frontiers | Frontiers in Forests and Global Change

TYPE Original Research
PUBLISHED 18 September 2025
DOI 10.3389/ffgc.2025.1622580

OPEN ACCESS

EDITED BY
Lingli Qing,
Guangzhou College of Commerce, China

REVIEWED BY
Roberto Alonso González-Lezcano,
CEU San Pablo University, Spain
Boyao Song,
Beijing Forestry University, China
Guang Yang,
Beijing Forestry University, China
Longbo Ma,
Qingdao Agricultural University, China

*CORRESPONDENCE
Hanxiang Luo
✉ lhx1997@webmail.hzau.edu.cn

RECEIVED 04 May 2025
ACCEPTED 02 September 2025
PUBLISHED 18 September 2025

CITATION
Wei J, Wang F, Xie T and Luo H (2025) Impact of collective forestland tenure reform on household forestry production efficiency: micro-level evidence from China. *Front. For. Glob. Change* 8:1622580. doi: 10.3389/ffgc.2025.1622580

Impact of collective forestland tenure reform on household forestry production efficiency: micro-level evidence from China

Jian Wei[1], Fangzheng Wang[1], Tianwei Xie[2] and Hanxiang Luo[3]*

[1]Fujian Agriculture and Forestry University, Fuzhou, China, [2]Graduate School of Business Administration, Dong Shin University, Naju, Republic of Korea, [3]College of Economics and Management, Huazhong Agricultural University, Wuhan, China

Improving forestry production efficiency is crucial for advancing rural economic development and ecological modernization in China. Using panel data from 13,536 rural households in 18 counties across nine provinces during 2003 and 2007–2019, this study investigates the impact of collective forestland tenure reform on household-level forestry production efficiency. A translog stochastic frontier production function model is applied to estimate efficiency, while Tobit and mediation effect models are used to explore the underlying mechanisms. The results show that tenure reform significantly enhances forestry production efficiency, primarily by increasing production inputs, expanding forestland management scale, and improving access to credit. Further heterogeneity analysis indicates that the positive effects are more pronounced among households with pure farming livelihoods, bamboo or economic forest cultivation, and in less-developed or forest-rich regions. These findings highlight the importance of tenure security in stimulating investment incentives, promoting efficient resource reallocation, and facilitating financial inclusion in rural forestry. Policy implications include strengthening forestland tenure security, developing transparent forestland transfer markets, and innovating credit systems, with particular emphasis on supporting the sustainable management of long-cycle timber forests to balance economic benefits with ecological goals.

KEYWORDS

collective forest tenure reform, forestry production efficiency, production inputs, management scale, credit accessibility, livelihood strategies

1 Introduction and literature review

Since the 18th National Congress of the Communist Party of China, the concept that "lucid waters and lush mountains are invaluable assets" has become a central tenet of ecological civilization. Forests, as critical ecological and economic resources, play a dual role in ensuring national ecological security and supporting rural livelihoods. However, challenges such as slow forest resource accumulation, limited income contribution to farmers, and insufficient ecological product supply have exposed deep-rooted structural problems, notably the low productivity of forestland. These issues stem from institutional deficiencies in property rights definition and protection within China's collective forest system. In response, the Chinese government launched a new round of collective forest rights reform, officially implemented nationwide in 2008, with the aim of clarifying tenure and granting farmers greater autonomy over forestland management. The latest policy blueprint—The Plan for Deepening the Reform of the Collective Forest Rights System (2023)—further emphasizes clarity of ownership, strict protection, orderly transfer, and effective oversight by 2025. Given that farmers are the most immediate actors in forest production, changes in property rights institutions directly influence their factor allocation decisions and management efficiency. Against this backdrop, this study investigates the impact of forest rights reform on farmers' forestry production efficiency and explores its underlying mechanisms. By identifying the behavioral pathways through which reform affects efficiency, the study contributes to the literature on institutional change in rural resource governance and offers practical guidance for promoting sustainable forestry development under China's evolving policy framework.

Research on forestry production efficiency is extensive. From the perspective of resource endowment, factors such as natural capital (Liang et al., 2022; Shi et al., 2024), human capital (Xue and Yao, 2017; Yang et al., 2018; Zhu et al., 2018), and financial capital (Xue and Yao, 2014) all affect farmers' forestry production efficiency. From the perspective of natural environmental factors, due to the unique natural attributes of forestry, natural elements such as heat, water, light, and soil nutrients that influence tree growth also have an impact on farmers' forestry production efficiency (Lu et al., 2018). In addition to resource endowment and natural environmental factors, differences in time, space, tree species, and management scale also produce heterogeneous effects on farmers' forestry production efficiency (Zhang and Jiang, 2023; Huang et al., 2016; Li et al., 2010; Li et al., 2014; Tian and Shi, 2017). However, the most widely discussed and academically emphasized factor is the institutional arrangement of forest land property rights (Li, 2010; Liu and Ravenscroft, 2016), which directly relates to the input–output level and operational efficiency of economic agents (Liu and Yu, 2007). Clear and stable forest property rights can motivate farmers to manage forest land more effectively, improve the refinement level of forestry production, and thereby enhance forestry production efficiency (Deacon, 1994; Gao, 2007). Correspondingly, without secure and long-term forest property rights, farmers are often reluctant to make long-term investments, thus reducing the efficiency of production factor allocation (Long, 2009; Wang et al., 2010). It is thus evident that ineffective property rights arrangements are a key cause of low forestry production efficiency (Das, 2022). Recent empirical evidence further substantiates this perspective. For instance, Yi (2023) finds that the devolution of forestland tenure significantly increased farmers' labor and capital inputs in afforestation and silviculture, stimulated long-term management incentives, and consequently improved forest resource conditions—manifested in higher average tree height, crown width, and stand volume, alongside enhanced ecological functions. Similarly, Xu and Hyde (2019) emphasize that China's second round of collective forest tenure reform, through enhancing policy stability, clarifying tenure boundaries, and extending contract periods, effectively boosted farmers' investment incentives and led to improved forestry management performance. In addition, some studies have shown that the type of ownership has a significant impact on farmers' forestry production efficiency (Qin and Xu, 2013; Wallace and Newman, 1986). When forest property rights are categorized by ownership into joint ownership and individual ownership, individual ownership has a significantly positive impact on forestry production efficiency compared to joint ownership (Wang et al., 2010; Zhang and Yu, 2009) which aligns with Gao (2007)'s view that forestry production efficiency under decentralized management is not necessarily lower than that under joint management. However, some studies argue that reclaiming self-managed forest land that is divided but not properly managed and placing it under unified collective management can also effectively improve forestry production efficiency (Yiwen, 2024).

A review of existing literature helps to clarify the relationship between forest rights reform and farmers' forestry production efficiency, offering important insights for this study. Most current research evaluating the policy effects of forest rights reform focuses on aspects such as forestland transfer, forestry production investment, and farmers' income growth. While many studies have investigated the economic impacts of forest rights reform—including forestland transfer, forestry investment, and income generation—few have directly examined its influence on forestry production efficiency at the household level. Yet households are the fundamental decision-making units in forest use and management, and their choices directly determine the allocation of production factors, investment horizons, and efficiency outcomes. Overlooking this level risks obscuring substantial heterogeneity in how reforms affect forest use. Moreover, among the limited studies that touch on production efficiency, most tend to treat it as a secondary outcome, without systematically exploring the underlying mechanisms. That is, the pathways through which forest rights reform affects farmers' forestry production efficiency have not yet been adequately revealed.

This study aims to fill these gaps by explicitly focusing on the household level and by constructing a theoretical framework that explains how forest rights reform influences forestry production efficiency. Drawing on household survey data from 18 counties across 9 provinces in China, the analysis considers both the direct and indirect effects of forest rights reform on forestry efficiency through the use of a mediation effect model, thereby enhancing our understanding of the policy's impact mechanisms. By doing so, this paper not only complements existing macro-level research but also provides a micro-level perspective that reveals behavioral heterogeneity and decision-making dynamics often hidden in aggregate analyses. Furthermore, the study explores the heterogeneous policy effects under varying conditions of forest resource endowment and regional economic development, as well as household livelihood strategies and planting structures—providing more targeted recommendations for policy design and contributing unique empirical evidence to the broader debate on institutional reforms and sustainable forest management.

2 Institutional background and research hypotheses

2.1 Institutional background

Since the 1980s, many countries—including China—have implemented forestland tenure reforms through decentralization (Akinola and Wissink, 2019). The primary goal of decentralization in forest governance is to reduce management costs and improve operational efficiency in forestry (De Soto and Diaz, 2002). However, due to inadequate tenure clarification and weak property rights protection in many developing countries (Yeh, 2004), forest decentralization has often failed to improve forest resource management effectively (Sunseri, 2003), and most tenure reforms have not achieved their intended outcomes (Edmunds and Wollenberg,

 10.3389/ffgc.2025.1622580

2001; Larson et al., 2007). China's new round of collective forest tenure reform (hereinafter referred to as "forest rights reform") represents an important component of its rural property rights reform. In 1981, the reform began with the "Three Fixes" policy, which marked the start of de facto household allocation of collective forestland. However, widespread deforestation and over-exploitation led to the suspension of the reform in 1987. In the late 1990s, the marketization of China's forestry sector drove up timber prices, increasing farmers' demand for secure property rights over forest resources. In 2003, the Central Committee of the Communist Party of China and the State Council issued the Decision on Accelerating Forestry Development, launching pilot programs in provinces such as Zhejiang, Jiangxi, Fujian, and Liaoning. These pilots sought to allocate use rights over collectively managed forestland to households through formal tenure confirmation. Building on the successes of the pilot programs, in 2008, the central government issued the Opinions on Comprehensively Promoting the Reform of the Collective Forest Tenure System, which marked the nationwide implementation of forest rights reform. This policy emphasized contracting collective forestland to households and granting them secure forestland use rights, including the rights to transfer, mortgage, and manage their holdings. In September 2023, the Plan for Deepening the Reform of the Collective Forest Rights System was issued by the CPC Central Committee and the State Council. The plan aims to establish, by 2025, a collective forest tenure system characterized by clear ownership, unified rights and responsibilities, strict protection, orderly transfer, and effective supervision. The new reform stage emphasizes easing governmental restrictions on forestland transfers and mortgages to diversify channels for realizing the value of forest property rights. Together with the confirmation and certification of tenure, mechanisms for circulation and mortgage have now become integral components of the reform's incentive structure. The 20th National Congress of the Communist Party of China also explicitly called for deepening the reform of the collective forest tenure system, reflecting the state's high-level policy commitment. It is evident that achieving high-quality development in China's forestry sector requires further improvements to the collective forest tenure system to enhance its attractiveness for long-term investment. This, in turn, provides a practical opportunity to improve the efficiency and productivity of forestland.

Against this backdrop, this paper investigates how forest rights reform affects farmers' forestry production efficiency under the new institutional context. The study offers both theoretical and practical value for strengthening farmers' capacity for sustainable forest management in the current policy environment.

2.2 Theoretical mechanisms and research hypotheses

2.2.1 Forest rights reform, forestry production investment, and farmers' forestry production efficiency

Clear and stable forest property rights help strengthen farmers' perception of tenure security, induce stable expectations, and incentivize increases in forestry capital and labor inputs, which in turn promote improvements in forestry production efficiency. Specifically, first, they enhance the exclusivity of forest property rights. Stable forest tenure can effectively reduce the risk of land being expropriated by governments, institutions, or other individuals (Demsetz, 1967), strengthen the actual control of operators over forestland, lower the risk of operational interruptions in forestry production, and stimulate farmers' willingness to increase forestry investment, However, it is important to note that increased investment alone does not automatically result in efficiency gains. According to the theory of capital deepening (Solow, 1956), investment improves efficiency only when capital is effectively allocated relative to labor and land. In forestry, this requires that additional investment be directed toward productivity-enhancing inputs such as advanced planting techniques, better seedlings, or improved soil management (Zhang et al., 2004). Moreover, stable property rights not only increase the volume of investment but also improve its quality and long-term orientation, reducing risk and encouraging more rational resource allocation. This combination of quantity and quality in investment contributes to more efficient use of production factors, thus enhancing overall production efficiency. Second, they enable the liberalization of property rights transactions. Strengthening the security of forest tenure can effectively reduce transaction costs and uncertainties, and by facilitating the effective physical concentration of forestland or its transfer to more capable operators, it encourages farmers to expand long-term forestry investments, thus optimizing the allocation efficiency of forestry production factors. Finally, they ensure the internalization of forestry returns. Forest rights reform, by clarifying property boundaries and the attributes of forestland as private property, limits the dissipation of rent in the public domain caused by ambiguous property rights, minimizes the risk of losing anticipated investment returns in forestry production, and enhances farmers' willingness to invest production factors, thereby exerting a positive impact on forestry production efficiency.

> *H1:* Forest rights reform incentivizes increased forestry input, thereby improving production efficiency.

2.2.2 Forest rights reform, expansion of forestland management scale, and farmers' forestry production efficiency

Forest rights reform improves forestry production efficiency by reducing forestland transaction costs and risks, thereby guiding farmers to expand their forestland management scale. First, forest rights reform facilitates the effective reallocation of forestland resources by promoting the transfer of land from farmers with low production efficiency to those with higher efficiency, which enhances the coordination and matching of key factors such as land, capital, and labor, thus improving forestry production efficiency. Second, strengthening the stability of forest property rights helps cultivate and improve the forestland transfer market. When farmers have the willingness to expand their forestland management scale, they are more likely to find lessors through a more transparent and well-functioning transfer market, which encourages greater investment in forestry production and promotes efficiency improvements. Finally, the current distribution of forestland based on equal shares per capita has led to fragmented and scattered forestland layout structures, resulting in high unit input costs per plot and limiting gains in production efficiency. Through forestland inflow, farmers can increase their management scale to approach or reach an optimal level, which not only helps reduce unit input costs and achieve moderate economies of scale, but also facilitates the introduction of more advanced technologies and management practices to optimize forestry production structures and ultimately enhance forestry production efficiency.

> *H2:* Forest rights reform promotes efficiency gains by incentivizing larger-scale forestland operations.

2.2.3 Forest rights reform, enhanced credit accessibility, and farmers' forestry production efficiency

Forest rights reform signifies that forest property rights receive credible recognition and protection through formal institutions on a long-term and stable basis. On this foundation, the reform further grants forestland the rights to be used as collateral and guarantees under contractual arrangements, significantly enhancing the liquidity of forest resources and the market value of forest property rights. On one hand, strengthening the stability of forest property rights can effectively overcome problems of adverse selection and moral hazard in the credit market caused by information asymmetry, reduce the contract supervision costs for financial institutions, as well as the costs of contract enforcement in cases of default, thereby increasing their willingness to supply credit. On the other hand, forest rights mortgage loans, as an extended mechanism of collateralization, help activate forestry assets to increase household wealth and strengthen financial institutions' confidence in the collateral value of forestry assets, thus alleviating the difficulty rural households face in lacking traditional effective collateral. Therefore, forest rights reform, by enhancing the credit accessibility of forest property rights, significantly improves the credit supply–demand relationship in rural forestry financial markets. This not only optimizes the allocation efficiency of forestry production factors such as land, capital, and labor, but also strengthens farmers' investment capacity in forestry, thereby improving forestry production efficiency. The relationship between credit access and efficiency can be explained through the theory of credit constraints (Feder et al., 1990; Petrick, 2004), which suggests that limited access to formal financing channels prevents rural households from acquiring timely inputs or adopting advanced technologies. When credit is made more accessible through the formal recognition of collateralized forest rights, farmers can overcome liquidity constraints and smooth consumption and investment cycles. Additionally, improved credit access enhances risk-taking capacity and allows for longer-term planning, both of which are essential for efficiency gains in forestry operations. In this context, forest rights reform not only increases credit availability but also indirectly promotes optimal input allocation and technological upgrading, further contributing to improvements in forestry production efficiency.

> *H3:* Forest rights reform enhances forestry production efficiency via improved credit access.

3 Research design

3.1 Data sources

The data used in this study are derived from the large-scale long-term household survey database established by the Development Research Center of the National Forestry and Grassland Administration. To ensure data accuracy, a stratified random sampling technique was employed. Nine provinces (regions)—Liaoning, Henan, Shandong, Sichuan, Guangxi, Hunan, Jiangxi, Zhejiang, and Fujian—were selected as the study areas. In each province (region), two counties were chosen; in each county, three townships were selected; in each township, three administrative villages were sampled; and in each village, 15 sample households were randomly selected. After removing invalid samples with inconsistent observation periods or contradictory questionnaire information, the final dataset consists of 13,536 household observations from the years 2003 and 2007–2019. Household-level data for 2004–2006 are unavailable because the national survey project was temporarily suspended during this period due to funding and organizational adjustments, and it resumed in 2007.

Using the rural means of production price index and the rural consumer price index, the data for relevant variables were converted into constant 1994 prices. Specifically, provincial-level rural Consumer Price Indices (CPI) published by the National Bureau of Statistics were used to deflate monetary variables, with 1994 set as the base year. This adjustment was applied to all value-related indicators, including forestry income, production inputs, and household expenditure. Using province-specific indices ensures that the spatial and temporal differences in inflation levels are accurately captured, thereby enhancing the intertemporal and interregional comparability of the micro-level data.

The selection of the nine provinces (regions) was based on their representativeness in terms of forest resource endowment, collective forestland distribution, and the progress of forest rights reform implementation. These provinces span different geographical regions (e.g., Northeast, Central, Southwest, and Southeast China) and ecological zones, and they cover most of the dominant collective forest types (e.g., coniferous, broadleaf, and mixed forests) as well as diverse tenure arrangements. Therefore, they provide a broadly representative picture of China's major collective forest areas. However, it should be noted that they do not fully capture contexts such as arid regions or areas dominated by state-owned forests in western China, where tenure systems and ecological conditions differ substantially. Hence, the results should be interpreted as representative of collective forest regions, and caution is warranted in making generalizations to other tenure contexts.

3.2 Variable selection

3.2.1 Dependent variable

This study uses the forestry production efficiency loss estimated by the translog stochastic frontier production function model as the representative variable for forestry production efficiency. The forestry input indicators include forestland management scale, forestry capital input, and forestry labor input, while the output indicator is the total value of forestry production. To ensure data stability, the logarithmic transformation of forestry production efficiency is applied in this study.

3.2.2 Core explanatory variable

The core explanatory variable in this study is forest rights reform. The primary mechanism through which the reform achieves the "allocation of forestland to individual households" is the confirmation and certification of tenure rights. At present, the majority of farmers have obtained forest tenure certificates for all their forestland plots, with property rights clearly defined. Only a small portion of farmers hold equity certificates—documents similar in function to forest tenure certificates—for a limited number of plots, while most of their forestland has already been confirmed and certified with forest tenure certificates. Although the government has recently promoted the issuance of real estate certificates and forest management right certificates based on the existing tenure system, their overall issuance rates remain low. Forest tenure certificates still constitute the dominant form of certification for collective forestland. Therefore, using the status of tenure confirmation and receipt of a forest tenure certificate as the policy variable for the new round of forest rights reform is both appropriate and representative. In this study, households that have completed tenure confirmation and obtained a forest tenure certificate are assigned a value of 1, while those that have not are assigned a value of 0.

3.2.3 Mediating variables

The mediating variables in this study include forestry production input, expansion of forestland management scale, and enhancement of credit accessibility. Forestry production input is represented by the household's forestry capital and labor inputs. Expansion of forestland management scale is represented by whether the household has transferred in forestland. Enhancement of credit accessibility is represented by whether the household has obtained a forest rights mortgage loan from a financial institution.

3.2.4 Control variables

The control variables in this study are categorized into four groups. First, market characteristic variables, including the price of non-agricultural labor and the price of timber. Second, household characteristic variables, including the age, gender, years of education, and health status of the household head, whether the household head is a village cadre, household size, proportion of labor force in the household, total household income, proportion of forestry income, and whether the household engages in non-agricultural employment. Third, resource characteristic variables, including forestland area. Fourth, village characteristic variables, including whether the road is paved, whether the village is located in a mountainous area, and the distance from the county seat. It should be noted that if a control variable is binary, it is coded as 0 or 1; otherwise, continuous variables are log-transformed. Detailed variable descriptions and descriptive statistics are provided in Table 1.

3.3 Model specification

3.3.1 Baseline model specification

Among the various methods for measuring production efficiency, Stochastic Frontier Analysis (SFA) is one of the most

TABLE 1 Variable definitions and descriptive statistics.

Variable Name	Variable definition	Mean	Standard deviation
Forestry production efficiency	Forestry production efficiency loss based on SFA model	0.6852	0.2001
Forest rights reform	Forest rights confirmed and certificate Issued (yes = 1; no = 0)	0.6162	0.4863
Forestry capital input	Total investment in forestry management (Yuan)	622.6112	3045.001
Forestry labor input	Total time spent on forestry management (person-days)	31.9945	65.6863
Expansion of forestland management scale	Whether the household transferred in forestland (Yes = 1; No = 0)	0.0725	0.2593
Enhanced credit accessibility	Whether the household obtained a forest rights mortgage loan (yes = 1; no = 0)	0.0165	0.1272
Livelihood strategy	Pure farming = 1; mixed farming = 2; Non-farming = 3	2.0287	0.7315
Non-agricultural labor price	Unit: yuan	52.8723	21.5415
Timber price	Unit: yuan	439.3289	97.3423
Age	Unit: years	52.149	11.0257
Gender	Male = 1; female = 0	0.9694	0.1721
Years of education of household Head	Unit: years	7.3187	2.8496
Health status	Healthy = 1; not healthy = 0	0.8951	0.3064
Household head is village cadre	Yes = 1; no = 0	0.2428	0.4288
Household size	Unit: people	3.9328	1.5076
Number of household laborers	Unit: people	2.7074	1.2344
Total household income	Unit: yuan	16946.2931	22027.3811
Proportion of forestry income	Unit: %	0.1123	0.2090
Non-agricultural employment	Yes = 1; no = 0	0.6923	0.4616
Forestland area	Unit: mu (1 Mu = 0.0667 Hectares)	38.3976	73.138
Paved road surface	Yes = 1; no = 0	0.7674	0.4225
Mountainous area	Yes = 1; no = 0	0.5580	0.4966
Distance to county seat	Unit: km	35.4196	31.3447

widely adopted approaches. SFA, initially developed by Aigner et al. (1977) and Meeusen and van Den Broeck (1977), enables the decomposition of deviations from potential output into two components: random noise and inefficiency. This is particularly important in forestry production, where output fluctuations are not solely attributable to farmers' decisions but are also significantly affected by uncontrollable environmental factors such as weather, pests, and soil variability.

In recent years, SFA has been widely applied in studies on agricultural and forestry production efficiency, especially in the context of institutional reforms and land tenure security. For instance, Yu et al. (2021) used SFA to examine the technical efficiency of collective forest operators in China, finding that collective forest tenure reform had a significant effect on efficiency outcomes. Similarly, Zhang and Chen (2022) applied SFA to assess the impact of land tenure on agricultural productivity. These studies demonstrate the suitability of the SFA approach in empirical contexts that involve property rights structures and natural resource-based production.

In specifying the production frontier, this study adopts a translog functional form rather than the commonly used Cobb–Douglas function. The translog form offers greater flexibility by not imposing restrictive assumptions such as constant returns to scale or unitary elasticity of substitution among inputs. This allows us to capture non-linear relationships as well as substitution and complementarity effects among production factors such as labor, land, and capital—features that are particularly relevant in forestry production, where input interactions are heterogeneous and complex. Thus, the translog SFA specification provides a more accurate and realistic representation of farmers' production technology.

Therefore, this study adopts a translog-form stochastic frontier production function model to estimate farmers' forestry production efficiency. The model is constructed as follows:

$$\ln Y_{it} = \beta_0 + \beta_1 \ln S_{it} + \beta_2 \ln K_{it} + \beta_3 \ln L_{it} + \beta_4 \ln S_{it}^2 + \beta_5 \ln K_{it}^2 + \beta_6 \ln L_{it}^2 + \beta_7 \left(\ln S_{it}\right)\left(\ln K_{it}\right) + \beta_8 \left(\ln S_{it}\right)\left(\ln L_{it}\right) + \beta_9 \left(\ln K_{it}\right)\left(\ln L_{it}\right) + V_{it} - U_{it} \quad (1)$$

In Equation 1, Y denotes forestry output; S denotes the area of forestland managed; K represents forestry capital input; L denotes forestry labor input; i represents the i-th household; t is the time variable; $\beta_0, \beta_1, \beta_2 \cdots \beta_9$ are the parameters to be estimated; V_{it} is the random error term, which follows an independent normal distribution with a mean of zero and variance of σ_v^2; That is, $V_{it} \sim N\left(0, \sigma_v^2\right)$; U_{it} represents the forestry production efficiency that is, the gap between actual output and the maximum attainable output on the production frontier. Loss term for farmers. It is assumed that U_{it} follows a truncated normal distribution, i.e., $U_{it} \sim N\left(u, \sigma_u^2\right)$, thereby reflecting the loss in forestry production efficiency.

Since the values of forestry production efficiency loss lie within the interval [0, 1], they represent censored data. Therefore, this study employs the Tobit model for econometric analysis. This is because the inefficiency term is a limited dependent variable, and applying ordinary least squares (OLS) would result in biased and inconsistent estimates. The Tobit model is more appropriate for dealing with censored outcomes and is widely adopted in two-stage stochastic frontier analysis frameworks (e.g., Battese and Coelli, 1995), where the inefficiency scores are treated as latent variables constrained within a specific range. Referring to the empirical model of Qian (2017), the baseline model is specified as follows:

$$u_{it} = \delta_0 + \delta_1 D_{it} + \delta_2 X_{it} + \theta_i + \varepsilon_{it} \quad (2)$$

In Equation 2, u_{it} represents the forestry production efficiency loss of farmers, indicating the gap between actual output and the output under the optimal technological level. D denotes whether the farmer has completed tenure confirmation and obtained a forest rights certificate; if yes, then $D_{it}=1$, otherwise $D_{it}=0$, X is the vector of control variables; ä$_0$ is the constant term; δ_1, δ_2 are parameters to be estimated, if δ is negative, it indicates that the corresponding variable has a positive effect on forestry production efficiency; conversely, if δ is positive, it indicates a negative effect; θ_i represents time fixed effects; ε_{it} is the random error term.

All parameter estimates of the stochastic frontier production function model determined by Equations 1, 2 can be obtained using the maximum likelihood estimation (MLE) method. The maximum likelihood function utilizes two variance parameters:

$$\gamma = \sigma_u^2 / \sigma_v^2 + \sigma_u^2 \left(0 \le \gamma \le 1\right) \quad (3)$$

In Equation 3, ä reflects the proportion of the production efficiency loss component within the composite error term. When ä pproaches 0, it indicates that the gap between actual output and the maximum possible output is primarily due to uncontrollable random factors, suggesting the absence of significant efficiency differences; in this case, the use of the stochastic frontier production function model may be inappropriate, indicating model misspecification. Conversely, when ä approaches 1, it implies that the gap is mainly attributable to production efficiency loss, making the application of the stochastic frontier production function model more appropriate.

3.3.2 Mediation effect model

This study primarily draws on the methodology proposed by Ye et al. (2002), and the mediation effect model is constructed as follows:

$$tran_{it} = \alpha_0 + \alpha_1 D_{it} + \alpha_2 X_{it} + \theta_i + \varepsilon_{it} \quad (4)$$

$$u_{it} = \gamma_0 + \gamma_1 D_{it} + \gamma_2 tran_{it} + \gamma_3 X_{it} + \theta_i + \varepsilon_{it} \quad (5)$$

In Equations 4, 5, $tran_{it}$ represents the mediating variable, α_1, γ_1, and γ_2 re parameters to be estimated, α_0, γ_0 are constant terms, and other variables are defined as above. The basic procedure for testing the mediation effect is as follows: first, test the estimated coefficient δ_1 in Equation 2; if δ_1 is statistically significant, then proceed to the second step, otherwise stop the test. Second, test the estimated coefficient α_1 in Equation 4; if α_1 is significant, proceed to the third step. Third, test the estimated coefficient γ_2 in Equation 5; if γ_2 is significant, a mediation effect is considered to exist.

4 Empirical results analysis

4.1 Regression results of the translog stochastic frontier production function

The regression analysis of Equation 1 is conducted using Stata software. As shown in Table 2, the Wald chi2(9) statistic for testing the null hypothesis of "no production efficiency loss" is 1231.15, with a *p*-value of 0.0000, indicating that the null hypothesis is rejected at the 1% significance level and confirming the existence of production efficiency loss. Based on the estimated values of parameters σ_v and σ_u from the regression results, the coefficient value of γ is calculated as 0.9925, suggesting that 99.25% of the composite error term originates from the production efficiency loss U, while the random error V accounts for only 0.75%. This indicates that the translog stochastic frontier production function provides a good fit for estimating the input–output relationship in farmers' forestry production.

4.2 Analysis of factors influencing farmers' forestry production efficiency

Table 3 reports the regression results of factors influencing farmers' forestry production efficiency. The results show that forest rights reform has a significant negative effect on forestry production efficiency loss at the 1% statistical level, indicating that the reform has a positive impact on improving farmers' forestry production efficiency. Timber prices also exhibit a negative effect on efficiency loss, suggesting that expanding the profit margin of forest products is an important driving force for improving production efficiency.

Among the control variables, several demonstrate effects consistent with theoretical expectations. Years of education of the household head, household size, and whether the head is a village cadre all show significant negative effects on efficiency loss at the 1% level, indicating that both human capital and social capital play vital roles in enhancing production efficiency. Total household income and the proportion of forestry income also exhibit significant negative coefficients, suggesting that the availability of material capital—especially income derived from forestry—is critical to sustaining efficient forestry practices. Forestland area shows a significantly negative relationship with efficiency loss, supporting the view that managing larger-scale forest plots (i.e., lower forest fragmentation) helps reduce inefficiencies, likely by enabling economies of scale and more intensive management.

Conversely, participation in non-agricultural employment significantly increases production efficiency loss. This finding may reflect the labor diversion effect: as household labor shifts toward non-forestry jobs, less attention is given to forest management, resulting in more extensive and less efficient forestry practices. Additionally, some natural and infrastructural variables show significant effects. For instance, paved road surface is negatively associated with efficiency loss, highlighting the importance of transportation infrastructure in improving market access and reducing transaction costs. Meanwhile, the coefficient for mountainous area is significantly negative, indicating that favorable agroecological conditions—such as sunlight, water, and heat—can support higher productivity in forestry operations.

4.3 Robustness check

To verify the reliability and consistency of the empirical findings presented in Section 4.2—particularly the effect of forest rights reform on forestry production efficiency—we conduct a series of robustness checks in this section. These tests aim to address potential endogeneity, sample selection bias, and omitted variable bias that may affect the baseline regression estimates. To ensure the robustness of the baseline regression results, a series of robustness checks were conducted (Table 4). First, the proportion of forestland with confirmed rights at the county level was used as a proxy for forest rights reform instead of the household-level variable, which helps to mitigate potential self-selection bias that may arise during pilot implementations of the reform. The results show that forest rights reform continues to have a significant positive effect on farmers' forestry production efficiency, confirming the robustness of the findings. Second, provinces that implemented forest rights reform earlier as pilot regions may be more representative than others; thus, after excluding the four earliest pilot provinces—Liaoning, Zhejiang, Fujian,

TABLE 2 Regression results of the stochastic frontier production function for farmers' forestry input and output.

Variable	Estimated coefficient	Standard error	Z-statistic	Variable	Estimated coefficient	Standard error	Z-statistic
Constant	6.8111***	0.1414	48.16	Forestland area × Forestry labor	−0.0002	0.0018	−0.13
Forestland area	0.0244	0.0224	1.09	Forestry production costs × Forestry labor	−0.0041***	0.0007	−5.90
Forestry production costs	0.1692***	0.0108	15.62	σ_v	0.8136***	0.0213	38.17
Forestry labor	0.1975***	0.0161	12.30	σ_u	9.3586***	0.0874	107.06
Squared forestland area	0.0331***	0.0023	14.31	Log likelihood	−42297.67		
Squared forestry production costs	0.0188***	0.0014	13.67	Wald chi2(9)	1231.15		
Squared forestry labor	0.0313***	0.0027	11.76	Prob > chi2	0.0000		
Forestland area × Forestry production costs	−0.0080***	0.0024	−3.29	Number of observations	13,536		

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

TABLE 3 Regression results of factors influencing farmers' forestry production efficiency.

Variable	Estimated coefficient	Standard error	T-statistic	Variable	Estimated coefficient	Standard error	T-statistic
Forest rights reform	−0.0209***	0.0019	−10.90	Non-agricultural employment	0.2475***	0.0210	11.81
Non-agricultural labor price	0.0000	0.0005	0.10	Forestland area	−0.0007***	0.0001	−5.61
Timber price	−0.0009***	0.0001	−8.32	Paved road surface	−0.0356*	0.0208	−1.71
Age	−0.0007	0.0009	−0.70	Mountainous area	−0.2094***	0.0179	−11.68
Gender	0.0705	0.0471	1.50	Distance to county seat	0.0003	0.0003	1.07
Years of education of household head	−0.0215***	0.0031	−6.88	Constant	3.7372***	0.1068	34.98
Health status	−0.0381	0.0358	−1.06	Year fixed effects	Yes		
Household head is village cadre	−0.1117***	0.0197	−5.68	Regional fixed effects	Yes		
Household size	−0.0237***	0.0061	−3.88	Log likelihood	−16234.311		
Number of household laborers	−0.0479	0.0376	−1.27	Prob > chi2	0.0000		
Total household income	−0.1512***	0.0074	−20.48	Number of observations	13,536		
Proportion of forestry income in household income	−3.9079***	0.0466	−83.80	Pseudo R^2	0.199		

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

TABLE 4 Robustness check.

Variable	Substitution of core explanatory variable	Exclusion of pilot provinces	Exclusion of confounding policy effects
Forest rights reform	−0.0183*** (0.0032)	−0.0149*** (0.0024)	−0.0169*** (0.0019)
Control variables	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Regional fixed effects	Yes	Yes	Yes
Constant	3.7175*** (0.1075)	3.4559*** (0.1446)	3.6739*** (0.1057)
Number of observations	13,536	7,752	13,536
Pseudo R^2	0.197	0.220	0.206

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

and Jiangxi—the results still indicate a significant positive effect of forest rights reform on forestry production efficiency. Third, during the implementation of forest rights reform, other related policies affecting farmers' forestry production efficiency may have been introduced concurrently, potentially confounding the estimated effects. The results show that after controlling for policies such as the logging quota management system, forest insurance programs, and participation in forestry cooperatives, the positive effect of forest rights reform on forestry production efficiency remains significant.

4.4 Endogeneity check

Given that endogeneity may affect the stability of parameter estimates, this study employs the instrumental variable Tobit (IV-Tobit) model to address the potential endogeneity of forest rights reform. For the choice of instrumental variable, this paper uses forestland adjustment, based on two main considerations. First, forestland adjustment is closely related to forest rights reform, as the government may select pilot areas for reform based on the historical frequency of forestland adjustments within a village. In villages that have undergone such adjustments, the implementation of forest rights reform may serve different purposes: where land-use conflicts are severe, the reform helps accumulate experience in tenure clarification; where such conflicts are relatively mild, the reform is easier to carry out. Therefore, regardless of the severity of land-use conflicts, villages with a history of forestland adjustment are more likely to be selected as reform pilots, satisfying the relevance condition of the instrumental variable. Second, forestland adjustment does not directly affect farmers' forestry production efficiency, but it is highly likely to influence it through forest rights reform. Specifically, what may affect farmers' efficiency is not the past occurrence of land adjustment per se, but the perceived likelihood of future adjustments. The expectation of future adjustments may undermine tenure stability and security, thereby reducing farmers' willingness to invest in and manage forestland. Forest rights reform, by reducing the uncertainty of future land adjustments, can enhance tenure stability and security. This satisfies the exclusion restriction required for instrument exogeneity (Table 5).

The estimation results using the instrumental variable approach are presented in Table 5. In the IV-Tobit model, the first-stage regression involves an ordinary least squares (OLS) regression of the instrumental variable—forestland adjustment. The coefficient of the instrument is positive and statistically significant at the 1% level. Furthermore, the F-statistic of the first-stage regression exceeds the conventional threshold of 10 and is significant at the 1% level, thereby rejecting the null hypothesis of a weak instrument. This indicates that forestland adjustment is strongly and positively associated with forest rights reform and can serve as a valid instrument, effectively addressing the potential endogeneity of the reform variable.

The second-stage regression results show that the exogeneity assumption of forest rights reform is rejected based on the Wald test for exogeneity, which is significant at the 1% level. This confirms the presence of endogeneity in forest rights reform, underscoring the necessity of using an instrumental variable approach. After correcting for endogeneity, the coefficient on forest rights reform remains significantly positive, indicating that the reform continues to exert a robust and favorable effect on farmers' forestry production efficiency. These findings affirm the validity of the study's core conclusion.

5 Further analysis

5.1 Mechanism analysis

To identify the role of the mediation effect, it is first necessary to estimate the impact of forest rights reform on the mediating variables (Table 6).

Table 6 reports the regression results of how forest rights reform influences farmers' forestry production efficiency through mediating variables. First, forest rights reform significantly promotes increased investment in forestry capital and labor [Table 5, columns (1)–(2)], and both forestry capital and labor have a significant negative effect on farmers' forestry production efficiency. After incorporating forestry capital and labor inputs, the positive effect of forest rights reform on farmers' forestry production efficiency remains significant [Table 6, columns (1)–(2)]. Therefore, it can be concluded that forestry capital and labor inputs play a mediating role, meaning that forest rights reform enhances farmers' forestry production efficiency by incentivizing increased forestry production inputs, which is consistent with the theoretical analysis and supports H1. Second, forest rights reform has a significant positive effect on farmers' expansion of forestland management scale [Table 5, column (3)], and both forest rights reform and the expansion of forestland management scale have a significant positive effect on farmers' forestry production efficiency [Table 6, column (3)]. This indicates that the expansion of forestland management scale plays a mediating role, meaning that forest rights reform improves forestry production efficiency by guiding farmers to expand forestland management scale, which aligns with the theoretical analysis and supports H2. Finally, forest rights reform has a significant positive effect on farmers' credit accessibility [Table 5, column (4)], and both forest rights reform and credit accessibility have a significant positive effect on farmers' forestry production efficiency [Table 7, column (4)]. Thus, credit accessibility plays a mediating role, meaning that forest rights reform improves farmers' forestry production efficiency by enhancing credit accessibility, which is consistent with the theoretical analysis and supports H3. In conclusion, under the constraints of initial resource endowment in forestry production, farmers' behavioral decisions have already formed inherent path dependencies. The changes in the allocation of production factors and management decisions brought about by forest rights reform have, to some extent, broken through the boundary of resource allocation capability, thus improving farmers' forestry production efficiency.

5.2 Extension analysis

It has been confirmed in the previous sections that forest rights reform has a significant positive effect on farmers' forestry production efficiency. However, does the actual effect of forest rights reform on forestry production efficiency vary among different farmers? To address this question, this section attempts to examine the heterogeneous effects of the forest rights reform policy from two

TABLE 5 Results of the endogenous regression.

Variables	Instrumental variable first-stage regression	Instrumental variable second-stage regression
Forestland adjustment	0.0463*** (0.0014)	
Forest rights reform		−0.0394*** (0.0069)
Control variables	Yes	Yes
Year fixed effects	Yes	Yes
Regional fixed effects	Yes	Yes
Constant	0.0233 (0.0477)	3.7242*** (0.1073)
F	214.12***	
Wald test		9661.76***
Wald test of exogeneity		7.90*** (0.0050)
Number of observations	13,536	13,536

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

TABLE 6 The impact of forest rights reform on mediating variables.

Variable	Forestry capital	Forestry labor	Expansion of forestland management scale	Enhanced credit accessibility
	(1)	(2)	(3)	(4)
Forest rights reform	0.1687*** (0.0159)	0.1903*** (0.0122)	0.0363*** (0.0046)	0.0648*** (0.0137)
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Regional fixed effects	Yes	Yes	Yes	Yes
Constant	−1.6167*** (0.0891)	−0.9796*** (0.0685)	−3.1097*** (0.2997)	−4.3845*** (0.5393)
Number of observations	13,536	13,536	13,536	13,536
Pseudo R^2	0.168	0.164	0.102	0.311

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

TABLE 7 Forest rights reform, mediating variables, and farmers' forestry production efficiency.

Variable	Forestry production efficiency			
	(1)	(2)	(3)	(4)
Forest rights reform	−0.0217* (0.0114)	−0.0200*** (0.0019)	−0.0204*** (0.0057)	−0.0153*** (0.0055)
Forestry capital	−0.0841*** (0.0270)			
Forestry labor		−0.0501*** (0.0140)		
Expansion of forestland management scale			−0.0996** (0.0450)	
Enhanced credit accessibility				−0.1180*** (0.0440)
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Regional fixed effects	Yes	Yes	Yes	Yes
Constant	3.7838*** (0.4105)	3.6862*** (0.1076)	4.5627*** (0.4149)	5.3176*** (0.3102)
Number of observations	13,536	13,536	13,536	13,536
Pseudo R^2	0.223	0.199	0.211	0.211

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

perspectives: the differences in land livelihood strategies and forestry planting structures at the household level, and the differences in forest resource abundance and economic development levels at the regional level.

5.2.1 Heterogeneity of livelihood strategies

Farmers with different resource endowments develop heterogeneous livelihood strategies by aligning their household resources with their labor advantages. This inevitably leads to significant differences in farmers' forestry management levels, which is an important factor affecting forestry production efficiency. This study, referring to Liu (2020), measures livelihood strategies based on the occupational types reflecting the production and management structure of farmers' households. The classification is made according to the proportion of non-agricultural employment in the household labor allocation, dividing farmers into pure farming households, mixed farming households, and non-farming households. Table 8 reports the impact of forest rights reform on farmers' forestry production efficiency under different livelihood strategies. The results show that the effect of forest rights reform weakens as the degree of non-agriculture in the livelihood strategy increases. Among samples with a low degree of non-agricultural livelihood strategies, such as pure farming households, forest rights reform has a greater positive effect on forestry production efficiency. However, for non-farming households, the reform does not show significant effects. Therefore, the positive feedback effect of forest rights reform on farmers' forestry production efficiency increases as the degree of non-agriculture in the livelihood strategy decreases.

This finding has broader implications for rural migration and labor transitions. The absence of significant reform effects among non-farming households indicates that as more rural labor shifts to off-farm employment, households become less responsive to forestry-related institutional incentives. This reflects a livelihood diversification trend in which non-farm households prioritize stable wage income over long-cycle forestry investment. From a policy perspective, this suggests the need for differentiated approaches: while tenure security and ecological compensation may further encourage forestry engagement among farming households, non-farming households may benefit more from policies facilitating forestland transfer, cooperative management arrangements, or mechanisms linking forestry rights with off-farm income opportunities. Such tailored measures can ensure that forest resources remain effectively utilized while also supporting rural households in their broader livelihood transitions.

TABLE 8 Policy effects of forest rights reform under different livelihood strategies.

Variable	Pure farming households	Mixed farming households	Non-farming households
Forest rights reform	−0.0123** (0.0055)	−0.0070** (0.0034)	−0.0022 (0.0124)
Control variables	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Regional fixed effects	Yes	Yes	Yes
Constant	3.2817*** (0.2581)	2.9469*** (0.2169)	6.4634*** (0.5083)
Number of observations	3,786	5,132	4,618
Pseudo R^2	0.359	0.221	0.304

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

5.2.2 Heterogeneity in forestry planting structures

Table 9 reports the effects of forest rights reform on farmers' forestry production efficiency under different forestry planting structures. The results show that forest rights reform has a significant positive effect on the forestry production efficiency of households engaged in bamboo and economic forest cultivation, but no significant policy effect on those managing timber forests. This suggests that after the reform, farmers still tend to prefer managing bamboo and economic forests, which are characterized by shorter growth cycles, higher levels of intensive management, and shorter investment recovery periods. Their traditional management mindset has not undergone a significant shift, and the enthusiasm for managing timber forests—which have longer growth cycles, lower levels of intensification, and extended economic return periods—has not been fully stimulated. To further confirm this finding, we subdivide the timber forest category into fast-growing and high-yield timber forests and general timber forests. The results indicate that forest rights reform has a significant positive effect on the forestry production efficiency of households managing fast-growing timber forests with shorter growth cycles, but no significant positive impact on those managing general timber forests with longer growth cycles. This further supports the above conclusion.

These results carry important policy implications. Although timber forests contribute less to short-term household efficiency, they play a critical role in long-term carbon sequestration, biodiversity conservation, and climate change mitigation. The weaker reform effects observed in this category suggest that existing incentives are insufficient to encourage households to invest in long-cycle timber forests. To better align economic and ecological objectives, future reforms could incorporate mechanisms such as carbon credit trading, ecological compensation, and enhanced tenure security to strengthen farmers' incentives for sustainable timber forest management. In this way, forest rights reform can contribute not only to rural livelihoods but also to national carbon neutrality and climate goals.

5.2.3 Heterogeneity in economic development level and forest resource abundance

Table 10 reports the estimated effects of forest rights reform on farmers' forestry production efficiency under different levels of economic development and forest resource abundance. Specifically, farmers are categorized by regional economic development level into those in the central and western regions and those in the eastern region, and by forest resource abundance into those in forest-rich southern regions and forest-scarce northern regions. The results show that forest rights reform has a significant positive effect on forestry production efficiency for farmers in the central and western regions as well as those in the southern forest-rich regions. In contrast, the reform does not have a significant effect on farmers in the eastern or northern regions. These findings indicate that differences in regional location lead to substantial variation in the market and natural environments faced by farmers, resulting in different production preferences and capabilities, which in turn shape heterogeneous production structures and income-generating capacities. Therefore, farmers in economically less developed and forest-rich regions tend to have a higher dependence on forest resources, which is more conducive to leveraging the comparative advantage of forestry production, enhancing efficiency, and expanding the profitability of forestry.

In particular, the more pronounced effect observed in central and western (often poverty-stricken) regions may be attributed to lower initial production efficiency, which allows forest rights reform to generate greater marginal improvements through enhanced tenure security and institutional incentives. These regions often face structural constraints in accessing capital, technology, and markets, so policy-driven improvements in forest property rights directly address key barriers to productive investment. Furthermore, poverty-alleviation programs and ecological compensation policies tend to concentrate in these areas, creating a synergistic environment that reinforces the reform's effect. These mechanisms together help explain why the efficiency gains from forest rights reform are more prominent in less developed areas.

5.2.4 Heterogeneity in the degree of forest tenure certification

The view that secure forestland tenure can enhance farmers' forestry production efficiency is widely supported in the academic literature (Li et al., 2014; Liu and Lv, 2007), and the findings of this study also confirm this perspective. At the national level, forest rights reform has contributed to improvements in farmers' forestry production efficiency. However, in the implementation process, the reform has been largely guided by a standardized approach to the delineation of collective forestland ownership and use rights. For example, one of the key indicators used to evaluate the reform's progress is the certification rate of collective forestland. Field investigations reveal that most farmers have received forest tenure certificates for all of their forestland plots, with ownership clearly defined. However, a small portion of farmers have not received

TABLE 9 Policy effects of forest rights reform under different forestry planting structures.

Variable	Bamboo forest	Economic forest	Timber forest	Fast-growing high-yield timber forest	General timber forest
Forest rights reform	−0.0209*** (0.0019)	−0.0211*** (0.0019)	−0.0378 (0.1180)	−0.0216*** (0.0019)	0.0062 (0.0138)
Control variables	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Constant	3.7287*** (0.1069)	3.7375*** (0.1071)	3.5700*** (0.6388)	3.7451*** (0.1080)	3.5341*** (0.7847)
Number of observations	13,536	13,536	13,536	13,536	13,536
Pseudo R^2	0.199	0.199	0.215	0.200	0.215

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

TABLE 10 Policy effects of forest rights reform under differences in economic development level and forest resource abundance.

Variable	Economic development level		Forest resource endowment	
	Eastern region	Central and western region	Northern region	Southern region
Forest rights reform	−0.0181 (0.0129)	−0.0267*** (0.0029)	−0.0103 (0.0343)	−0.0215*** (0.0024)
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Constant	5.1074*** (0.3725)	4.2746*** (0.1719)	3.2595*** (0.2091)	3.8065*** (0.1303)
Number of observations	5,856	7,680	4,416	9,120
Pseudo R^2	0.1852	0.2463	0.2112	0.1797

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

certificates for all of their forestland. Although the majority of their plots have been certified, the remaining uncertified plots are still under their management, and the associated income remains with the farmers. This raises an important question: does the proportion of certified forestland affect farmers' investment decisions, and thereby influence forestry production efficiency? As shown in Table 11, a higher certification ratio of collective forestland is associated with a greater improvement in forestry production efficiency. This finding suggests that even though farmers retain the income rights to uncertified plots, certified plots exert a stronger policy incentive effect on their forestry behavior and efficiency outcomes.

6 Conclusion and policy recommendations

6.1 Conclusion and discussion

Based on nationally representative rural household survey data from China, this study aims to explore the impact and underlying mechanisms of forest rights reform on farmers' forestry production efficiency from the perspective of household behavior. The main findings and their broader implications are discussed below.

First, forest rights reform has a significant promoting effect on farmers' forestry production efficiency, indicating that the reform has led to a qualitative improvement in farmers' production decision-making without causing an over-concentration of production factors. This finding is consistent with the conclusions of Li et al. (2014). However, building upon existing research, this study further analyzes the underlying reasons behind the positive correlation between forest rights reform and forestry production efficiency. It finds that increased forestland investment, expansion of forestland management scale, and enhanced credit accessibility play important mediating roles in the process through which forest rights reform improves production efficiency. Nonetheless, the efficiency-enhancing effect of forest rights reform faces several challenges amid the evolving socio-economic environment and changing forestry-related policies. For example, rising factor prices may reduce farmers' willingness to invest in forestry; irregularities in the forestland transfer market may lead to a low rate of land inflow; and alternative credit channels with interest rates comparable to or even lower than forest rights mortgage loans—without requiring physical collateral—may diminish the advantages of such loans. These realities not only weaken the positive effects of forest rights reform on production efficiency but also constrain the transformation of traditional self-sufficient smallholders into specialized and professionalized forestry operators, such as large-scale forestry households, cooperatives, family forest farms, and forestry enterprises. Moreover, they also hinder the development of emerging forestry-related industries such as forest tourism and forest wellness services.

Second, regarding the heterogeneous effects of forest rights reform on farmers' forestry production efficiency under different forestry planting structures, the reason why forest rights reform significantly improves the production efficiency of farmers cultivating bamboo forests, economic forests, and fast-growing high-yield timber forests—but not those managing general timber forests—lies in the risk perception associated with insecure forest property rights. In general, the lack of secure property rights increases the risk of forestry investment for farmers, often resulting in short-sighted behavior and a preference for planting tree species with shorter growth cycles. Bamboo, economic forests, and fast-growing timber forests are characterized by short growth cycles, a high degree of intensive management, and short investment recovery periods, whereas general timber forests are the opposite. Therefore, the differences in growth

TABLE 11 The impact of the certification ratio of collective forestland on farmers' forestry production efficiency.

Variable	Forestry production efficiency	
	(1)	(2)
Collective forestland certification ratio	−0.0513*** (0.0029)	−0.0325*** (0.0023)
Control variables		Yes
Year fixed effects		Yes
Regional fixed effects		Yes
Constant	2.0333*** (0.0259)	3.8453*** (0.1066)
Number of observations	13,536	13,536
Pseudo R^2	0.008	0.201

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

cycles among tree species lead to variations in management levels. Although forest rights reform has strengthened the de facto stability of forest property rights, farmers still tend to prioritize economic returns and thus prefer species with shorter production and management cycles, showing limited enthusiasm for cultivating general timber forests with long production cycles. Their traditional management mindset has not fundamentally changed.

This raises an important issue: whether planting bamboo, economic forests, or fast-growing timber forests, these types of management typically require intensive cultivation involving human intervention and excessive use of chemical fertilizers and pesticides to shorten the growth period and quickly obtain economic benefits. Such practices inevitably lead to overly homogeneous forest structures, which are detrimental to the long-term provision of ecosystem services and the sustainable management of forests. Especially in the current stage, as China transitions toward its "dual carbon" goals, timber forests—which account for more than 50% of total forestland—play a crucial role in ecological functions such as soil and water conservation, climate regulation, and carbon sequestration. For general timber forests with longer growth cycles, their carbon sequestration capacity and total carbon storage increase over time, thereby enhancing the ecological value of natural resources. As such, balancing national ecological goals with farmers' economic interests remains a key practical issue that forest rights reform must address.

Third, as the degree of non-agriculture in livelihood strategies decreases, the positive effect of forest rights reform on farmers' forestry production efficiency shows an increasing trend. For pure farming households, since forestry income occupies an important position in their household income structure, strengthening the stability of forest property rights will encourage farmers to improve forestry production efficiency by increasing forestry production inputs or optimizing the allocation of forestry production factors, thus enhancing their comparative advantage in forestry production. It is noteworthy that the lower the degree of non-agriculture in livelihood strategies, meaning the more singular the source of household livelihood, the higher the farmers' dependence on forestry production, making them more vulnerable to shocks from changes in the market environment. Fortunately, farmers with a comparative advantage in forestry production are more likely to transition from traditional smallholders to new forestry operators such as large forestry households, forestry enterprises, family forest farms, and forestry cooperatives after forest rights reform, thus gaining economies of scale by improving forestry production efficiency.

For mixed farming households, their reliance on forestry production is relatively weaker than that of pure farming households. Therefore, the effect of forest rights reform on improving mixed farming households' forestry production efficiency is relatively weaker, mainly due to the combined effects of the "push" of disadvantages in forestry production comparative returns and the "pull" of the advantages of non-agricultural employment comparative returns, which further enables the effective linkage between rural labor force and the non-agricultural employment market. This leads to a weakening of the incentive effect for forestry production investment caused by the labor force's non-agricultural migration. For non-farming households, their dependence on forestry production is even smaller, and they generally do not rely on forestry production as their primary source of livelihood, resulting in less investment in forestland production. Clearly, the higher the degree of non-agriculture in livelihood strategies, the more non-farming households with a comparative advantage in non-agricultural employment will tend to accelerate the further non-agricultural migration of household labor to strengthen their comparative advantage in non-agricultural employment. This leads to a relative increase in non-agricultural income, which gradually weakens the economic security function of forestland, causing forest rights reform to have no significant effect on their forestry production efficiency.

This finding also resonates with international experience. In Africa and Latin America, tenure reforms have been shown to enhance investment incentives primarily among households that continue to rely on land and forests, whereas those transitioning to non-farm livelihoods benefit less unless complemented by land transfer markets, cooperatives, or ecological compensation programs. This suggests that China's forest rights reform could further benefit from differentiated strategies that account for household livelihood diversification and migration trends.

Finally, several limitations of this study should be acknowledged. First, although the data used are drawn from nationally representative rural household surveys, the specific sample areas primarily cover forest-rich regions in southern China. This may limit the generalizability of the findings to other regions with different forest tenure structures, ecological conditions, or institutional environments. Second, while the model includes a broad range of control variables to account for household heterogeneity, potential omitted variables—such as detailed forestland quality indicators, farmers' risk attitudes, or access to forestry extension services—may still influence the relationship between forest rights reform and production efficiency. These unobserved factors may introduce bias into the estimation results. Future studies could consider applying panel data and advanced identification strategies (e.g., instrumental variables or natural experiments) to improve internal validity and assess the robustness of these findings across regions and time.

6.2 Policy recommendations

1) Consolidate forest tenure security and ensure long-term policy consistency

10.3389/ffgc.2025.1622580

While forest rights reform has significantly improved farmers' forestry production efficiency, several implementation challenges remain. These include incomplete tenure confirmation and certification, unresolved disputes over overlapping claims on collective forestland, and uncertain future policy orientations—all of which weaken farmers' expectations of long-term returns and deter investment in sustainable forest management. The government should accelerate the completion of forestland rights confirmation, registration, and certification, while further reinforcing the long-term stability of forest tenure. Institutional mechanisms must be established to protect farmers' lawful rights over contracted forestland, thus strengthening their intrinsic motivation to engage in both ecological conservation and productive forest management.

2) Promote standardization and marketization of forestland transfers

To improve the efficiency of forestland allocation, it is critical to support the development of intermediary service organizations in the forestland transfer market, improve the legal and institutional frameworks governing forest property rights transactions, and encourage the aggregation of forestland to farmers or enterprises with comparative advantages. In particular, differentiated policies should be considered to support the transfer and consolidation of long-cycle timber forest plots, which often require larger scales of operation to justify long-term investment and generate ecological value.

3) Innovate forest rights-based financing mechanisms

The current forest rights mortgage system is constrained by high transaction costs and risk perceptions among financial institutions. Through institutional innovation, these barriers should be lowered by enhancing risk-sharing mechanisms, strengthening forest asset valuation standards, and developing inclusive financial products tailored for forestry. Especially for long-rotation timber forests, which have limited short-term liquidity but considerable ecological and future economic value, specialized credit instruments and government-backed guarantees may be necessary to unlock financing potential.

In practical terms, local rural commercial banks could establish dedicated forest-rights mortgage loan programs, in which certified forest tenure certificates serve as collateral and repayment schedules are aligned with the long growth cycles of forestry production. Rural credit cooperatives could adopt collective-guarantee models to reduce default risk, enabling smallholders without sufficient collateral to access credit. Forestry cooperatives and associations could further serve as intermediaries, securing bulk credit lines from financial institutions and redistributing funds to member households based on their production needs. In addition, integrating carbon credit trading and ecological compensation schemes into rural finance systems could provide farmers—particularly those managing long-cycle timber forests—with advance payments or low-interest loans linked to the expected ecological value of their forests. These concrete mechanisms would strengthen the connection between tenure security and financing access, thereby amplifying the positive effects of forest rights reform on forestry production efficiency.

4) Enhance differentiated policy support to balance ecological and economic goals

Greater attention should be given to farmers with low capacity to engage in non-agricultural livelihoods. Targeted support should encourage their transformation into professional forestry operators such as large-scale households, family forest farms, and forestry enterprises. Site-specific guidance on tree species selection and diversified forest management models—such as agroforestry, forest-based health services, and undergrowth economy—should be promoted to raise land-use efficiency and economic resilience. In particular, a differentiated ecological compensation system should be established to reward households engaged in long-cycle ecological forestry. Subsidy standards can be calibrated based on forest type, growth cycle, and expected ecological benefits, thereby incentivizing sustained investment in ecological forestry and facilitating a synergy between environmental protection and economic development.

5) Promote ecologically sustainable forestry through incentive-based regulation and structural guidance

To balance economic efficiency and ecological sustainability, differentiated ecological compensation mechanisms should be further developed to support the cultivation of long-rotation timber forests with high ecological value. This can include payment schemes for ecosystem services (PES), subsidies linked to carbon sequestration performance, or tax incentives for biodiversity-friendly forestry practices. In practical terms, compensation can be structured in multiple ways—for example, per hectare of forestland to provide a stable baseline subsidy, per ton of carbon sequestered to directly support climate goals, or based on biodiversity and ecosystem service indicators (such as species diversity or soil and water conservation capacity) to encourage broader ecological outcomes. A hybrid design that combines area-based payments with performance-based bonuses could balance simplicity, fairness, and ecological effectiveness.

Meanwhile, forest management guidelines should encourage species diversification and reduced chemical inputs, especially in areas dominated by short-cycle economic species. In regions undergoing rapid forestland transfer and intensified production, regulatory frameworks should include ecological red lines and minimum reforestation standards. By embedding sustainability into the incentive and regulatory system, it is possible to align farmers' economic interests with long-term ecological goals.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JW: Writing – original draft, Software, Formal analysis, Conceptualization, Data curation, Methodology, Investigation. FW: Funding acquisition, Methodology, Writing – original draft, Data curation, Investigation, Conceptualization. TX: Conceptualization, Investigation, Writing – original draft. HL: Resources, Software, Visualization, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by Youth Project of Fujian Provincial Social Science Fund (FJ2025C158) by JW; Fujian Agriculture and Forestry University Innovation Special Fund Project Grant Program (KCX23F24A) by JW; China National Forestry and Grassland Development Research Center Commissioned projects (JYC-2024-0041) by JW.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aigner, D., Lovell, C. A. K., and Schmidt, P. (1977). Formulation and estimation of stochastic frontier production function models. *J. Econom.* 6, 21–37. doi: 10.1016/0304-4076(77)90052-5

Akinola, A. O., and Wissink, H. (2019). Trajectory of land reform in post-colonial African states. Cham, Switzerland: Springer Naturyrland AG. doi: 10.1007/978-3-319-78701-5

Battese, G. E., and Coelli, T. J. (1995). A model for technical inefficiency effects in a stochastic frontier production function for panel data. *Empir. Econ.* 20, 325–332. doi: 10.1007/BF01205442

De Soto, H., and Diaz, H. P. (2002). The mystery of capital. Why capitalism triumphs in the west and fails everywhere else. *Can. J. Lat. Am. Caribb. Stud.* 27:172.

Deacon, R. T. (1994). Deforestation and the rule of law in a cross-section of countries. *Land Econ.* 70, 414–430. doi: 10.2307/3146638

Demsetz, H. (1967). Toward a theory of property rights. *Am. Econ. Rev.* 57, 347–359. doi: 10.1057/9780230523210

Das, B. K. (2022). How to make forest governance reform real? Formal and informal institutions during implementation of the forest rights act 2006 in India. *Environmental Development*. 43:100729. doi: 10.1016/j.envdev.2022.100729

Edmunds, D., and Wollenberg, E. (2001). Historical perspectives on forest policy change in Asia: an introduction. *Environ. Hist.* 6, 190–212. doi: 10.1093/envhis/6.2.190

Feder, G., Lau, L. J., Lin, J. Y., and Luo, X. (1990). The relationship between credit and productivity in Chinese agriculture: a microeconomic model of disequilibrium. *Am. J. Agric. Econ.* 72, 1151–1157. doi: 10.2307/1242524

Gao, L. Y. (2007). Analysis of collective forestland scale management: discussion with forestland scale management view. *Issues Forest. Econ.*, 4:376–379. doi: 10.16832/j.cnki.1005-9709.2007.04.020

Huang, S., Wang, G., Deng, X., and Chen, J. (2016). Analysis on pattern and regional difference of forestry production efficiency in China. *World Forest. Res.* 29, 80–85. doi: 10.13348/j.cnki.sjlyyj.2016.03.009

Lu, S., Chen, N., Zhong, X., Huang, J., and Guan, X. (2018). Factors affecting forestland production efficiency in collective forest areas: A case study of 703 forestland plots and 290 rural households in Liaoning, China. *Journal of Cleaner Production*. 204, 573–585. doi: 10.1016/j.jclepro.2018.09.013

Larson, A. M., Pacheco, P., Toni, F., and Vallejo, M. (2007). Trends in Latin American forestry decentralisations: legal frameworks, municipal governments and forest dependent groups. *Int. Forestry Rev.* 9, 734–747. doi: 10.1505/ifor.9.3.734

Li, F. N., Huang, A. S., and Zhang, C. X. (2010). An empirical analysis of bamboo operating efficiency DEA in Fujian Province: one of the studies on bamboo operating efficiency. *J. Central South Univ. Forest. Technol.* 4, 12–14. doi: 10.14067/j.cnki.1673-9272.2010.02.032

Li, H., Yao, S. B., Liu, C., and Guo, Y. (2014). Production factors input and efficiency of different commercial forests under collective forest decentralization: based on three-stage DEA model and farmer survey data in Fujian and Jiangxi provinces. *Forestry Science* 50, 122–130.

Liang, C., Wei, X., Meng, J., and Chen, W. (2022). How to improve forest carbon sequestration output performance: an evidence from state-owned forest farms in China. *Forests* 13:778. doi: 10.3390/f13050778

Liu, C. (2020). The reforms of collective forestland tenures transfer in China: retrospectives, key issues and path selection. *Reform* 4, 133–147.

Liu, P., and Ravenscroft, N. (2016). Collective action in China's recent collective forestry property rights reform. *Land Use Policy* 59, 402–411. doi: 10.1016/j.landusepol.2016.09.011

Liu, C., and Lv, J. Z. (2007). The study on collective forestland tenure in China. *Instit. Econ. Res.*, 80–105.

Liu, C., and Yu, F. W. (2007). Technical efficiency and poverty alleviation of collective forest system in southern China: a case study of Muchuan, Jinzhai and Suichuan counties. *China Rural Survey* 40, 16–26. doi: 10.20074/j.cnki.11-3586/f.2007.03.0022007

Long, D. G. (2009). Land right transaction and production factor combination: 1650–1950. *Econ. Res.* 44, 146–156.

Meeusen, W., and van Den Broeck, J. (1977). Efficiency estimation from cobb-Douglas production functions with composed error. *Int. Econ. Rev.* 18, 435–444. doi: 10.2307/2525757

Petrick, M. (2004). Farm investment, credit rationing, and governmentally promoted credit access in Poland: a cross-sectional analysis. *Food Policy* 29, 275–294. doi: 10.1016/j.foodpol.2004.05.002

Qin, P., and Xu, J. (2013). Forest land rights, tenure types, and farmers' investment incentives in China: an empirical study of Fujian Province. *China Agric. Econ. Rev.* 5, 154–170. doi: 10.1108/17561371311294829

Qian, H. (2017). Skills and knowledge-based entrepreneurship: Evidence from US cities. *Regional Studies* 51, 1469–1482. doi: 10.1080/00343404.2016.1213383

Shi, X., Zhao, S., Lu, S., Wang, T., and Xu, X. (2024). The effect of farmers' livelihood capital on non-agricultural income based on the regulatory effect of returning farmland to forests: a case study of Qingyuan Manchu autonomous county in China. *Small-Scale For.* 23, 59–83. doi: 10.1007/s11842-023-09554-y

Solow, R. M. (1956). A contribution to the theory of economic growth. *Q. J. Econ.* 70, 65–94. doi: 10.2307/1884513

Sunseri, T. (2003). Reinterpreting a colonial rebellion: forestry and social control in German East Africa, 1874–1915. *Environ. Hist.* 8, 430–451. doi: 10.2307/3986203

Tian, J., and Shi, C. N. (2017). Study on the allocative efficiency of forestry production factors and its influencing factors of farmers with different scale of forest management. *Issues Forest. Econ.* 37, 73–78, 109. doi: 10.16832/j.cnki.1005-9709.2017.05.013

Wallace, T. D., and Newman, D. H. (1986). Measurement of ownership effects on forest productivity in North Carolina from 1974 to 1984. *Can. J. For. Res.* 16, 733–738. doi: 10.1139/x86-131

Wang, C. J., He, X. R., Xu, X. Y., and Wang, S. (2010). Forestland scale efficiency and forestland transfer among farmers: an empirical study from Zhejiang province. *J Agrotech Econ*, 58–65. doi: 10.13246/j.cnki.jae.2010.10.001

Wang, Y. J., Huang, S. W., and Su, S. P. (2019). Property right heterogeneity, forestland transfer and forestry management efficiency: a survey of 664 mountainous households in Fujian Province. *Res. Dev. Market* 35, 162–167.

Xu, J., and Hyde, W. F. (2019). China's second round of forest reforms: observations for China and implications globally. *Forest Policy Econ.* 98, 19–29. doi: 10.1016/j.forpol.2018.04.007

Xue, C. X., and Yao, S. B. (2014). Forest management behavior and technical efficiency of different types of farmers in western China: a survey of farmers in ya'an city, Sichuan Province. *J. Forest. Econ.* 34, 298–303. doi: 10.16832/j.cnki.1005-9709.2014.04.002

Xue, C. X., and Yao, S. B. (2017). The impact of household labor allocation on the operating efficiency of non-wood forest products in western China: based on the analysis of cost efficiency and profit efficiency. *Iss. Forest. Econ.* 37:108, 65–72. doi: 10.16832/j.cnki.1005-9709.2017.05.012

Yang, S. S., Xu, X. Y., and Shi, D. J. (2018). Effects of aging labor force on utilization efficiency of bamboo forestland: an empirical study based on mediation effect. *For. Sci.* 54, 132–142.

Yeh, E. T. (2004). Property relations in Tibet since decollectivisation and the question of 'fuzziness'. *Conserv. Soc.* 2, 163–187.

Yi, Y. (2023). Devolution of tenure rights in forestland in China: impact on investment and forest growth. *Forest Policy Econ.* 154:103025. doi: 10.1016/j.forpol.2023.103025

Yu, J., Wei, Y., Fang, W., Liu, Z., Zhang, Y., and Lan, J. (2021). New round of collective Forest rights reform, forestland transfer and household production efficiency. *Land* 10:988. doi: 10.3390/land10090988

Yiwen, Z. (2024). Governance structures, resource mobilization, and organizational performance of community forest enterprises: Evidence from China. *Forest Policy and Economics*. 163:300. doi: 10.1016/j.forpol.2024.103229

Ye, X.-J., Wang, Z.-Q., and Li, Q.-S. (2002). The ecological agriculture movement in modern China. *Agriculture, Ecosystems & Environment*. 92:261–281. doi: 10.1016/S0167-8809(01)00294-8

Zhang, J., and Chen, Q. (2022). The impact of farmland tenure security on China's agricultural production efficiency: a perspective of agricultural production factors. *Sustainability* 14:16266. doi: 10.3390/su142316266

Zhang, Y. S., and Yu, W. S. (2009). Economic power structure and optimal allocation of factors of production. *Econ. Res.* 44, 65–72.

Zhang, B., Zhang, Y., Chen, D., White, R. E., and Li, Y. (2004). A quantitative evaluation system of soil productivity for intensive agriculture in China. *Geoderma* 123, 319–331. doi: 10.1016/j.geoderma.2004.02.015

Zhu, Y., Liu, Q., and Wu, W. G. (2018). The feminization of forestry labor force and its impact on forestry production efficiency: a case study of bamboo production. *J Agrotech Econ* 5, 104–111. doi: 10.13246/j.cnki.jae.2018.05.009

Zhang, B., and Jiang, X. (2023). Research on forestry labor input measurement and forestry industry development in China. *Forestry Economics Review*, 5, 2–22. doi: 10.1108/FER-03-2023-0003