

Article

The Impact of Collective Forest Tenure Reform on Forest Carbon Sequestration Capacity—An Analysis Based on the Social–Ecological System Framework

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Abstract: Against the backdrop of industrialization, urbanization, and the increasingly urgent issue of climate change, the latest round of collective forest tenure reform in China demonstrates the characteristics of institutional change and capital-biased technological progress. Using provincial panel data from 1994 to 2015, which is related to the main task of the reform, this study combined the Social–Ecological System (SES) framework to explore the impact of the latest round of collective forest tenure reform on forest carbon sequestration capacity. The study found that (1) the collective forest tenure reform enhances forest carbon sequestration capacity, especially in areas with abundant collective forests and clear property rights. Regional differences in per capita forestry income do not affect the reform’s impact on this capacity; (2) the forest tenure reform affects carbon sequestration capacity by improving capital productivity, but labor productivity has no significant effect; (3) under the macro background, the interaction between forest tenure reform-supporting measures and factor productivity have a sustainable impact on carbon sequestration capacity. Therefore, deepening the collective forest tenure reform is an important measure for continuously improving the carbon sequestration capacity of collective forests.

Keywords: institutional change; capital-biased technological progress; Social–Ecological System; forest carbon sequestration



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1. Introduction

The reform of China’s collective forest tenure system is currently in a critical stage. After the reform and opening up in 1978, China’s more than 40 years of collective forestry development has undergone multiple rounds of reforms. The forest tenure reform referred to in this article is the latest round of collective forest tenure system reform that was piloted in 2003 and fully launched in 2008. Compared with previous forest tenure reforms, the scarcity of forest resources and the low efficiency of forestry production have pushed the new round of forest tenure reform in the direction of household-based forest tenure certification, and the mandatory nature of top-down reform has clarified the goal of this round of reform to achieve dual growth in farmers’ forestry income and forest resources. Although the main task of the reform, which is forest land tenure certification to households, has been basically completed, problems still exist, such as insufficient protection of collective forest tenure, which hinders the development of collective forestry [1]. Therefore, forest tenure reform has entered a stage of deepening, including measures such as the separation of ownership, management, and use rights and the transfer of forest land use rights to promote flexible management. In the deepening stage, forest tenure reform not only faces the task of improving the efficiency of forest management but also faces new era backgrounds such as common prosperity, rural revitalization, and carbon neutrality. It puts forward new requirements on how to better balance economic benefits and ecological benefits, especially in the new background, where the ecological function of collective forests is more prominent. Compared with the economic benefits of forest tenure reform, the

ecological benefits have not received much attention from scholars in the past. Therefore, how to achieve multiple goals, such as economic benefits, social benefits, and ecological benefits at the same time, and better highlight ecological benefits, especially how to play a role in mitigating climate change, have become the focus of discussions on deepening the reform. This article provides new ideas from the perspective of property rights reform by summarizing the experience of this round of forest tenure reform, which is also the significance of this paper.

The focus of this article is on the impact of the new round of forest tenure reform on the carbon sequestration capacity of forests. While there is a wealth of research on the collective forest tenure system reform, most of it has focused on the relation of income and reform [2–7]. In the study of the ecological benefits of forest tenure reform, especially the impact on forest carbon sequestration, more attention has been paid to the analysis of the impact of forest tenure reform on timber and carbon leakage or on carbon trading systems in forest tenure reform [1,8–10]. There is basically no direct analysis of the impact of forest reform on carbon sequestration, and previous literature on forest reform issues has mainly focused on the micro-level; there have been few studies involving a macro-level quantitative analysis of the impact of forest reform on forest carbon sequestration. The theoretical framework of this article is based on the latest frontier achievements of the SES framework and will also involve discussions of institutional change and induced and biased technological progress, ensuring the systematic analysis of the paper. In terms of research methods, this article mainly uses the Multi-timepoint Difference-in-Differences (MTDID), which can model time changes, remove the effects of time trends and other potential confounding variables, and more accurately measure the policy effects of forest tenure reform by comparing the differences in the affected and unaffected provinces before and after the impact of the reform. The paper will also involve the application of Event Study Methodology (ESM) and Difference in Difference in Difference (DDD) model.

In terms of the structure of the entire article, the first focus will be on the policy background of forest tenure reform and the analytical framework of the article, and research hypotheses will be proposed. Subsequently, it will involve data description analysis, model construction, robustness testing, mechanism analysis, and heterogeneity analysis of the impact of forest tenure reform on forest carbon sequestration, as well as discussion of dynamic effects, and, finally, corresponding discussion and conclusions will be presented.

2. Concept Definition, Policy Background, and Analysis Framework

2.1. Connotations of Forest Carbon Sequestration Capacity, Induced Technological Progress, and Biased Technological Progress

Forest carbon sequestration is the transformation of atmospheric carbon dioxide into organic carbon within trees and soil by expanding forest coverage or managing forests, leading to a reduction in atmospheric carbon dioxide and a subsequent alleviation of climate change. China's forest carbon sequestration contributed 80% to the land ecosystem's carbon sequestration from 2001 to 2010 [11]. As defined by the Intergovernmental Panel on Climate Change (IPCC), it includes carbon sequestration of undergrowth plants and soil. In this article, forest carbon sequestration capacity refers to carbon storage density, a widely used indicator [12,13].

The induced technological progress theory, also known as the Hicks–Suzuki–Ramsey–Binswanger hypothesis, suggests that farmers always seek technological choices that can replace increasingly scarce production factors under market economy conditions, influenced by their prices [14]. In forestry, it refers to choosing methods that save labor and utilize abundant capital [15–17].

Biased technological progress favors the more abundant production factor when two factors are substitutable [18]. In the context of forest tenure reform and China's forestry sector's low productivity, the capital factor shows higher substitutability with labor [19,20]. This has led to a bias towards capital, increasing the output efficiency of capital factors in forestry, not labor.

2.2. Background of the Collective Forest Tenure Reform

Up until the forest tenure reform referred to in this article, China's collective forest tenure system had undergone three major reforms.

The First Forest Tenure Reform (Early 1980s): Initiated under the rural household contract responsibility system, the Three-Fix Forestry Policies were implemented nationwide. However, the third National Forest Resources Inventory (NFRI) data (1984–1988) revealed a decrease of 18.5568 million cubic meters in southern collective forest areas. This decline was attributed to the lack of clear property rights, leading to short-term gains by farmers and indiscriminate logging [21,22]. Additionally, some scholars emphasized the lack of funds for the forestry sector and the long production cycle characteristic of forestry, which led to rational behavior by farmers to pursue short-term cash gains [23].

The Second Round of Forest Tenure Reform (1990s): Characterized by marketization, this reform saw local governments auctioning off barren land, leading to the concentration of forest resources in various hands. This concentration not only intensified social contradictions but also decreased farmers' enthusiasm for forest management, resulting in a decline in the quality of collective forests. The fifth (1994–1998) and sixth (1999–2003) NFRI data further highlighted the productivity level of collective forests being only 38.36% and 40.65% of state-owned forests, respectively, a significant drop from the previous period [24].

The Third Round of Forest Tenure Reform (2003–2014): Beginning as a pilot program in 2003 and fully implemented in 2008, this reform was guided by the *Opinions on Comprehensive Promotion of the Reform of the Collective Forest Tenure System*, which is also referred to in this article. The main task was to clarify both the contract management rights of forestland and the ownership of forest trees, transferring them to households within five years [25,26]. After the reform was fully implemented, supporting measures such as forest insurance, farmers' cooperatives, and forest tenure mortgage loans were also implemented [27]. By 2014, the main tasks of the national reform had been basically completed, and the area of collective forests that had been clarified and registered to households was about 18 million hectares, accounting for 99% of the total area of collective forests¹. The full implementation of this round of forest tenure reform coincided with the 2008 financial crisis, and stable forestry production became an investment area for hedge funds. Clarifying property rights can also improve the investment and output level of land [28], which created favorable conditions for the effective implementation of forest tenure reform. In addition, the rapid development of industrialization and urbanization since entering the 21st century, as well as the increasingly prominent global climate issues, have further deepened the reform of the collective forest tenure system towards the direction of separating the ownership, contract, and management rights.

2.3. Analysis Framework

2.3.1. The SES Framework

The SES framework is a framework for analyzing limited natural resource use problems, such as forests and fisheries, originally proposed by Ostrom (2009) [29]. Compared to previous analyses of these types of problems, the SES provides a cross-disciplinary and widely applicable analytical framework. The SES is also an evolution of the Institutional Analysis and Development (IAD) framework, but emphasizes the integrality of social and ecological systems and their dynamic feedback mechanisms, particularly nonlinear feedback mechanisms [30,31]. Currently, this theoretical framework is still in rapid development. Figure 1 shows the first-tier variables of the SES framework, which consist of four parts: the Resource System (RS), the Resource Unit (RU), the Governance Systems (GS), and the Actors (A). These components interact with each other to produce the interaction (I) and outcome (O) of the action situation, which is also influenced by the social, economic, and political context (S) and the relevant ecological system (ECO). It can be seen that the four components in the SES not only act as conditions or inputs that ultimately affect the results, but the final results also feed back to the four components mentioned above, causing them to make corresponding adjustments.

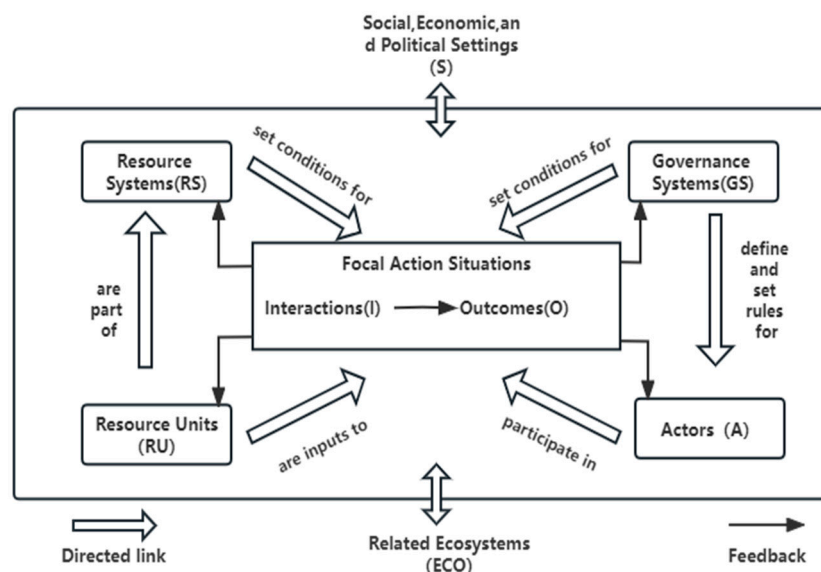


Figure 1. The SES Level 1 Variables.

2.3.2. Scenario Description of the Impact of Forest Tenure Reform on Carbon Sequestration Capacity under a Macro Background Based on the SES

Based on the improved the SES framework of McGinnis and Ostrom (2014), this paper will combine Janssen (2013), Anderies (2013), and Su, Qin, and Wang (2020) [32] with a description of the robustness and structure of the SES framework. This paper analyzes the impact of forest tenure reform on forest carbon sequestration capacity under the macro background based on the SES. In this paper, based on the existing first-tier and second-tier variables of the SES, combined with forest tenure reform and carbon sequestration issues, the SES framework is decomposed into the third-tier variables (Table 1), and Table 1 only shows the third-tier variables involved. Under the background of China's integration into globalization (S1), the acceleration of urbanization (S2), and the urgency of global response to climate change (ECO1), based on the goal of narrowing the income gap between urban and rural areas, increasing farmers' income (O1a) and promoting the increase in forest resources (O2a). Summarize the past experience of forest tenure reform (GS4a). To promote the implementation of a new round of confirmation of collective forest rights to households (GS4b), i.e., to determine farmers as the main body of collective forest contractual management rights, to enhance farmers' property rights expectations and enthusiasm for forest management and to enhance farmers' income from forest management (O1a). Farmers are also facing the decline of forestry output value in the national economy (RU4b) and the increasing prominence of forest ecological value (RS5a). This promotes the change in factor allocation in forestry production (RU5a), and the positive impact of property rights reform has further promoted biased technological progress, i.e., institutional changes have brought about an improvement in the production efficiency of related production factors (I1a). The above results, together with the change in farmers' income from forestry (O1a), have a positive impact on the first-tier variables, including the GS, affecting the adjustment of farmers' factor inputs (RU5a), ultimately gradually improving the forest carbon sequestration capacity (O2a). Certainly, the improvement of forest carbon sequestration capacity does not depend only on individual farmers but is the result of collective action. In addition, this paper also needs to consider whether the distribution of collective forest resources (RU7a), the differences in income from forestry for farmers in different regions (A2a), and the implementation status of property rights reform (GS4d), which may further impact the effect of forest reform on forest carbon sequestration capacity (O2a). This constitutes the SES framework of the impact of forest tenure reform on forest carbon sequestration capacity in the macro context [25,26,31,33,34].

Table 1. The SES framework combined with forest tenure reform on carbon sequestration.

Social, Economic, and Political Settings (S)	
S1—Economic development; S2—Demographic trend; S3—Political stability; S4—Other governance systems (forestry classification and regulation reform); and S5—Markets (forestry marketization reform)	
Resource Systems (RS)	Governance Systems (GS)
RS1—Sector (forests) RS5—Productivity of system RS5a—Forests are the largest carbon pool on land	GS1—Government organizations GS1a—Government’s attention to forest resources GS4—Property rights system GS4a—Past experiences of forest tenure reform GS4b—Confirmation of collective forest rights to households GS4c—Perception of forestland property rights security GS4d—Clarity of forestland property rights boundaries GS4e—Implementation of supporting measures for forest tenure reform
Resource Unit (RU)	Actors (A)
RU2—Growth or replacement rate RU2a—Changes in forest coverage RU2b—Change in newly planted forest area RU4—Economic value RU4a—Changes in the relative price of labor and capital factors RU4b—Changes in the proportion of forestry output value to the national economy RU5—Number of units RU5a—Changes in the input of forestry factors RU7—Spatial and temporal distribution RU7a—Proportion of collective forest resources	A2—Socioeconomic attributes A2a—Differences in income from forestry among households in different regions A2b—Increase in non-farm income for farmers A3—History or past experiences A3a—Accumulation of farmers’ experience in silviculture A8—Importance of resource A8a—Dependence of farmers on forest resources A9—Technologies available A9a—Improvement of farmers’ silviculture technology
Action Situations: Interactions (I) → Outcomes (O)	
I1—Harvesting I1a—Improvement of production efficiency of capital factors I4—Conflicts I4a—The conflict of institutional change and technological progress O1—Social performance measures O1a—Increase in farmers’ income and enhancement of social sustainability O2—Ecological performance measures O2a—Improvement and sustainability of collective forest resources and carbon sequestration capacity O2b—Differences in forest carbon sequestration capacity	
Related ecosystems (ECO)	
ECO1—Climate patterns	

2.3.3. Mechanism Analysis and Research Hypothesis

Increasing forest resources is one of the goals of collective forest tenure reform. Achieving this goal not only relies on the improvement of forest coverage but also requires an improvement in forest quality, which has even greater potential. However, there has been ongoing debate in academia about whether forest tenure reform can sustainably improve the enthusiasm of farmers and, in turn, have a positive impact on the quantity of forest resources, including the carbon sequestration capacity of forests. For example, during the Three-Fix Forestry Policies period in China in the 1980s, the instability of forest tenure reform policies led to a decrease in forest cover in the southern forest tenure reform regions [22]. Effective forest governance does not rely solely on formal property rights systems, either. Instead, the roles of community and market in forest governance became increasingly prominent [35]. Although property rights systems have been challenged in forest governance, it still plays a core role in modern forest governance systems. Culas (2007) proposed that improving property rights can help reduce the pressure on forest resources and promote forest protection [36]. Even in community forest management projects, the enforcement of property rights is crucial for community forest management,

and it can have an important incentive effect on forest operators and thus affect the quality of community forests [37]. The above explanation indicates that although the impact of property rights on forest governance has been challenged, it may still have an impact on the quantity and quality of forest resources, including the carbon sequestration capacity of forests.

Compared with previous forest tenure reforms, the current forest tenure reform policy is more stable and sustainable. Starting from the pilot project of the new round of collective forest tenure reform marked by the release of the *Decision of the Central Committee of the Communist Party of China and the State Council on Accelerating the Development of Forestry* in 2003 to the promulgation of the *Opinions on the Comprehensive Promotion of the Reform of Collective Forest Tenure System* in 2008, the entire forest tenure reform process has been orderly promoted based on the summary of past experience. In addition, the *Opinions on the Comprehensive Promotion of the Reform of Collective Forest Tenure System* clearly stipulates that the contracted operation period of forests is 70 years, and the contract can be renewed according to relevant national regulations when it expires. Combined with the *Rural Land Contract Law of the People's Republic of China* promulgated in 2002 and the *Property Law of the People's Republic of China* promulgated in 2007, this forest tenure reform highlights the non-infringement of the attribute of beneficial use rights of forest tenure held by farmers, stabilizes farmers' confidence in this reform, and ensures the stability of the policy (S3). This creates a good policy background for the achievement of the ecological goals of forest tenure reform and also helps to resolve the problem of damage to forest resources caused by unstable policy expectations in the past. At the same time, the emphasis on the confirmation of collective forest rights to households (GS4b) in this forest tenure reform further clarifies the property rights boundaries of this reform, reduces transaction costs, and enhances the willingness of farmers to operate forests, allowing them to obtain better returns (O1a). The supporting measures for subsequent forest tenure reform (GS4e), including forest tenure mortgage loans and the promotion of forestry cooperatives, further demonstrate the continuity of the policy and have produced positive feedback effects, promoting the improvement of forest management quality and achieving sustained enhancement of ecological benefits (O2a). Based on this, this paper puts forward Hypothesis 1:

Hypothesis 1. *Collective forest tenure reform enhances and sustains the carbon sequestration capacity of forests.*

Under the context of industrialization and population mobility, while the forestry production factors are being redistributed, the reform of forest tenure system has also led to a biased technological progress characterized by the improvement of forestry capital productivity. In the discourse on effective institutions, North and Thomas (1973) pointed out that an efficient institution needs to meet two conditions [38]. The first is that the production behavior of each member of society can be effectively protected. The second is that each member of society can fully develop their talents. With regard to the first condition, property rights security can be addressed, for example, clear property rights systems can provide property protection for deforested land, thus avoiding undervaluation of land value [39]. With regard to the second condition, to achieve optimal allocation of resources, property rights systems can also be met. In addition to land factors, labor and capital factors are the two major production factors of forestry. In the context of industrialization (S1) and rural population mobility (S2), the increase in non-agricultural employment opportunities and the improvement of non-agricultural income (A2b) affect the relative prices of production factors (RU4a), thereby leading to the redistribution of factors, including forestry production (RU5a). This means that labor gradually shifts to non-agricultural employment, and the new round of forest tenure reform implemented to household (GS4b) is accompanied by an enhanced sense of property rights security among farmers (GS4c). The input of production factors also brings about changes in forestry production factor efficiency (I1a) in the process of achieving further quantitative changes

(RU5a), mainly manifested in the improvement of capital factor productivity, i.e., the biased technical progress caused by the relatively abundant forestry capital factor. At the same time, the feedback effect of this change will also further optimize forestry input factors (RU5a). Evidently, the above interactive process will affect the forest carbon sequestration capacity (O2a).

Hypothesis 2. *In the context of industrialization and population mobility, the collective forest tenure system may enhance forest carbon sequestration through capital-induced biased technical progress.*

The degree to which forest carbon sequestration capacity is improved by forest tenure reform (O2a) may be influenced by other factors. Firstly, the abundance of collective forest resources (RU7) is analyzed, which is an important carrier of the forest tenure reform policy (GS4b). Differences in abundance of collective forest resources (RU7) can lead to differences in regional resource dependency (A8a), which can evidently affect the input of forestry factors by farmers (RU5a) and the level of specialization (A3a) (A9a) as well as the level of attention from local governments (GS1a), which, in turn, affects the forest carbon sequestration capacity (O2a) in different regions. Previous research has found that the income-increasing effect of forest tenure reform is affected by the state of collective forest resources [40] but has not addressed the ecological benefits. Therefore, this article needs to focus on whether the differences in collective forest resources (RU7a) between regions will impact the effect of forest tenure reform on forest carbon sequestration (O2a).

In addition to the abundance of collective forest resources, the clarity of property rights boundaries (GS4d) in forest tenure reform itself may also affect the degree to which the property rights reform goals are achieved. The fuzziness of property rights boundaries can increase transaction costs and thus affect farmers' property rights expectations. In this case, it will affect the income-increasing target (O1a) as one of the goals of forest tenure reform and, through feedback effects, ultimately affect the ecological goals (O2a) of forest tenure reform. The exercise of property rights is the utilization of property attributes by property subjects [41], and the emphasis on household property rights in this forest tenure reform (GS4b) will inevitably be influenced by the actual situation of property rights, especially the degree of household property rights (GS4d) in this forest tenure reform, which is related to the amount of transaction costs and further affects the rational expectations formed by farmers based on property rights [42,43], thus affecting the efficiency of forestry production factors allocation under the background of changes in factor allocation (I1a) and ultimately affecting forest carbon sequestration effects and sustainability (O2a).

Moreover, the differences in forestry income among regions (A2a) reflect, to some extent, the importance of forest resources to farmers in different regions (A8). The most direct reflection is the differences in forestry input by farmers (RU5a), which may lead to differences in the ecological benefits of forests between different regions (O2a) under forest tenure reform. In addition, economic variables have always been an element that cannot be avoided in the study of forest carbon sequestration issues, and there is controversy over whether they are effective and to what extent. In the study of forest carbon sequestration projects in Mozambique, scholars found that farmers' income from carbon sequestration projects did not produce significant carbon sequestration effects [44,45]; other scholars believe that income from carbon sequestration projects can have a positive effect on carbon sequestration, but the visibility and sustainability of income need to be ensured [46]. Therefore, this article believes that forestry income, especially the differences in forestry income between regions (A2a), should be taken into account when considering the carbon sequestration effect of forest tenure reform. In summary, this article proposes Hypothesis 3.

Hypothesis 3. *The differences in the abundance of collective forest resources, the clarity of property rights boundaries, and the differences in forestry income between regions may affect the effect of forest tenure reform on forest carbon sequestration capacity.*

3. Samples and Data

Descriptive Statistics

- Dependent variable

The dependent variable of this paper is forest carbon sequestration capacity, as mentioned earlier, which is measured using forest carbon stock density. This helps to compare the differences in carbon sequestration capacity among forests in different provinces. The sample of this paper includes 30 provincial-level units other than Shanghai, which has not carried out forest tenure reform [40]. The carbon stock data are calculated using the stock expansion method, which estimates the carbon sequestration capacity by calculating the carbon stock of trees, undergrowth vegetation, and soil. This method can reflect the overall trend in changes. The specific calculation formula is as follows

$$C_S = \sum(A_{ij} * C_{ij}) + \alpha \sum(A_{ij} * C_{ij}) + \beta \sum(A_{ij} * C_{ij}) \quad (1)$$

$$C_{ij} = V_{ij} * \delta * \rho * \gamma \quad (2)$$

In the above formula, C_S represents the total carbon storage, and A_{ij} , C_{ij} , and V_{ij} represent the forest area, carbon density, and carbon stock per unit area of forest j in region i , respectively. According to data published by the IPCC, the ratio of forest biological carbon sequestration to undergrowth vegetation carbon sequestration α is 0.195; the ratio of forest biological carbon sequestration to soil carbon sequestration β is 1.244; the biomass expansion factor δ is 1.9; the density conversion factor ρ is 0.5 t/m³; and the carbon content rate γ is 0.5 t/m³². The carbon stock data used in the above calculation is from the NFRI data. As the above data are only collected once every five years, and missing data were imputed using the mean to calculate the forest carbon sequestration capacity data from 1994 to 2015. Additionally, to verify the robustness of the results, this paper also used the Global Forest Products Model (GFPM) to impute missing values and obtain a new dependent variable [12,13,47]³, Table 2 displays the specific variable details, including the dependent variable.

Table 2. Descriptive Statistics.

Variables		(1) N	(2) Mean	(3) Sd	(4) Min	(5) Max
Forest tenure reform		660	0.406	0.491	0	1
Forest carbon sequestration capacity	ton/hm ²	651	45.33	33.96	4.050	192.4
Forest carbon sequestration capacity (CFPM)	ton/hm ²	651	45.23	33.96	4.050	192.4
Temperature	°C	660	13.38	5.506	2.600	25.55
Precipitation	mm	660	920.0	452.5	172.9	2079
Forest coverage	%	651	28.03	17.29	0.366	66.29
Afforestation area	thousand hm ²	657	179.6	166.3	3	907.4
Industrialization level	%	660	84.19	8.050	54.03	99.39
Level of urbanization	%	660	44.46	15.27	10.63	88.84
Forestry output value	hundred million US dollars	657	5.05	4.21	0.08	20.63
Labor force per unit growing stock	per/ten thousandm ³	586	41.78	45.06	0.102	375.1
Physical capital per unit growing stock	US dollars/m ³	651	1.52	2.14	0.00063	19.01

- Core explanatory variables

The core explanatory variable in this paper is the implementation of the new round of forest tenure reform. If the sample provinces have experienced the implementation of the reform at and after a certain point in time, the variable value is 1, otherwise it is 0.

- Control variables

This article selects control variables based on the SES framework, focusing on social and ecological aspects. In the ecological direction, temperature, precipitation, and forest coverage are considered. Specifically, temperature and precipitation are key factors for measuring climate change (ECO1) [48], compiled from over 2400 meteorological stations in China. Additionally, forest coverage (RU2a) is considered, reflecting changes in land use and significantly influencing whether an area becomes a carbon sequestration source or sink [49], thereby affecting final carbon storage (O2a). The forest coverage data are sourced from the NFRI data.

In addition to natural factors, social factors are also considered, including the level of urbanization, industrialization, afforestation area, and forestry output value. Urbanization considers population mobility (S2), affecting labor input in forestry production. Industrialization reflects the external economic impact (S1) on carbon sequestration, with provincial differences potentially affecting relative factor prices (RU4a) and allocation (RU5a). Afforestation area (RU2b) and forestry output value, reflecting the importance of forestry in economic life (RU4b), are also considered. The data for urbanization and industrialization are sourced from the National Bureau of Statistics of China, whereas afforestation area and forestry output value data come from the China Forestry Statistical Yearbook.

- Other variables

The mediator variables include forestry intermediate consumption per unit growing stock and forestry labor per unit growing stock. Intermediate consumption reflects material and service capital consumption in forest management, including inputs like seedlings, fertilizers, pesticides, machinery, and services such as planning, design, training, pest control, fire prevention, and protection. Forestry labor data are calculated based on rural population numbers and age structures, proportionate to forestry output value. Additional data, such as rural household forestry income, is sourced from relevant statistical yearbooks, with economic output value data converted to ensure comparability.

4. Econometric Models and Empirical Results

4.1. Benchmark Regression

$$cd_{it} = \beta_0 + \beta_1 D_{it} + \sum_{j=1}^J \omega_j Control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (3)$$

The benchmark model used in this paper is the MTDID model, where cd_{it} reflects the forest carbon sequestration capacity of province i at time t , D_{it} is whether province i implements forest tenure reform policy at time t , and, if implemented, it is 1, otherwise it is 0. β_1 is the coefficient of whether the forest tenure reform policy is implemented, which reflects the impact of the policy implementation on the forest carbon sequestration capacity. $Control_{it}$ is the control variable of province i at time t , ω_j is the coefficient of different control variables, γ_t is the time fixed effect, μ_i is the province fixed effect, and ε_{it} is the corresponding disturbance term. Table 3 reflects the benchmark regression results.

Model (1) represents the benchmark regression results without considering the control variables. It can be observed that the implementation of forest tenure reform policy has a positive impact on the carbon sequestration capacity of forests. In model (2), this paper only considers the natural factors that affect carbon sequestration capacity. The results show that the increase in temperature in natural factors actually has a negative effect on carbon sequestration capacity in addition to the positive impact of forest tenure reform on carbon sequestration capacity. Furthermore, in model (3), this paper considers the control variables related to social factors. At this time, forest tenure reform still has a positive impact on the carbon sequestration capacity of forests.

Table 3. Benchmark Regression.

Variables	(1) Forest Carbon Sequestration Capacity	(2) Forest Carbon Sequestration Capacity	(3) Forest Carbon Sequestration Capacity
Forest tenure reform	2.927 ** (1.116)	2.392 ** (0.972)	2.420 ** (0.948)
Temperature		−1.420 * (0.825)	−1.204 ** (0.563)
Precipitation		−0.004 ** (0.002)	−0.004 ** (0.002)
Forest coverage		0.588 ** (0.255)	0.278 (0.339)
Afforestation area			−0.002 (0.003)
Industrialization level			−0.453 (0.632)
Level of urbanization			−0.068 (0.166)
Forestry output value			0.179 ** (0.086)
Constant	39.732 *** (1.948)	50.539 *** (11.456)	88.067 * (48.458)
Observations	651	651	650
Number of province_1	30	30	30
R-squared	0.261	0.305	0.377
Province FE	Y	Y	Y
Year FE	Y	Y	Y

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; Y: controlled variables in the model.

4.2. Parallel Trend Test

$$cd_{it} = \beta_0 + \sum_{k=1}^K Pre_k D_{i,t-k} + \sum_{m=0}^M Post_m D_{i,t+m} + \sum_{j=1}^J \omega_j Control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (4)$$

In conducting MTDID analysis, the premise is that there are no systematic differences in the trends between the treatment group and the control group. To verify this premise, this paper uses ESM to test whether it is satisfied. Based on this method, a model is constructed that not only analyzes whether the parallel trend assumption is satisfied but also observes whether the effect of forest tenure reform on carbon sequestration capacity is sustainable. In the above model, $D_{i,t-k}$ represents the k th pre-period of the forest tenure reform, and, if the corresponding coefficient Pre_k is not significant, it indicates that the parallel trend assumption is satisfied between the treatment group and the control group before the forest tenure reform; thus, the premise for applying the benchmark model is satisfied. In the model, $D_{i,t+m}$ represents the m th post-period of the forest tenure reform, and, if the corresponding coefficient $Post_m$ is significant, it indicates that the effect of the forest tenure reform on the carbon sequestration capacity of forests is sustainable. This paper will analyze the sustainability issue in subsequent analysis.

Figure 2 reflects the nine years before the implementation of the forest tenure reform policy until the current period, and the confidence intervals of the coefficients, except for the current period, all include 0. This indicates that there is no systematic differences in the trends between the treatment group and the control group, and the parallel trend test has been passed.

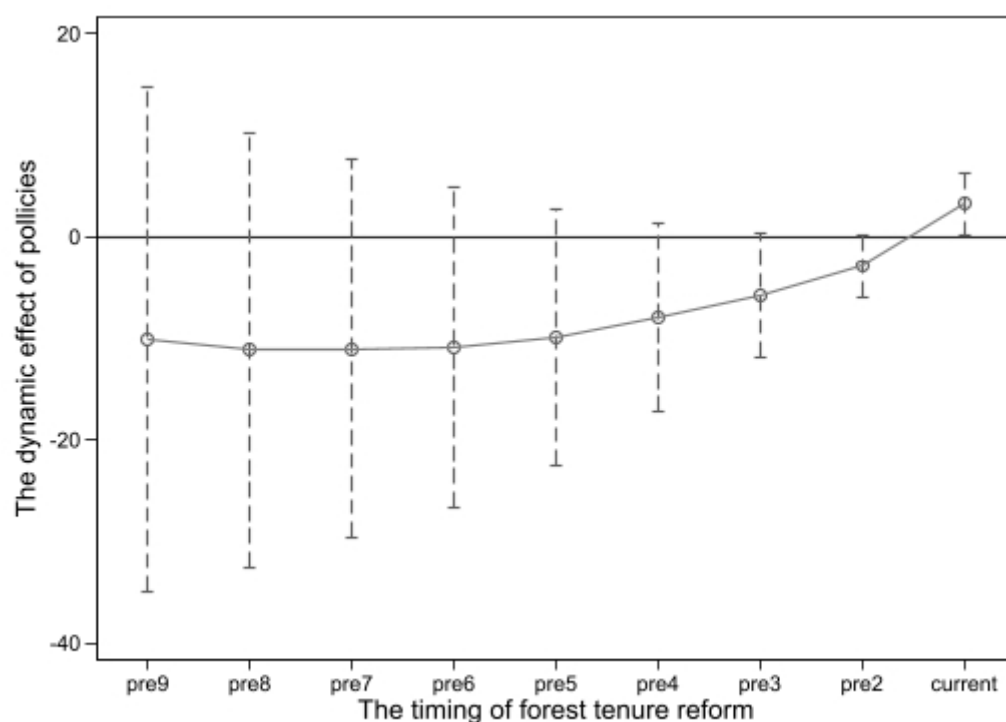


Figure 2. Parallel Trend Test.

4.3. Excluding the Impact of Other Policies

Although the benchmark model passed the parallel trend assumption, the improvement in forest carbon sequestration capacity may have been affected by other policies during the sample period. For robustness considerations in regression analysis, this paper will exclude other policies that may affect forest carbon sequestration capacity.

Firstly, consider the *General Outline of Forestry Economic System Reform* promulgated in 1995, which is the forestry market-oriented reform during the second round of the forest tenure reform. It is consistent with the background of China's macroeconomic market-oriented reform. In the second round of forest tenure reform, not only was the market-oriented operation of commercial forests emphasized, but also adjustments were made to the rules of timber and forest product circulation, such as proposing to gradually abolish the dual-track system for timber circulation. Yin and Newman (1997) pointed out that the market-oriented reform of timber prices in the 1980s played an important role in the changes in timber resources, and the coexistence of market-oriented timber prices and state procurement prices was one of the important reasons for the market-oriented reform of timber resources and the reduction in timber resources [21]. However, when it comes to the content of forest tenure reform in the 1980s, Zhang, Uusivuori, and Kuuluvainen (2000) also pointed out that the reform of timber harvesting did not have a negative impact on China's forest coverage [50]. It can be seen that there are certain differences among scholars regarding whether the market-oriented reform (S5) has an impact on forestry resources. Therefore, it is necessary to consider its impact on forest and even silvicultural conditions and forest carbon sequestration capacity (O2a).

Apart from the market-oriented reform of forestry, this paper also considers the impact of the forestry classification regulation reform (S4) in 2001 on forest carbon sequestration capacity (O2a) [51]. During this period, the forestry authority reviewed the annual forest harvesting volume during the tenth five-year plan period, and the main change was the harvesting quota for commercial forests, especially the harvesting quota for collective commercial forests. It showed a trend in relaxation, but stricter harvesting systems were implemented for public welfare forests. Overall, the proportion of forest harvesting quotas to standing timber volume decreased during this period and remained below 2% in the following years. Evidently, the classification and regulation reform may have an impact on

forest management and thus on forest carbon sequestration capacity, but whether it will have a positive effect on forest carbon sequestration is worth considering. He Wenjian, Xu Jingwen, and Zhang Hongxiao (2016) found that this classification reform would cause more serious damage to forest resources due to the survival pressure on forest farmers. In fact, previous studies on harvesting quotas in China have also found that harvesting quotas contribute little to forest expansion in China [52,53]. Therefore, it is necessary to consider the impact of the forest tenure reform (GS4b) on forest carbon sequestration capacity (O2a) under the background of the classification and regulation reform (S4). Table 4 below shows the regression after excluding relevant policies.

Table 4. Robustness Regression Results.

Variables	(4) Forest Carbon Sequestration Capacity	(5) Forest Carbon Sequestration Capacity	(6) Forest Carbon Sequestration Capacity	(7) Forest Carbon Sequestration Capacity (CFPM)
Forest tenure reform	2.420 ** (0.948)	2.420 ** (0.948)	2.420 ** (0.948)	2.394 ** (0.935)
Market-oriented reform of forestry	8.893 * (4.978)		3.076 (3.058)	
Classification and regulation reform		8.893 * (4.978)	5.817 (3.715)	
Constant	88.067 * (48.458)	88.067 * (48.458)	88.067 * (48.458)	87.833 * (48.393)
Observations	650	650	650	650
Number of province_1	30	30	30	30
R-squared	0.377	0.377	0.377	0.371
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y

** $p < 0.05$, * $p < 0.1$; Y: controlled variables in the model.

Models (4) and (5) are regressions on the impact of collective forest tenure reform on forest carbon sequestration capacity in the context of the forestry marketization reform and the classification regulation reform, respectively. It can be found that forest tenure reform still has a significant impact on forest carbon sequestration capacity under the impact of relevant policies. In model (6), the above policies are simultaneously included in the analysis. The results are still significant and consistent with the benchmark regression results, which indicates that the impact on forest carbon sequestration capacity does come from collective forest tenure reform rather than the impact of other policies during the same period. This further highlights the robustness of the conclusion.

4.4. Robustness Test

In order to further prove that the impact of forest tenure reform policy on forest carbon sequestration capacity is robust, this paper introduces a placebo test for the effect of forest tenure reform and uses two sampling methods for placebo test. In the first sampling method, the samples are grouped according to different provinces, and then a year is randomly selected from each provincial group as the implementation time of the policy in the province for regression. The above sampling is repeated 500 times to obtain the placebo test Figure 3. In the second sampling method, First, in the year variable, one datum was randomly selected for each province as the year of policy implementation and regression, the cycle was 500 times, and the placebo test in Figure 4 was obtained. In Figure 3, the figure (a) is the kernel density plot of regression coefficients, in which the dotted line is the mean of 500 regression virtual coefficients, and the solid line is the baseline regression coefficient plot. It can be seen that the results of the placebo test are far away from the

true coefficients. The figure (b) in Figure 3 is the p -value scatter plot, in which the scatter points are mostly located near 0, far away from the reference regression result and mostly located above the 10% dotted line. The figure (c) is the kernel density graph of the t value, in which the solid line is the true value, the long dashed line is the placebo test result, and the two short dashed lines are the corresponding 10% significance levels. It can be seen that the t value of placebo test is not significant. The results in Figure 4 are similar to those in Figure 3, indicating that the regression results are robust and also pass the placebo test.

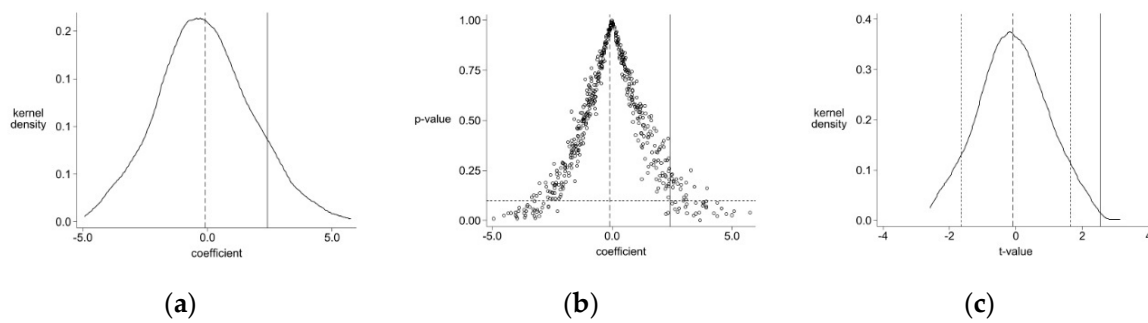


Figure 3. Placebo Test 1.

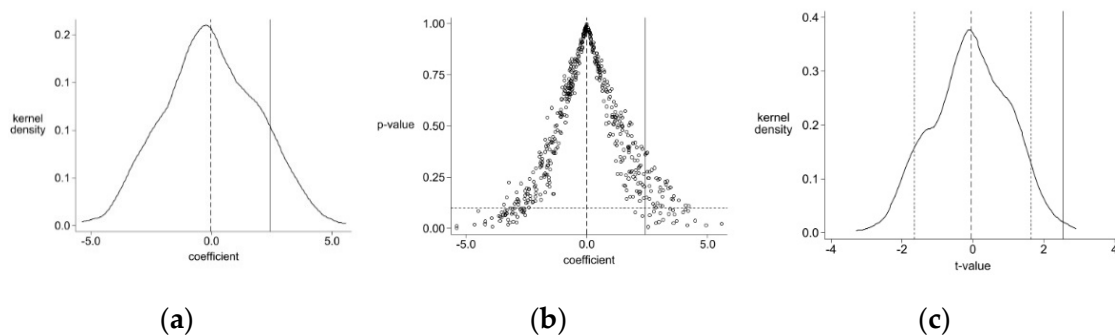


Figure 4. Placebo Test 2.

At the same time, in order to further test the robustness of the model, by replacing the explained variables in model (7) and introducing the carbon sequestration density data obtained by using the GFPM for analysis, it can be found that the impact of forest tenure reform policy on forest carbon sequestration capacity is still significant, which further proves that forest tenure reform does have a positive impact on forest carbon sequestration capacity.

5. Mechanism and Heterogeneity Analysis

5.1. Mechanism Analysis and Dynamic Effect

As mentioned earlier, the forest tenure reform policy has a positive impact on forest carbon sequestration capacity, and this impact, like the previous two rounds of forest tenure reforms, is influenced by the social and ecological background of industrialization, population mobility, financial crisis, and climate change. The policy change in forest tenure reform has led to biased technological progress combined with income effects, resulting in the improvement and sustained impact on forest carbon sequestration capacity. To analyze this mechanism, this paper first shows the results of the dynamic changes in forestry labor and capital inputs over time based on the mixed panel regression models (8) and (9) in Table 5. It is found that forestry capital investment is positively correlated with time, whereas forestry labor input is decreasing. This indicates that the allocation of forestry factors has changed with macroeconomic development, and the phenomenon of capital substitution for labor is significant, showing the characteristics of induced technological progress, which is also a prominent feature of China's agricultural development [54,55].

Table 5. Mixed Regression Results.

Variables	(8) Forestry Material Capital	(9) Forest Management Labor Force
Year	0.603 *** (0.203)	−2.189 ** (0.940)
Constant	−1188.283 *** (404.322)	4457.838 ** (1867.498)
Observations	507	389
R-squared	0.567	0.363
Controls	Y	Y

*** $p < 0.01$, ** $p < 0.05$; Y: controlled variables in the model.

Model (10) in Table 6 shows the impact of forest tenure reform on forestry income, where forestry income is measured in a logarithmic form. It can be seen that forest tenure reform (GS4b) does have a significant income effect (O1a), consistent with the conclusions of most scholars. At the same time, in order to further clarify the mechanism of forest tenure reform as an institutional change on forest carbon sequestration capacity during this period, this paper explores the role of labor input per unit growing stock and capital input per unit growing stock in measuring efficiency changes in models (11) to (14).

Table 6. Mechanism Regression Results.

Variables	(10) Income from Forest Management	(11) Labor per Unit Stock	(12) Forest Carbon Sequestration Capacity	(13) Physical Capital per Unit Stock	(14) Forest Carbon Sequestration Capacity
Forest tenure reform	0.155 ** (0.070)	0.921 (2.590)	1.271 (1.403)	−2.277 ** (0.902)	1.977 ** (0.952)
flaborlgs			−0.041 (0.025)		
ufmc_lgs					−0.130 *** (0.026)
Constant	4.171 *** (0.578)	59.118 (63.812)	111.369 ** (54.384)	−9.644 (14.689)	91.380 *** (19.292)
Observations	497	388	585	651	651
Number of province_1	29	30	30	30	30
R-squared	0.751	0.304	0.366	0.161	0.349
Controls	Y	Y	Y	Y	Y
Province FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y

*** $p < 0.01$, ** $p < 0.05$; Y: controlled variables in the model.

To ensure the robustness of the results, the above mechanism results were randomly sampled 1000 times. It was found that forest tenure reform significantly impacted forest carbon sequestration capacity through the improvement of capital factor production efficiency.

Figure 5 shows the dynamic effect of forest tenure reform obtained based on ESM. It can be seen that the confidence intervals of the impact of forest tenure reform on carbon sequestration capacity are all above the 0 axis, except for the current period. This indicates that the effect of forest tenure reform on carbon sequestration capacity is significant in the long term.

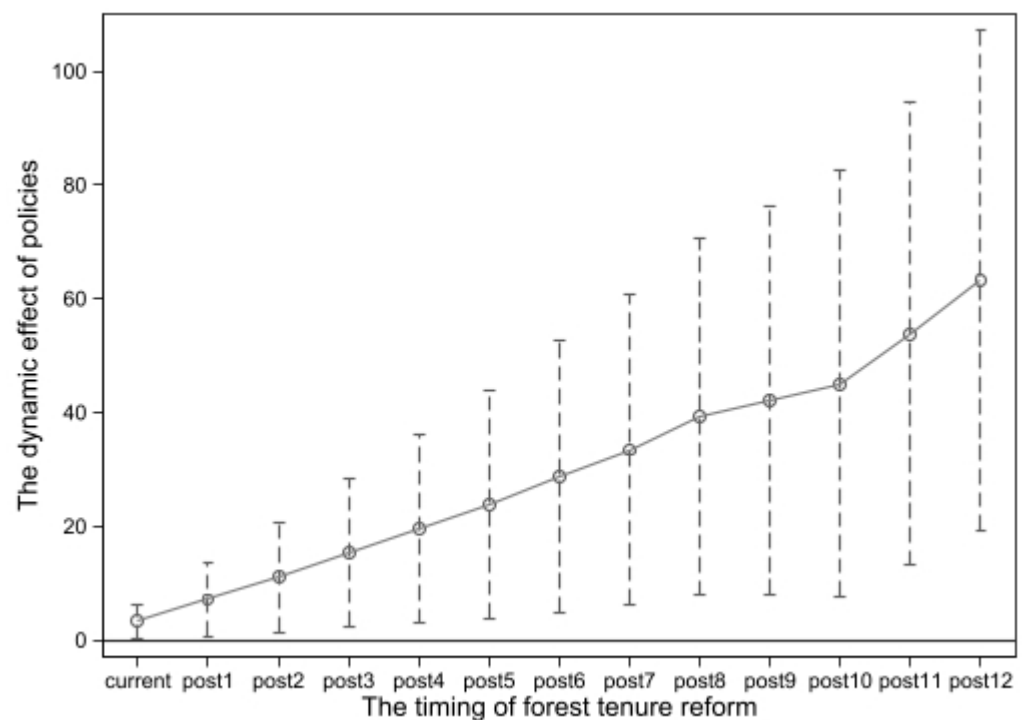


Figure 5. Dynamic Effect of Forest Tenure Reform Policy.

5.2. Heterogeneity Analysis

The impact of collective forest tenure reform on forest carbon sequestration capacity is achieved not only through direct factors related to the forest tenure reform but also partially through an improvement in capital productivity. However, the realization of this result within the framework of the SES is influenced by the resource condition (RU) of the study objects, the characteristics of participating farmers (A), and the overall social governance environment (GS). Based on these considerations, this paper analyzes the impact of the forest tenure reform on the carbon sequestration capacity of forests under the differences in the abundance of collective forest resources, forestry income, and property rights boundaries. To explore this heterogeneity, the paper introduces DDD model for analysis.

In this paper, the coverage rate of collective forest in each province is selected as the index of the richness of collective forest resources. In view of the clarity of property rights boundary, this paper selects the degree of confirmation of rights to households in each province in the process of implementing the forest tenure reform policy. Although the forest tenure reform has made it clear that the right should be confirmed to households, there is a way of confirmation of rights with equal shares and profits in the actual implementation process. Among them, Jiangsu province and Guangdong province only adopt the average profit per share, whereas Hebei province, Hubei province, Hunan province, and Qinghai province adopt both the confirmation of rights to households and the average profit per share. Therefore, in this paper, all the provinces that implement the confirmation of rights to households are assigned a value of 3, some of them are assigned a value of 2, and all of them are assigned an value of 1. Table 7 shows the results of the heterogeneous regression. The collective forest coverage and the degree of confirmation of rights significantly influence the forest carbon sequestration capacity in interactions with forest tenure reform, whereas the interaction between forestry income and forest tenure reform do not have a significant impact on forest carbon sequestration capacity.

Table 7. Heterogeneity analysis and regression.

Variables	(15) Forest Carbon Sequestration Capacity	(16) Forest Carbon Sequestration Capacity	(17) Forest Carbon Sequestration Capacity
Forest tenure reform *	13.629 ***		
Collective forest coverage	(1.539)		
Forest tenure reform * forestry income		0.011 (0.008)	
Forest tenure reform * degree of right confirmation			1.973 ** (0.954)
Forest tenure reform	−8.110 *** (1.442)	2.479 ** (0.977)	−3.040 (2.887)
Constant	26.253 ** (10.972)	92.094 *** (21.141)	89.625 *** (18.801)
Observations	616	531	650
Number of province_1	28	30	30
R-squared	0.546	0.282	0.382
Controls	Y	Y	Y
Province FE	Y	Y	Y
Year FE	Y	Y	Y

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; Y: controlled variables in the model.

6. Discussion

6.1. Interpretation of Empirical Results

Compared to collective forests without forest tenure reform, the implementation of forest tenure reform increases the carbon sequestration capacity of collective forests by 2.42 tons/hectare. In models (2) and (3), where natural and social factors are included as control variables, this conclusion still holds. Even after excluding policies that might affect the above conclusion and conducting placebo tests, the aforementioned conclusion still stands, demonstrating that this finding is robust. Furthermore, an increase in temperature has a negative impact on forest carbon sequestration, which is consistent with previous studies. This also means that while forests sequester carbon, global climate warming also has a negative impact on the carbon sequestration effect of forests [48]. In addition, it can also be seen in model (3) that forest coverage does not have a significant impact on carbon sequestration capacity. This may be mainly because this study focuses on carbon sequestration capacity rather than carbon sequestration storage. If it was the latter, an increase in forest coverage might have a significant positive impact.

For the mechanism regression, forest tenure reform affects forest carbon sequestration capacity (O2a) by improving capital factor efficiency (I1a). This, along with the income effect of the reform (O1a), refines resource allocation and farmers' behavior (A) in resource units (RU), enhancing carbon sequestration capacity (O2a). The capital factor's efficiency contributes 12.23% to this capacity, aligning with capital-biased technological progress theory, whereas labor input's efficiency is not significant.

For the dynamic effect and the heterogeneity regression, the feedback from outcomes (I1a) (O1a) influences forestry resource input (RU) and farmers' behavior (A), leading to adjustments in the property rights system and supporting measures for forest tenure reform (GS4e). This highlights the interaction between technology and institutions (I4a) [38,56], fostering a virtuous cycle outcome (O2a). The synergy of increased income, capital productivity enhancement, and forest tenure reform support sustains forest carbon sequestration, as shown in Figure 5, based on ESM. Model (15) shows that provinces with richer collective forest resources have a greater impact on forest carbon sequestration capacity, highlighting the effect of collective forest tenure reform in such areas. Model (16) reveals that regional differences in forestry income (A2a) do not influence the reform's impact on carbon sequestration capacity, likely due to small income differences among provinces, with 90% of surveyed farmers earning 12.57 US dollars or less per capita, based on 1994 as the

base year. Additionally, the confirmation of rights to households (GS4b) strengthens the effect of forest tenure reform (O2a), mainly due to variations in property rights transfer (GS4d) [57], enhancing property rights exclusivity, forest resource protection, and reducing transaction costs.

6.2. Limitations

This study, while providing valuable insights into the impact of forest tenure reform on carbon sequestration capacity, has certain limitations that must be acknowledged. Firstly, the data utilized in this research may only extend up to the year 2015. A more extensive dataset, encompassing more recent years, could allow for a more nuanced exploration of the effects during the period of forest tenure reform's supporting measures. The limitation in the temporal scope of the data may constrain the comprehensiveness of the findings. Secondly, the results are primarily based on provincial-level panel data. If more micro-level data were available, such as county-level information, the results could potentially be more detailed and reflective of local variations and specificities. The reliance on provincial data may mask underlying heterogeneities that could be vital for a more granular understanding of the subject. Lastly, in the mechanism part of the study, the focus has been mainly on the impact of capital efficiency. While this provides significant insights, there may exist other pathways of influence that have not been explored in this research. These unexamined aspects could offer additional perspectives on the subject and are worth further investigation.

The recognition of these limitations does not diminish the value of the study but rather points to areas where future research could expand and deepen the understanding of forest tenure reform and its effects on carbon sequestration capacity. By addressing these limitations in subsequent studies, the field can move closer to a more comprehensive and nuanced understanding of this complex and vital subject. These insights also lay the groundwork for the conclusions and policy implications that follow, as they highlight the key findings and their practical applications.

7. Conclusions and Policy Implications

This paper, through the construction of the SES framework and the use of various models and theories, delves into the impact of the new round of forest tenure reform on forest carbon sequestration capacity. The key conclusions are: (1) reform has had a positive and sustainable impact on forest carbon sequestration capacity, verified for robustness; (2) the effect is achieved through the improvement of capital factor productivity, reflecting capital-biased technological progress; (3) the abundance of collective forest resources and the degree of confirmation of forest rights to households influence the impact, whereas regional differences in forestry income do not significantly affect it.

Based on the above conclusions, the following policy implications are obtained: (1) as the improvement of forest carbon sequestration capacity by forest tenure reform has a positive effect, it is necessary to continuously deepen the relevant supporting measures of forest tenure reform, including clarifying property rights boundaries, especially in areas with abundant collective forest resources, to achieve sustainable growth of forest carbon sequestration; (2) considering the important role played by the improvement of capital factor productivity in the carbon sequestration effect of forest tenure reform, under the premise of clear property rights, forest land circulation and the construction of new forest management entities should be actively promoted to enable forest capital factor to play a greater role in forestry development while removing relevant institutional barriers, promoting the professional development of forestry, and reducing reliance on traditional labor elements, thereby enhancing forest carbon sequestration capacity; (3) the analytical framework of this article also reminds us that the improvement of forest carbon sequestration capacity is not a single goal. When considering the social-ecological background, the achievement of the goal of forest tenure reform for increased income should also be considered, and the

sustainable enhancement of forest carbon sequestration capacity can be better promoted through feedback effects.

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

Notes

- ¹ Chinese government website, “The State Forestry Administration and other departments will improve the collective forest land system reform from four aspects,” Chinese government website, 13 January 2014. http://www.gov.cn/govweb/wszb/zhibo601/content_2565308.htm (accessed on 24 March 2023).
- ² UNFCCC. Methodological Issues: Land-use, Land-use Change and Forestry [EB/OL]. Submissions from Parties, SBSTA 13th Session, Lyon, 11–15 September 2000. <http://unfccc.int/resource/docs/2000/sbsta/misc06.pdf> (accessed on 20 February 2023).
- ³ The data in Table 2 shows an average value of 45 tons/hectare, lower than Brazil’s 125 tons/hectare but higher than China’s 35 tons/hectare based on Global Forest Resource Assessment data. However, China’s average value does not consider litter and soil carbon storage, making it inaccurate. Overall, the selected forest carbon sequestration capacity data are reasonable and reflects carbon storage trends.

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