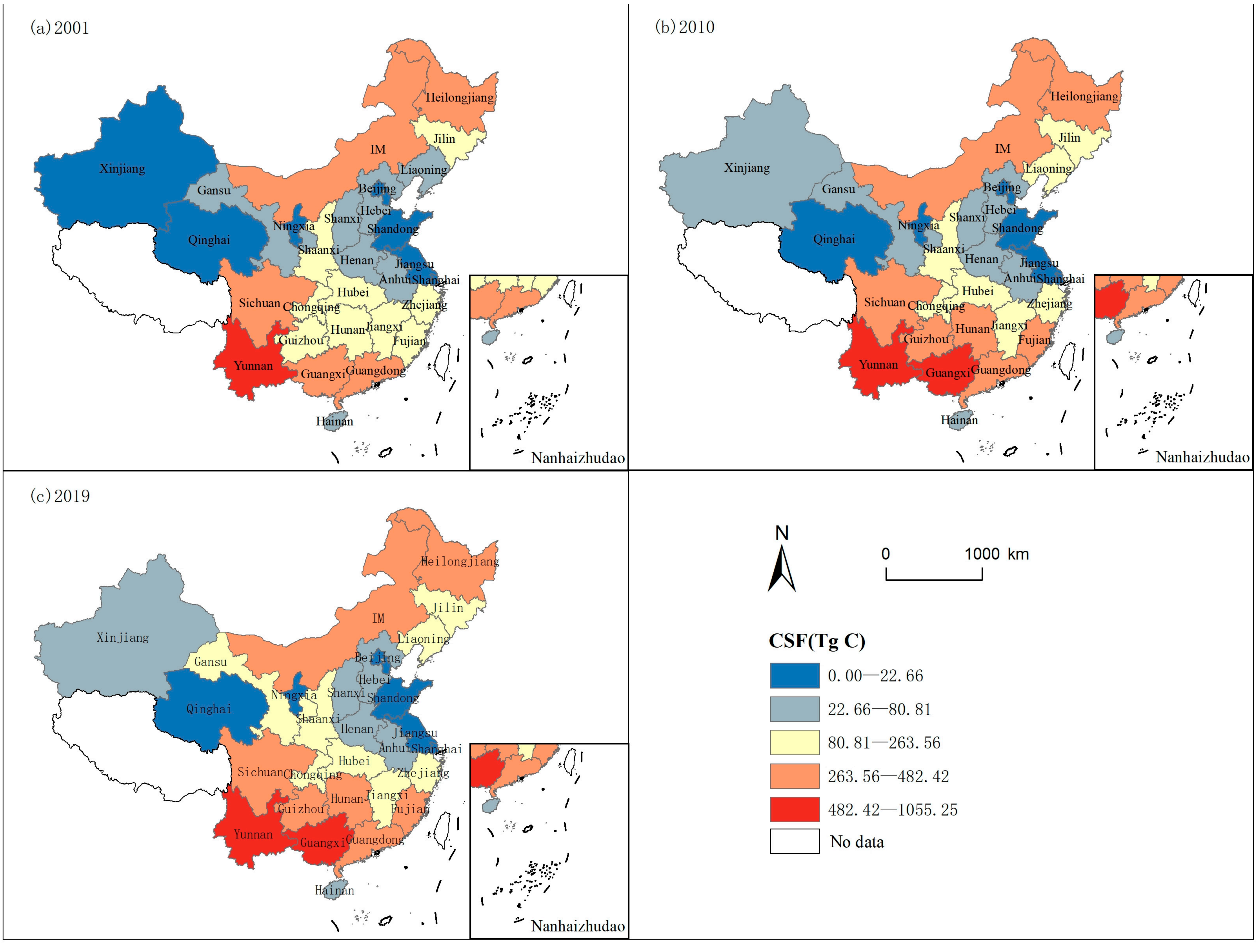

Figure 3. Spatial distribution of carbon sequestration of forest vegetation (*CSF*) in China.

The *CSF* in most regions significantly increased in 2010, owing to the implementation of forestry programs. Specifically, one-third of the provinces in SCR achieved a leap in *CSF*, with Guizhou, Hunan, and Fujian moving from the medium-value zone to the higher-value zone and Guangxi moving from the higher-value zone to the high-value zone. Among the other forest areas, the *CSF* in Xinjiang increased from the low-value zone to the lower-value zone, and Liaoning increased from the lower-value zone to the medium-value zone.

The spatial distribution pattern of *CSF* in 2019 was basically the same as in 2010, with only Gansu's *CSF* rising from the lower- to medium-value areas. At that time, the rhythm of most forestry programs slowed down, and the effect of significantly increasing the *CSF* diminished.

3.2. Effectiveness Analysis of Forest Measures

3.2.1. Direct Effect Estimates

This study used the panel fixed effects model to estimate the direct effect of forest measures on *CSF*, including afforestation and forest tending. In addition, considering the spatial heterogeneity of the *CSF*, we further estimated the marginal contribution of forest measures to the *CSF* in different regions to choose more regionally appropriate forest measures. The results are presented in Table 2.

Table 2. Estimation results of the direct effect of forest measures on vegetation carbon sequestration.

Independent Variable	Model 1		Model 2	
	Coefficient	Standard Error	Coefficient	Standard Error
affor	0.042 ***	0.008		
SR#affor			0.022	0.015
NCR#affor			0.041 ***	0.007
NWR#affor			0.062 ***	0.018
NER#affor			0.056 ***	0.010
SWR#affor			0.076 **	0.035
tend	0.188 *	0.099		
SR#tend			0.253 *	0.139
NCR#tend			0.070 **	0.026
NWR#tend			−0.098 *	0.054
NER# tend			1.327 ***	0.181
SWR# tend			−2.885	1.712
labor	1.064 *	0.615	4.226 ***	0.758
fixin	0.055 ***	0.016	0.059 ***	0.021
GDP	−0.764 **	0.308	−0.404 *	0.223
*GDP*2	0.003 *	0.002	0.001	0.001
popu	−0.001	0.005	0.001	0.004
temp	1.660	1.880	2.010	1.674
prec	−0.003	0.005	−0.005	0.005
*CSF*_1	0.163 ***	0.028	0.099 ***	0.026
cons	149.136 ***	40.173	121.570 ***	32.699

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; the standard errors in the table are robust standard errors.

Table 2 (Model 1) shows the impact of afforestation on the *CSF*. The cumulative afforestation area positively affected *CSF* at the 1% significance level. All other things being equal, if the cumulative afforestation area increased by 10,000 ha, the *CSF* would increase by 0.04 Tg C. Moreover, Table 2 (Model 2) shows that afforestation positively affected *CSF* at the 1% significance level in all regions except for the SR. The marginal contribution of afforestation to *CSF* is higher in NWR and SWR than in SR and NER. Afforestation in China is mainly located on barren, sandy, and fallow lands in the west, where the soil layer is thin, vegetation is scarce, and carbon content is low. In addition, afforestation in these regions could increase the above-ground biomass and thus increase *CSF*.

The impact of forest tending on *CSF* is shown in Table 2 (Model 1). The tending area positively affected *CSF* at the 10% significance level. All other things being equal, if the tending area increased by 10,000 ha, the *CSF* would increase by 0.19 Tg C. Table 2 (Model 2) also shows that in SR, NCR, and NER, tending has a significant positive effect on *CSF*, and the vegetation carbon sequestration capacity of tending in these regions is greater than that of afforestation, irrespective of the significance level. However, tending in NWR negatively influenced *CSF* at the 10% significance level, most likely because of poor climatic conditions and because trees could not survive easily. To ensure the qualified rate in the later stages, the initial planting density was too high. Therefore, the intensity of tending cutting may be higher, resulting in a short-term decrease in the *CSF*.

As shown in Table 2 (Model 1), we compared the vegetation carbon sequestration capacity of different forestry measures. The marginal contribution of forest tending to *CSF* was about 4.48 times higher than that of afforestation; with other things being equal, tending contributes more to *CSF* than afforestation.

In addition, we compared the spatial differences in the effects of different forest measures on vegetation carbon sequestration. For the sake of observation, we converted the results of Table 2 (Model 2) into Table 3, which shows that the marginal contribution of afforestation to *CSF* was higher than that of tending in NWR and SWR, whereas the marginal contribution of tending was greater than that of afforestation in SR, NCR, and NER.

Table 3. Options for forest measures in each region.

	Afforestation	Tending	Afforestation vs. Tending
SR		√	Tending
NCR	√	√	Tending
NWR	√		Afforestation
NER	√	√	Tending
SWR	√		Afforestation

A tick in the table indicates that forest measures can significantly increase *CSF*.

Table 2 (Model 1) displays the effects of the control variables on *CSF*. Forestry labor positively and significantly affected *CSF*. Generally speaking, as a production factor, the higher the input of forestry labor, the better the increase in forest stock, thus increasing the *CSF*. Forestry fixed assets positively affected *CSF* at the 1% significance level. An increase in forestry fixed assets indicates the availability of more forestry equipment and operational tools, which can effectively improve the operational conditions of forestry production, increase the efficiency of forestry operations, and thus increase forest stock and vegetation carbon sequestration capacity. *CSF* showed a trend of decreasing followed by increasing with the increase in *GDP*. There was a U-shaped relationship between *GDP* and *CSF*, which follows the law of environmental Kuznets curve and forest transition path. Specifically, when the *GDP* reached USD 17.83 billion, it would cross the inflection point of the environmental Kuznets curve, and the forest transition would begin to carry out the conservation phase. The coefficient of *CSF*_1 was significantly positive, indicating that the better the initial resource endowment, the more favorable the growth of forest vegetation, and the stronger its vegetation carbon sequestration capacity.

However, the effects of the regional population, temperature, and precipitation on *CSF* were not significant. Although population growth increases the demand for forest products, increasing the pressure on land bearing and leading to a shift in the type of forest land use, the high priority given to forestry ecology in recent years has reduced the negative impact of human activities on forestry resources. Temperature and precipitation are only conducive to vegetation growth if they are in the correct range—neither too high nor too low is feasible.

3.2.2. Estimation of Lagged Effects of Forest Measures

This study further analyzed the lagged effects of afforestation and forest tending on the *CSF*. Specifically, we combined different lagged terms of afforestation and forest tending while keeping the control variables constant and observed the significance and trends of their marginal contributions to *CSF* (see Table 4).

The control variables were controlled for the estimation of each lagged term of the forestation measures. The values in brackets are the marginal contribution coefficients of different lagged afforestation and forest tending to the *CSF*. affor_1 denotes the afforested area in one lagged period. tend_1 denotes the tending area in one lagged period, and so on for the other symbols; Unit: Tg C/10^4 ha.

First, we observed the duration of the effects of forest measures on the *CSF*. The effect of afforestation on *CSF* was no longer significant when the number of lags was greater than 8, while the effect of tending on *CSF* was no longer significant when the number of lags was greater than 2, indicating that the effect of afforestation on vegetation carbon sequestration lasted significantly longer than that of tending.

Second, we observed the trends in the marginal contribution of the forest measures to the *CSF*. In general, both afforestation and forest tending had an inverted U-shaped effect on *CSF*, with marginal contributions of [0.03, 0.05] and [0.15, 0.29] (Tg C/10^4 ha), respectively. The *CSF* of afforestation reached its maximum near lag 4, whereas the *CSF* of tending reached its maximum at lag 2. The optimal combination of coefficients for forest measures was (0.05, 0.30) (Tg C/10^4 ha).

3.2.3. Calculation of Vegetation Carbon Sequestration Costs for Different Forest Measures

Considering the marginal contribution of forest measures to the *CSF*, only environmental effectiveness can be examined, but the choice of forest measures is also influenced by the costs. Therefore, we need to further analyze the rationality of the choice of forest measures in terms of cost-effectiveness.

Using the optimal combination of marginal contribution (0.05, 0.30) (Tg C/10^4 ha) as the standard, the national average cost of *CSF* for afforestation was USD 412.53/t, while the average cost of *CSF* for tending was only USD 9.28/t, as measured by Equation (5). The *CSF* cost of afforestation was 44.44 times higher than that of tending, indicating that the return on carbon sequestration for afforestation was much lower than that for tending.

As shown in Figure 4, the cost of *CSF* by afforestation showed a pattern of high in the east and low in the west, whereas that by tending showed a characteristic of high in the west and low in the east. The low costs of afforestation were mainly in the western regions of Yunnan, Ningxia, and Qinghai, whereas the cost of afforestation in Yunnan was approximately USD 72.47/t, and the cost of afforestation in the eastern regions of Beijing, Shanghai, Tianjin, and Jiangsu were generally high, with the cost of afforestation in Beijing being as high as USD 7105.65/t. The low costs of tending were mainly in Henan, Hebei, Guizhou, and Tianjin, where the cost of tending in Henan was only USD 1.05/t, and the high costs of tending were mainly concentrated in Shanghai, Beijing, Guangxi, Sichuan, and Yunnan provinces. Shanghai and Beijing are economically developed regions with high prices for various factors and relatively high costs. The average cumulative tending investment in Guangxi, Sichuan, and Yunnan was USD 73.16 million, whereas the national average was only USD 27.87 million. As a result, they had a relatively high cost of *CSF* by tending.

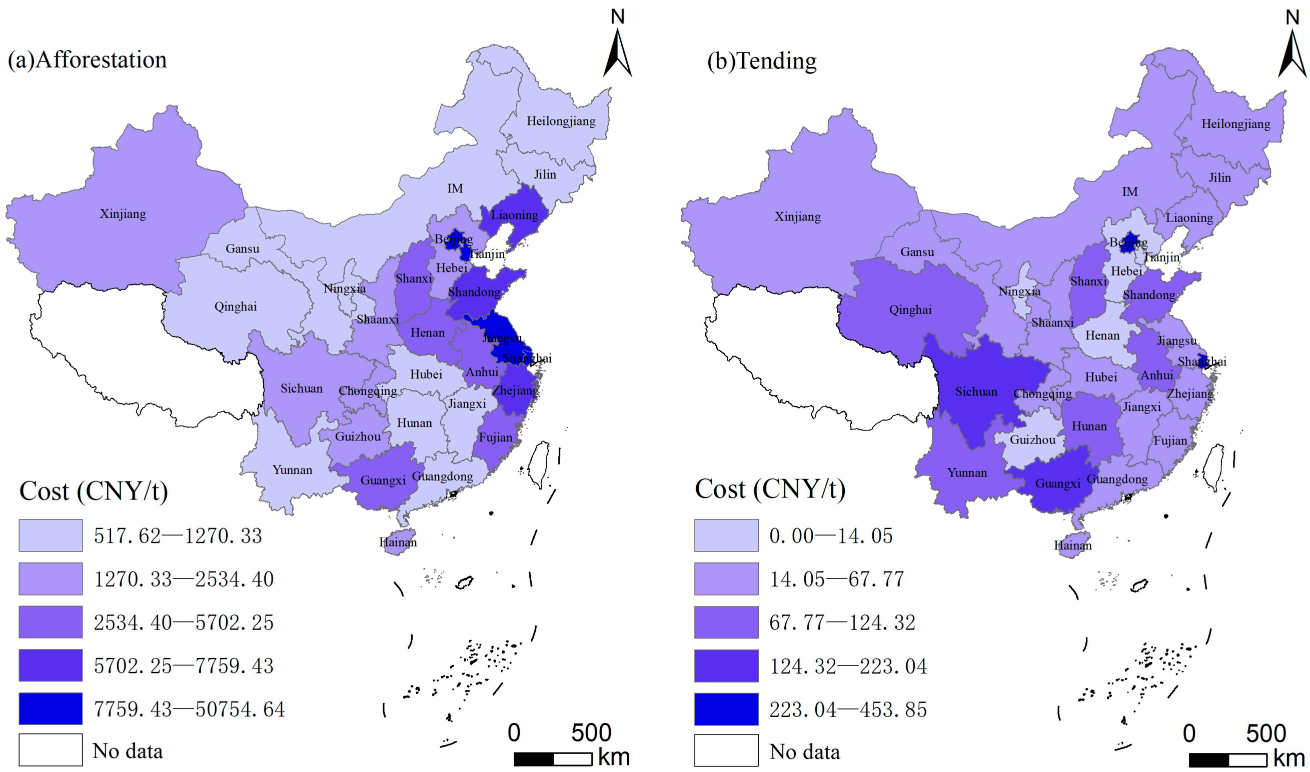

Figure 4. Distribution of vegetation carbon sequestration (*CSF*) costs for forest measures in China.

Table 4. Estimated lagged effects of forest measures.

Tending / Afforestation	*tend*	tend_1	tend_2
affor	(0.042, 0.188)	(0.040, 0.271)	(0.038, 0.210)
affor_1	(0.043, 0.194)	(0.041, 0.276)	(0.040, 0.212)
affor_2	(0.044, 0.179)	(0.042, 0.258)	(0.043, 0.216)
affor_3	(0.037, 0.196)	(0.035, 0.293)	(0.035, 0.272)
affor_4	(0.048, 0.195)	(0.047, 0.256)	(0.046, 0.212)
affor_5	(0.048, 0.206)	(0.047, 0.291)	(0.045, 0.239)
affor_6	(0.035, 0.189)	(0.035, 0.280)	(0.033, 0.206)
affor_7	(0.029, 0.173)	(0.029, 0.239)	(0.028, 0.147)
affor_8	(0.027, 0.185)	(0.028, 0.261)	(0.026, 0.156)

4. Discussion

Our analysis illustrated the effects and costs of different forest measures on vegetation carbon sequestration, including afforestation and forest tending. Unlike previous studies, our analysis has three contributions: (1) we stripped the actual vegetation carbon sequestration effects of different forest measures using econometric methods to control for the effects of unobservable factors; (2) we identified more regionally appropriate forest measures; and (3) we analyzed the difference in vegetation carbon sequestration costs of forests at different growth stages.

Both afforestation and forest tending could significantly increase the *CSF* in general, but the vegetation carbon sequestration ability of forest tending was stronger than that of afforestation from the perspective of marginal contribution. While afforestation contributes to the increase in forest area and total carbon sink, tending mainly increases the level of stocking by adjusting the stand structure, especially in young- and middle-aged forests, which are in the fast-growing stage and have a higher rate of vegetation carbon sequestration. Gao et al. also found that compared with China's extensive afforestation, the US generated more carbon sinks in a smaller area of newly planted forests by focusing on forest management [12]. Therefore, more emphasis should be placed on forest tending rather than simply afforestation.

Our results show that afforestation should be the main measure to increase the *CSF* in NWR and SWR, and tending should be chosen to increase the total *CSF* in SR, NCR, and NER. Existing forestable land, standless forest land, and sparse forest land are mainly located in arid and semi-arid regions in the northwest, dry and hot river valleys, and rocky desertification areas in the southwest [18]. Therefore, by continuing to promote afforestation, the forest cover in these sparsely vegetated areas can be effectively increased to improve the *CSF*. There is less forestable space and limited potential to enhance *CSF* through afforestation in the SR, NCR, and NER. Moreover, these areas are relatively economically developed with higher land use costs and opportunity costs for developing silvicultural projects. Therefore, it is more suitable to increase the productivity of forest land, improve forest quality, and increase *CSF* by tending within limited forest-land space.

There were significant lag effects of forest measures on carbon sequestration by vegetation. As perennial plants, forests have a long growth cycle, and their conditions in the current year are influenced by previous forest measures (inputs). Therefore, we should focus on the long-term management of forests and extend the period of management and transactions related to forests.

Forest tending is more cost-effective than afforestation in terms of vegetation carbon sequestration in China. The EU carbon price was USD 49.8/tCO_2e on 1 April 2021 [29], which is lower than the cost of vegetation carbon sequestration through afforestation in China, indicating that it is not yet economically viable for provinces to increase their carbon sinks through afforestation in international markets. However, this price is higher than the cost of vegetation carbon sequestration through tending in most provinces in China. Therefore, it is more economically advantageous to sequester carbon by tending to the international carbon market. In addition, the price in the Chinese carbon market was USD

6.86/ton in 2021 [30], which is much lower than the cost of vegetation carbon sequestration through afforestation. However, if USD 7/t is used as the trading standard, there will still be a profit space for vegetation carbon sequestration through tending in many provinces, such as Guizhou, Hebei, Henan, Ningxia, and Gansu. Overall, increasing the *CSF* through tending is more cost-effective, which can be economically profitable in the carbon market and provide an incentive for market players to participate in carbon market transactions.

Additionally, the relative size of the regional *CSF* is similar to that reported by Cai et al. [4]. SR has higher forest cover due to favorable natural conditions and more obvious advantages of non-state economic afforestation. SWR and NER have always been relatively rich in forest resources, with a more concentrated distribution of natural forests and a particularly important ecological status. They are also located in areas where NFPP and SLCP were implemented, protecting and nurturing forest resources [16]. NWR has an arid climate and fewer initial forest resources. It is a key area for national forestry investment, and forest resources have increased significantly in recent years. However, its forest stand conditions are poor, and it faces severe water resource constraints. Therefore, the task of consolidating afforestation achievements is difficult, and forest resources are still insufficient. NCR is mainly dominated by plantations and secondary and tertiary industries. Forestry plays only a complementary ecological role in this region, and forest resources are insufficient. Therefore, the carbon sequestration of vegetation is low.

5. Conclusions

By analyzing the effects of forest measures, including afforestation and forest tending, on vegetation carbon sequestration, we found that forest tending was more effective than afforestation. Meanwhile, forest tending is more cost-effective than afforestation in sequestering carbon in forest vegetation. There was significant spatial heterogeneity, specifically, afforestation was more effective in NWR and SWR, while forest tending was more effective in SR, NCR, and NER.

The findings of this study have several implications. First, it is essential to strengthen the management of existing forests. Enhancing the carbon sink capacity requires a fundamental improvement in forest quality, and area expansion is not a long-term solution. Second, ecological policy implementation needs to be based on regional resource endowments to achieve better fulfillment of ecological goals and cost-effectiveness. Third, unlike agriculture, forestry is more long-term, and returns are lagging, therefore requiring longer operating rights and trading periods to reduce the risk of individual operations. Finally, forest management carbon sink projects have great potential, and the inclusion of relevant projects in the carbon trading market would provide incentives for micro-entities to participate actively in forest management. In addition, due to data limitations, forest tending was studied as the main measure of forest management in this study, and the role of forest management on vegetation carbon sequestration may have been underestimated. In the future, we hope to obtain more detailed data for related studies.

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