Forest Policy and Economics 161 (2024) 103168

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Does an inconsistent land tenure certificate affect technical efficiency of smallholder rubber farming: Evidence from a panel data in Southwest China

Shi Min [a], Junfei Bai [b,c], Xiaobing Wang [d,*], Hermann Waibel [e]

[a] College of Economics and Management, Huazhong Agricultural University, China
[b] Beijing Food Safety Policy & Strategy Research Base, China Agricultural University, China
[c] College of Economics and Management, China Agricultural University, China
[d] China Center for Agricultural Policy, School of Advanced Agricultural Sciences, Peking University, China
[e] Institute of Development and Agricultural Economics, Leibniz University Hannover, Germany

ARTICLE INFO

Keywords:
Forestland tenure
Inconsistency
Rubber farming
Technical efficiency

ABSTRACT

The existing rural land tenure system in many developing countries is characterized by imperfections and conflicts. In rural regions of China, although most farmers possess land tenure certificates, there are instances where these certificates do not align with the actual land use. This study examines the technical efficiency (TE) of smallholder rubber farming at the plot level in Xishuangbanna Dai Autonomous Prefecture (XSBN) in Yunnan Province, China, using three-wave panel data. Additionally, the study aims to estimate the impact of inconsistent land tenure certificates on rubber plantations. The TE of smallholder rubber farming in XSBN ranged from 0.01 to 0.89, with an average of 0.554. The possession of a land tenure certificate indirectly enhances the TE of smallholder rubber farming by optimizing factor inputs. Furthermore, the TE of rubber plantations with forestland tenure certificates surpasses that of rubber plantations with farmland tenure certificates. This investigation sheds light on the issue of inconsistent land tenures in the context of economic forest expansion in southern China and advocates for further research in related areas. The findings contribute to the existing empirical evidence on the TE of smallholder rubber farming.

1. Introduction

While land tenure reform has been conducted in most developing countries in past decades, the current rural land tenure systems remain imperfect and sometimes run with some flaws or violations. In rural China, although land tenure and institutional reforms have made most farmers obtain land tenure certificates, the type of land tenure certificate is occasionally inconsistent with actual land use. This situation typically emerges when the use of farmland is converted into economic forests, but the farmland tenure is not correspondingly changed to forestland tenure, and it is particularly prevalent in mountainous areas. For example, in recent decades, the land use in the upper Mekong region in Southwest China has dramatically changed, and rainforest, secondary forest, jungle, and farmland have been converted to monoculture rubber plantations (Chapman, 1991; Xu et al., 2005; Fu et al., 2009; Fox and Castella, 2013; Min et al., 2017a, 2019). Because of legal concerns, rubber plantations converted from rainforests cannot be issued tenure certificates, while those converted from economic forests can obtain forestland tenure certificates. However, rubber plantations that have been converted from farmland can be granted either farmland or forestland tenure certification in an early period. With land conversion under the ‘Grain to Green’ program,[1] farmland-converted rubber plantations are frequently issued forestland tenure certificates. Nevertheless, the farmland-converted rubber plantations, which are not supported by the ‘Grain to Green’ program, are only granted farmland tenure certificates. Accordingly, plantations growing natural rubber may have different types of land tenure certificates.

A question arises as to whether different types of land tenure certificates for rubber plantations could result in variations in rubber production. Do the similarities or differences in the two types of land tenure

* Corresponding author at: Room 418, Wangkezhen Building, No. 5 Yiheyuan Road, Haidian District, Beijing 100871, China.
E-mail addresses: min@mail.hzau.edu.cn (S. Min), jfbai@cau.edu.cn (J. Bai), xbwang.ccap@pku.edu.cn (X. Wang), waibel@ifgb.uni-hannover.de (H. Waibel).

[1] A program implemented in some regions of China to improve the local ecological environment by encouraging the conversion of farmland to forestland. For details, please refer to the study of Xu et al. (2006).

https://doi.org/10.1016/j.forpol.2024.103168
Received 29 December 2022; Received in revised form 12 January 2024; Accepted 28 January 2024
Available online 8 February 2024
1389-9341/

certificates play significant roles in the performance of rubber production? In the literature, numerous studies have investigated the productivity effects of land property rights and land tenure systems (Anderson and Lueck, 1992; Place and Hazell, 1993; Ouedraogó et al., 1996; Gavian and Ehui, 1999; Smith, 2004; Place, 2009; Huang et al., 2017; Lawin and Tamini, 2018). However, the findings are ambiguous. For instance, the study by Place and Otsuka (2002) concluded that tenure implications were considered by farmers when making investments, while tenure had no impact on the productivity of crop farming in central Uganda. In contrast, Holden et al. (2009) found significant and positive effects of the low-cost land certification implemented in Ethiopia on the investment in trees and land productivity. The systematic review by Place (2009) found heterogeneities in the relationships between land tenure security and agricultural productivity in Africa. It argued that the relations might hinge on the overarching macro and sectoral conditions within which tenure systems operate.

In rubber production, although some studies have examined productivity and technical efficiency (TE) (Son et al., 1993; Suyanto et al., 2001; Giroh and Adebayo, 2007, 2009; Edirisinghe et al., 2010; Giroh et al., 2011; Mustapha, 2011; Longpichai et al., 2012; Poungchompu and Chantanop, 2015; Kittilertpaisan et al., 2016; Parichatnon et al., 2018), few studies have focused on the impacts of land tenure status. For example, Aliyu et al. (2017) found that the average TE was 0.73 for smallholder rubber farming in Malaysia and showed that it was influenced by the number of household members, tapping experience, and the visiting frequency of extension agents. Based on a case study of rubber production in Indonesia, Suyanto et al. (2001) found an insignificant difference in the efficiency of the two rubber production systems between newly emerging private ownership and customary ownership. The authors argued that this finding was because tree planting conferred more substantial individual rights to land with weak rights, such as family land, under customary land tenure systems.

The limited empirical evidence on the impacts of land tenure status on the TE of rubber production is insufficient to support relevant policy decision-making. Especially in China, a research gap remains on the TE of rubber production due to limited data accessibility. In recent years, the self-sufficiency ratio of natural rubber in China has been <30% and continues to decrease. A better understanding of the TE of rubber production can promote improved rubber production efficiency and natural rubber strategic resource self-sufficiency. Moreover, whether rubber plantations with different land tenure statuses show heterogeneous production performance in China is also unclear. The answer to this question is related to whether land tenure certificates for rubber plantations need to be reissued. Compared with other rubber planting countries, such as Malaysia and Indonesia, the land tenure system in China is relatively more complex; therefore, more studies on the TE of rubber production and the impacts of land tenure status in China are needed.

The objective of this study is to investigate the TE of smallholder rubber farming and examine the impact of inconsistent land tenure certificates of rubber plantations. We use a translogarithmic stochastic frontier production function and technical inefficiency model to reach the objective. Relying on a panel of rubber production data collected from approximately 600 smallholders in XSBN, this study empirically examines the impact of land tenure status on the TE of smallholder rubber farming. A mechanism analysis is conducted to test whether inconsistent land tenure certificates affect TE by changing input factors. A propensity score matching (PSM) approach was used for robustness checks to control the potential selection bias of land tenure status due to observable variables. The treatment effects were calculated to assess the impact of different land tenure certificates on the TE of smallholder rubber farming.

The contributions of this study are threefold. First, this study underlines the phenomenon of inconsistent land tenure in the context of the expansion of economic forests in Southwest China. While many previous studies focus on land tenure certifications in China (e.g., Ma et al., 2017; Gao et al., 2017; Ren et al., 2020), the inconsistency between land use certificates and actual land use is not noticed. Thus, this study contributes new insights for land tenure-related studies and calls for more studies on the related issues of inconsistent land tenure certificates. Second, the study supplements the literature on the productivity and TE of smallholder rubber farming in China and provides rigorous evidence on the management of efficient rubber plantations. Third, the findings of this study have an important reference implication for tree crop plantations with inconsistent land tenure certificates in developing countries that may also have multiple categories in their land tenure systems.

The remaining components of this paper are organized as follows. The next section presents a conceptual framework regarding inconsistent land tenure certificates and rubber production and proposes two research hypotheses. Section 3 presents the model specification and empirical strategy, and Section 4 introduces the data source and statistically describes the critical variables used in this study. Section 5 reports the estimation results of the established production function and technical efficiency model. Section 6 is the mechanism analysis, while Section 7 presents a series of robustness checks. The final section concludes with major findings and policy implications.

2. Conceptual frameworks

2.1. Inconsistent land tenure certificate

The various types of land tenure certificates in rural China have some commonalities but also differences in land use regulations (Table A.1). In the 1990s, China's central government established a fixed 30-year certificate for farmland tenure (Wang et al., 2011) and then policies on the reform of collective forestland rights (Huang, 2019). Thereafter, China implemented a new round of collective forestland tenure reform during 2003–2013 (Xie et al., 2014), while forestland tenure certificates were issued to individual households with an effective period of 70 years (Yin et al., 2013). Both types of land tenure certificates can be renewed upon maturity and contribute to guaranteeing farmers' property rights and protecting their land security (Table A.1). However, the actual land use regulations vary in the different types of tenure certificates. The disparities in primary land use restrictions are distinct between land holding a farmland tenure certificate and one with a forestland tenure certificate (see Table A.1). For example, in the case of land possessing a farmland tenure certificate, the conversion of crops to any legally recognized agricultural crop and temporary trees, such as seedling trees, is considered lawful. However, in light of escalating concerns regarding food security, China explicitly prohibits the cultivation of economic trees such as fruit trees and rubber trees on farmlands. In certain regions, fruit trees planted on farmlands are even compulsory replaced with grain crops. Consequently, a farmland tenure certificate does not provide sufficient guarantees for the property rights associated with economic trees.

Over the past few decades, there has been a significant increase in rubber cultivation among smallholder farmers in Southwest China, with rubber even being cultivated on farmlands. Accordingly, rubber plantations in Southwest China can be categorized into three types based on the status of land tenure certification: 1) rubber plantations without a land tenure certificate (*N*), 2) rubber plantations with farmland tenure certificates (*L*), and 3) rubber plantations with forestland tenure certificates (*F*). The second type of land tenure certificate (*L*) is inconsistent with actual land use and is defined as an inconsistent land tenure certificate in this study.

While both farmland and forestland tenure certificates contribute to ensuring land security, forestland tenure certificates offer greater protection for smallholders' property rights in relation to rubber plantations compared to farmland tenure certificates. Firstly, in terms of primary land use restrictions outlined in Table A.1, the cultivation of rubber trees on farmlands is deemed illegal, with a risk of compulsory conversion into grain production. Conversely, the conversion of rubber plantations under forestland tenure certificates into other tree crops or forested areas requires the approval of the local forestry administration; any changes in land use without proper authorization may result in penalties.

To sum up, tenure security in rubber plantations varies depending on the type of land tenure certificate. Forestland tenure certificates (*F*) provide the strongest guarantee of property security for rubber plantations, followed by farmland tenure certificates (*L*). Rubber plantations without a land tenure certificate (*N*) have the lowest level of security. Generally, land tenure status determines the perceived security of land tenure by smallholders (Xu and Hyde, 2018; Ren et al., 2020). Thus, smallholders' perceptions of land tenure security (P) of rubber plantations with different types of land tenure certification should have the relationship:

$$P_N < P_L < P_F. \tag{1}$$

2.2. Impact of an inconsistent land tenure certificate on TE

Previous studies suggest that land tenure certificates play an important role in agricultural production and technical efficiency (Ma et al., 2017; Michler and Shively, 2015; Suyanto et al., 2001). For instance, the study of Gao et al. (2017) found significant impacts of land tenure certificates on agricultural investment. Similarly, forestland tenure status also significantly affected forest management and investment intensity (Qin and Xu, 2013; Xie et al., 2014). Unfortunately, to date, the impacts of inconsistent land tenure certificates remain unclear due to the lack of empirical evidence. Referring previous studies, we further draw a framework regarding the impact of land tenure status of rubber plantations on the TE of smallholder rubber farming (Fig. A.1.). The rest of this section would conceptually illustrate the possible impacts of inconsistent land tenure certificates on TE of smallholder rubber farming.

Referring to prior studies (Son et al., 1993; Yi et al., 2014; Chen et al., 2017; Xu and Hyde, 2018), the production of natural rubber (Y) could be expressed simply as a function of various inputs (I):

$$Y = f(I) \tag{2}$$

where I is a vector of input factos such as labor and capital. Following the conceptual framework linking land tenure and agricultural production developed by Place (2009), improved land tenure security can promote agricultural investments (Yi et al., 2014; Qin and Xu, 2013; Gao et al., 2017). Thus, the vector of various inputs of rubber plantations (I) could be written as a function of the perceived security of land tenure (P):

$$I = g(P) \tag{3}$$

where the fucntion, $g(P)$, is an increasing function, i.e., $\frac{\partial I}{\partial P} > 0$.

By incoporating Eq. (3) into Eq. (2), we can yield that improved land tenure security could encourage farmers to invest more in rubber plantations and thereby affect the production and efficiency, in a line with previous studies (Zhang and Owiredu, 2007; Zhou et al., 2022). Suppose that the production of rubber plantations (Y) may correspondingly increase with inputs, i.e., $\frac{\partial Y}{\partial I} > 0$. Thus, the impact of land tenure security on the production of rubber plantations could be expressed as $\frac{\partial Y}{\partial P} = \frac{\partial Y}{\partial I} * \frac{\partial I}{\partial P} > 0$, i.e., improved security of land tenure could promot the production of rubber plantation.

Considering that both P_L and P_F are larger than P_N in inEq. (1), the first hypothesis could be expressed as follows:

H1. Compared with no land tenure certificate, both farmland and forestland tenure certificates could improve the TE of smallholder rubber farming.

Furthermore, given that $P_N < P_L < P_F$ in inEq. (1), the hypothesis with regard to the inconsistent land tenure certificate could be derived as follows:

H2. TE of rubber plantations with inconsistent (farm) land tenure certificates should be relatively low compared to that of rubber plantations with forestland tenure certificates.

The third hypothesis regarding the impact mechanism of land tenure status on the TE of smallholder rubber farming could be derived as follows:

H3. Inputs should be a mechanism through which land tenure status affects the TE of rubber plantations.

3. Empirical methods

To test the research hypotheses, this study employs a translogarithmic stochastic frontier production function and technical inefficiency model. Numerous studies have been conducted to examine the productivity and TE of forestry and agroforestry, including natural rubber (Giroh and Adebayo, 2009; Chand et al., 2015; Susaeta et al., 2016; Wang et al., 2016; Aliyu et al., 2017; Murtaza and Thapa, 2017). For instance, Chen et al. (2017) employed stochastic frontier analysis to examine the production efficiency of the forestry industry in China. Son et al. (1993) employed a time-varying stochastic frontier production function model to analyze the TE of natural rubber production by state farms in Vietnam, while Parichatnon et al. (2018) investigated the TE of rubber production in Thailand using a three-stage data envelopment analysis (DEA) model. Following Son et al. (1993), this study is based on the conceptual framework of the stochastic production frontier. Furthermore, referring to previous studies (e.g., Battese, 1992; Coelli, 1995; Yao and Liu, 1998; Jin et al., 2010; Michler and Shively, 2015; Huang et al., 2016; Aliyu et al., 2017), a translogarithmic stochastic frontier production function and technical inefficiency model were developed in this study. Notably, to characterize the rubber production process, a production function with inputs of labor and operating capital was developed in this study by following the studies of Newman and Wear (1993) and Yin and Newman (1997).

3.1. Stochastic production function model

Following Pitt and Lee (1981), Dawson et al. (1991), and Michler and Shively (2015), we defined a stochastic production function model with multiplicative disturbances as follows:

$$y = F(x)e^{\epsilon} \tag{4}$$

where x is a vector of input factors, including labor and operating capital (Yin and Newman, 1997); $F(x)$ is the theoretical maximum output; y is the observed yield; and ϵ is a stochastic error term composed of two independent elements. Following the specification of Aigner et al. (1977) and Meeusen and van den Broeck (1977), ϵ can be expressed as follows:

$$\epsilon = u + v \tag{5}$$

where the symmetric component v is a stochastic variable representing uncontrolled random shocks in the production process, such as temperature, rain, and disease. We assumed that v was independently and identically distributed as $N(0, \sigma_v^2)$. In $u \sim N(0, \sigma_u^2)$, the one-sided distributed component $u \leq 0$ represents technical inefficiency relative to the production frontier, reflecting that the output lies on or below the frontier. In other words, the absolute value of u reflects the distance from the observed efficiency to the production frontier.

The model was further adjusted to accommodate panel data by assuming that production can be represented by a log-linear function (Dawson et al., 1991). Then, a variance components model could be derived by combining Eqs. (4) and (5):

$$y_{it} = f(x_{kit}, \beta)e^{u_{it}+v_{it}} \quad (6)$$

where x_{kit} denotes the k^{th} input ($k = 1, \ldots, m$) on the i^{th} rubber plot in the observed year t, and β is a vector of parameters to be estimated. Thus, the plot-level TE can be measured by the ratio of observed yield to the maximum achievable stochastic level given that TE is fully realized:

$$e^{u_{it}} = \frac{y_{it}}{f(x_{kit})e^{v_{it}}} \quad (7)$$

3.2. Model specification

While both the Cobb–Douglas specification and the translogarithmic form for the production function (6) have been used in previous studies that have estimated the TE for rubber plantations (Son et al., 1993; Edirisinghe et al., 2010; Mustapha, 2011), we preferred the translogarithmic form of the stochastic production frontier for conceptual reasons (Michler and Shively, 2015). According to the conceptual framework presented above and referring to previous studies on forest production (Newman and Wear, 1993; Yin and Newman, 1997), the production function of rubber can be specified as follows:

$$ln(y_{it}) = \beta_0 + \beta_1 ln(x_{1it}) + \beta_2 ln(x_{2it}) + \frac{1}{2}\beta_{11}(lnx_{1it})^2 + \frac{1}{2}\beta_{22}(lnx_{2it})^2 + \beta_{12} ln(x_{1it}) ln(x_{2it}) + u_{it} + v_{it} \quad (8)$$

In the equation, the yield of natural rubber (y_i) in kilograms per mu of each rubber plot hinges on two quantitative inputs: x_{1it} represents the total input of labor force measured in workdays per mu of each rubber plot in year t, and x_{2it} indicates the input of operating capital measured in Yuan per mu of each rubber plot in year t.

With Eq. (7), the empirical TE of rubber production for the i^{th} rubber plot in the observed year can be written as follows:

$$TE_{it} = \frac{y_{it}}{\widehat{y_{it}}} = \frac{y_{it}}{f(x_{kit})e^{v_{it}}} = \frac{f(x_{kit})e^{u_{it}+v_{it}}}{f(x_{kit})e^{v_{it}}} = e^{u_{it}} \quad (9)$$

where TE (u_{it}) is assumed to hinge on the land tenure certificate status (lt) and the characteristics of rubber plots (p), rubber plantations (r), and households (h). Thus, u_i can be written in a linear form:

$$exp(u_{it}) = \alpha_0 + \sum_j \theta_j lt_{jit} + \sum_l \vartheta_l p_{lit} + \sum_m \mu_m r_{mit} + \sum_n \rho_n h_{nit} \quad (10)$$

In the equation, the explanatory variables are described in detail in Table 1, while the coefficients θ, ϑ, μ, and ρ are used to capture the impacts of these variables on efficiency.

3.3. Estimation procedure

First, the stochastic frontier denoted in Eq. (8) is estimated by additionally controlling for the characteristics of rubber trees, plots, and elevation as well as the fixed effects of year and village because natural rubber is perennial, and the production process is different from that of annual crops, such as rice and wheat. Second, the predicted TE from the estimation of Eq. (8) is incorporated into Eq. (10) to assess the impacts of land tenure status on the TE of smallholder rubber farming. Because this study employs panel data on smallholder rubber farming, we adopt a fixed-effect model and a random-effect model. A Hausman test, then, is used for the choice of models. In the estimation, the fixed effect of the year is included to control for all time-invariant differences, while the fixed effect of the village is also used to control for all time-variant changes and possible spatial heterogeneity (Sibhatu et al., 2022).

Determining the causal impact of land tenure status on natural rubber production might be affected by confounding factors and/or reverse causality. However, by reviewing the issuing process of land tenure certificates among smallholder rubber farmers in XSBN, we determined that land tenure status is exogenous in explaining rubber production. First, the issuance of land tenure certificates is implemented by the local government and is fair for all smallholders and land; thus, the land tenure status is orthogonal to the ability of smallholders or the productivity of specific land. Second, the issuance of land tenure certificates is not implemented if there are any disputes and conflicts on the specific land. If there is unclear ownership due to traditional land use rights among the different ethnic groups and the previous uncontrolled expansion of rubber plantations, the land rights may be disputed among farmers, villages, and local state farms (Min et al., 2017d). Therefore, some rubber plantations do not have land tenure certificates. In summary, we believe that assessing the impact of land tenure status on rubber production does not suffer from reverse causality.

Table 1
Descriptive statistics of the variables.

Symbol	Variable	Unit and Coding	Mean		
			2012	2014	2018
Plot level					
Y	Yield of rubber cake	kg/mu	105.963	108.449	112.439
x_1	Labor	workday[a]/mu	27.670	12.960	12.898
x_2	Operating capital	Yuan/mu	193.483	141.695	98.639
lt_1	Farmland tenure certificate	1 = own; 0 = otherwise	0.247	0.059	0.029
lt_2	Forestland tenure certificate	1 = own; 0 = otherwise	0.641	0.861	0.930
p_1	Plot area	mu	11.868	12.249	11.541
p_2	Slope of land	1 = yes; 0 = otherwise	0.893	0.900	0.914
p_3	Condition of land (poor)#	1 = yes; 0 = otherwise	0.053	0.052	0.047
p_4	Condition of land (general)	1 = yes; 0 = otherwise	0.571	0.648	0.602
p_5	Condition of land (good)	1 = yes; 0 = otherwise	0.376	0.331	0.351
r_1	Rubber variety (a)	1 = yes; 0 = otherwise	0.516	0.446	0.482
r_2	Rubber variety (b)	1 = yes; 0 = otherwise	0.077	0.089	0.115
r_3	Rubber variety (c)	1 = yes; 0 = otherwise	0.115	0.150	0.139
r_4	Rubber variety (other)#	1 = yes; 0 = otherwise	0.292	0.316	0.253
r_5	Age of rubber tree	Years after growing	17.465	17.068	19.536
r_6	Density of rubber tree	trees/mu	34.748	34.693	35.885
Obs.			833	855	892
Household-level					
h_1	Age of household head	year	48.060	48.337	50.087
h_2	Education of household head	year	4.163	4.321	4.597
h_3	Gender of household head	1 = female; 0 = otherwise	0.060	0.080	0.072
h_4	Ethnicity (Dai)	1 = yes; 0 = otherwise	0.690	0.673	0.702
h_5	Ethnicity (Hani)	1 = yes; 0 = otherwise	0.175	0.190	0.173
h_6	Ethnicity (other) #	1 = yes; 0 = otherwise	0.135	0.137	0.125
h_7	Household size	number	5.269	5.441	5.360
h_8	Elevation (above sea level)	m	705.833	716.753	690.703
Obs.			467	424	414

Source: Author's survey; # reference group in the estimation.
[a] Eight hours per workday.

4. Data and descriptive statistics

4.1. Data sources

The data used in this study were from XSBN, located in the southern region of Yunnan Province, China. Because the profits of rubber farming were relatively higher than the benefits previously obtained by cultivating other crops (Liu et al., 2006; Xu, 2006; Ahrends et al., 2015), natural rubber plantations have expanded rapidly in the region. From 2004 to 2016, the area of rubber plantations in XSBN increased from 2.59 to 4.57 million mu, which produced 0.32 million tons of dry rubber by 2016 (Bureau of Statistics of Xishuangbanna Dai Autonomous Prefecture, 2017). Natural rubber production is currently the primary land use in XSBN (Fu et al., 2009; Ahrends et al., 2015; Zhang et al., 2015).

Data were collected from a three-wave household survey conducted in 2013, 2015, and 2019. In March 2013, we conducted a baseline survey of smallholder rubber farmers in XSBN. To ensure the representativeness of the samples, we applied a stratified random sampling approach by accounting for the rubber planting area per capita and the distribution of rubber planting areas across townships (Min et al., 2017a). Details of the sample selection procedure can be found in Min et al. (2017b). In the field survey, a household questionnaire that included detailed information on the socioeconomic characteristics of all family members, land use, rubber farming activities in the last production season and farm and nonfarm income sources, and other questions relevant to rubber were used. A village questionnaire was used to interview the head of each sampled village to collect the necessary village-level information, such as population, agricultural development, infrastructure, and transportation. Finally, information on 612 smallholder rubber farmers from 42 villages in 8 townships in XSBN was collected. Two waves of follow-up surveys were conducted in March 2015 and March 2019; accordingly, approximately 600 smallholder rubber farmers were successfully traced.

The data of rubber plantation at the plot level were also included in the household questionnaires and collected during the survey. As there are many plots of land in each household in this mountainous area, it is tough to collect the detailed data of all plots in a limited interview time. Thus, three rubber plots were randomly selected for each household in the survey for detailed inquiries on inputs and outputs. For households with fewer than three rubber plots, all existing plots were included. To better mark these selected rubber plots, their locations relative to the interviewed household were also asked to draw on the questionnaires. Thus, according to the information of location, plot area, ages of rubber trees and so on, these three selected rubber plots were also traced in the follow-up surveys. In this study, to estimate the production function and the TE of smallholder rubber farming, only the sampled rubber plots in the harvesting phase were used. As an increasing number of rubber plots become harvestable over time, 833, 855, and 892 rubber plots were selected in 2013, 2015, and 2019, respectively.

4.2. Descriptive statistics

Table 1 presents the summary statistics for the variables at the plot and household levels that were used to estimate the stochastic frontier production and the technical efficiency equations. The dependent variable y is the rubber cake yield (kg/mu),[2] with a mean of 105.963 kg/mu in 2012, 108.449 kg/mu in 2014, and 112.439 kg/mu in 2018. The inputs of labor and operating capital were used in the stochastic frontier production function. On average, in 2012, the rubber production per mu required approximately 27.67 workdays and 193.483 yuan of operating capital. By 2018, the inputs of labor and operating decreased to approximately 12.898 workdays and 98.639 yuan per mu, respectively. These two input variables were expected to affect the production of rubber cakes significantly and positively. The average land areas per plot were approximately 11.868 mu in 2012, 12.249 mu in 2014, and 11.541 mu in 2018, which may have scale effects on the production of rubber. Interestingly, from 2012 to 2018, decreases in the inputs but increases in the yield of rubber were simultaneously shown. This is possible. On the one hand, in 2012, the average farm gate price of rubber was very high and reached 21 Yuan/kg (Min et al., 2017a). In the context of a high rubber price, there may be some overinput in rubber farming; accordingly, the reduction in overinputs may not affect the yield of rubber farming. On the other hand, the yield of rubber may increase over time, as the yield of rubber farming generally increases with rubber age before the peak (approximately 20 years old). Accordingly, these results also imply that the production efficiency of rubber farming may also increase.

The explanatory variables at the plot level included land tenure status, the nature of the rubber plots, and rubber management. In 2012, 11.2% of the sample rubber plots had no land tenure certificate, while approximately 24.7% and 64.1% had farmland and forestland tenure certificates, respectively. Surprisingly, approximately 24.7% of rubber plots have inconsistent (farm) land tenure certificates. Nevertheless, the percentage of rubber plots with an inconsistent (farm) land tenure certificate decreased from 2012 to 2018, while the percentage of rubber plots with a forestland tenure certificate increased. The rubber plots without a land tenure certificate were treated as the reference group in the estimation. The coefficients of the variables representing farmland and forestland tenure certificates reflect their impacts on technical efficiency. The plot conditions comprised slope, quality, and area, which are important variables determining the production of rubber farming. The respondents in the household survey subjectively evaluated the threshold of slope and condition of rubber land. Moreover, the production of smallholder rubber farming may also vary with the variety, age, and density of rubber trees (Diaby et al., 2013; Aliyu et al., 2017). The estimation results of these explanatory variables could provide a reference for the site selection and management of rubber rotations and other newly established rubber plantations.

As the primary decision maker in a household, the characteristics of the household heads, along with the socioeconomic situations of the households, were expected to play a significant role in explaining the TE of farming (Amos, 2007; Alwarritzia et al., 2015). For instance, the differences in the TE of rubber farming between ethnic groups likely occurred because the history, culture, knowledge, and experiences of the smallholders differed, which was reflected in the heterogeneity of their agricultural practices (Colfer et al., 1989; Brush et al., 2007; Min et al., 2017d). Furthermore, the production efficiencies of rubber plots may differ with the selected villages; therefore, the fixed effect of villages was also included in the model of technical efficiency.

Table 2 shows the differences in the mean values of rubber yields and various inputs among the three types of land tenure certificates. First, the average yields of rubber plots without a land tenure certificate were significantly lower than those of rubber plots with farmland or forestland tenure certificates. This result may be due to the relatively high inputs of labor and operating capital applied to the rubber plots with

Table 2
Mean comparison of the yield and inputs by land tenure status.

	No certificate#	Farmland tenure certificate	Forestland tenure certificate
Yield (kg/mu)	76.168	101.886**	114.512***
Labor (workday/mu)	14.556	17.108	18.169
Operating capital (Yuan/mu)	80.110	135.316**	151.835***

Note: # reference group of a mean comparison test; ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.

[2] A rubber cake is the storage form of relatively dried rubber latex by farmers; on average, the conversion ratio from rubber latex to rubber cakes is 3:1 in XSBN.

either a farmland or forestland tenure certificate compared to those without a land tenure certificate. Second, the mean inputs between the rubber plots with farmland or forestland tenure certificates were only slightly different but not statistically significant; however, the difference in the mean yield was significant at the 10% level. Overall, these results imply that issuing land tenure certificates may be positively correlated with yield as well as production efficiency due to the increased input allocation of rubber farming. Meanwhile, both inputs and outputs of the rubber plots with a farmland tenure certificate seem slightly lower than those with a forestland tenure certificate.

Table A.2 further shows the differences in variables between the rubber plantations with different land tenure certificates. Interestingly, most variables regarding the nature of the rubber plots and management are significantly different between the rubber plantations with different land tenure certificates. These variables likely determine the type of land tenure certificate (or the lack of it), while they are also assumed to affect the TE of smallholder rubber farming. Thus, to control for the potential endogeneity of the land tenure certificates, these variables probably affecting both the production, TE, and the type of land tenure certificate of smallholder rubber farming must be controlled in the empirical models.

5. Estimation results

5.1. Estimation results of the production function

Table 3 reports the estimation results of the translogarithmic production function. In the estimation, taking the logarithm of the yield of natural rubber could address the possible heteroscedasiticy. The results of all variance inflation factors are <10, indicating that there is no multicollinearity among indenpendent variables in the model. The result of the Wald Chi^2 test (638.29) is significantly different from zero, confirming the model's overall explanatory power. In general, the results of these statistic test indicate the quality of the complete model appears to be satisfactory.

The parameter estimates for the translogarithmic production function show that the effects of labor, operating capital, and plot area on the yield of natural rubber differ. The first-order coefficients of labor (x_1) and capital (x_2) inputs were statistically positive, indicating positive partial production elasticities in the sample mean. The interaction terms $\ln^2(x_1)$ and $ln^2(x_2)$ were significant, suggesting that labor and capital are nonlinear inputs in rubber production. The coefficient of the interaction term $ln(x_1) * ln(x_2)$ was significantly negative, revealing the existence of a possible substitution of labor and capital in rubber production. However, the size of the rubber plot appeared to have a negative effect on the production of rubber, showing that the production of smallholder rubber farming declined in plot size.

Based on the estimation results, we also calculated the sample mean production elasticities of all the input factors. The results showed that the elasticities of labor and capital inputs on rubber production were 0.015 and 0.038, respectively. The change in rubber production due to a one-unit increase in labor was similar to that due to the marginal products of capital inputs. The result indicates that for an increase in the input of labor by one unit, the rubber yields decreased by 0.015, while the rubber yields increased by 0.038 for an increase in the input of capital by one unit. Obviously, the marginal product of capital inputs is higher than that of labor input in smallholder rubber farming in XSBN.

Table 3
Estimates of the translogarithmic production function.

Variable	Coef.	Robust Std. Err.
$ln(x_1)$	0.115**	0.050
$ln(x_2)$	0.039***	0.010
$0.5\ ln^2(x_1)$	−0.036*	0.021
$0.5\ ln^2(x_2)$	0.006***	0.002
$ln(x_1)*ln(x_2)$	−0.008***	0.003
p_1	−0.208***	0.301
p_2	−0.068	0.059
p_3	–	
p_4	−0.020	0.093
p_5	−0.024	0.093
r_1	0.104**	0.045
r_2	0.124	0.077
r_3	0.075	0.067
r_4	–	
r_5	0.028***	0.009
r_5^2	−0.0005**	0.0002
r_6	0.005	0.005
r_6^2	−0.00003	0.00004
h_8	0.0007	0.0005
Fixed effect of year	Controlled	
Fixed effect of village	Controlled	
Constant	3.354***	0.577
Log-likelihood	−3482.815	
Wald Chi^2	638.29***	
Number of obs.	2580	

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.

5.2. Estimation results of the TE of smallholder rubber farming

The TE for each rubber plot in the observed year was calculated based on the estimates of the stochastic frontier production function of rubber farming. The TE scores of smallholder rubber farming in XSBN ranged from 0.005 to 0.888, with a mean of 0.554, which was slightly lower than the calculated TEs of rubber farming in other countries, such as 0.57 in northeast Thailand (Poungchompu and Chantanop, 2015), 0.69 in Changwat Sakon Nakhon, Thailand (Kittilertpaisan et al., 2016), 0.72 in Nigeria (Giroh and Adebayo, 2007), and 0.73 in Malaysia (Aliyu et al., 2017). The differences in TE among these countries may be due to climatic and other ecological conditions. Nevertheless, to some extent, the relatively low TE score of rubber farming in this study also reveals that a relatively high amount of space remains to boost the TE of smallholder rubber farming in XSBN.

Table 4 presents the estimation results of the TE model by the random-effect regression (RE) and the fixed-effect regression (FE). The significant Wald Chi^2 test results for RE (218.31) and FE (3.4) regressions validate the specification of the empirical model. The result of Hausman test (FE vs. RE) is 21.93 and can not reject the null hypothesis, confirming that the RE regression results are more efficient than those of the FE regression. The critical variables we related to the land tenure status of rubber farming were the two dummy variables for whether the plot had a farmland tenure certificate (lt_1) or a forestland tenure certificate (lt_2). As shown in the results of the RE regression in Table 4, both coefficients, i.e., lt_1 and lt_2, were always significantly different from zero. Compared with those of the reference group that did not have a land tenure certificate, the positive signs of the coefficients suggest that rubber farming with a farmland or forestland tenure certificate increased the TE of smallholder rubber farming.

The impacts of the type of land tenure certificate on the TE of smallholder rubber farming are probably through the management of rubber plantations. Issuing land tenure certificates can increase land tenure security and reduce the risk of land loss, while secure land tenure is also significantly associated with farm management practices (Lokonon and Mbaye, 2018). Thus, compared with rubber plantations without a land tenure certificate, farmers prefer to improve farm management in those with land tenure certificates. Better farm management of rubber plantations can help optimize the allocation of input factors and improve the yields under a given set of inputs, thereby increasing the TEs of rubber plantations.

Table 5 further shows the TE of rubber production in the plots with different types of land tenure certificates. The rubber plots without a land tenure certificate, with a farmland tenure certificate, and with a forestland tenure certificate had TEs of 0.528, 0.537, and 0.562, respectively. The kernel density distributions of rubber plots with

Table 4
Estimates of the TE model.

Variable	Random-effect regression		Fixed-effect regression	
	Coef.	Std. Err.	Coef.	Std. Err
lt_1	0.056**	0.023	0.048	0.035
lt_2	0.076***	0.220	0.083**	0.033
p_1	−0.0098*	0.006	−0.010	0.118
p_2	0.006	0.158	−0.054	0.303
p_3				
p_4	0.026	0.021	−0.793	0.647
p_5	0.039*	0.021	−0.480	0.525
r_1	0.008	0.011	0.632***	0.243
r_2	−0.020	0.016		
r_3	0.006	0.016	0.244	0.304
r_4				
r_5	−0.002	0.002	−0.004	0.008
r_5^2	0.000	0.000	−0.00003	0.0002
r_6	0.002**	0.000	0.001	0.005
r_6^2	−0.000***	0.000	−0.000***	0.000
h_1	−0.001**	0.0005	−0.001	0.001
h_2	−0.006***	0.0015	0.004	0.007
h_3	0.014	0.017	0.036	0.044
h_4				
h_5	−0.026	0.044		
h_6	0.010	0.054		
h_7	−0.007**	0.003	−0.0262***	0.009
h_8	0.0001	0.0001	0.0003	0.0002
Fixed effect of year	Controlled		Controlled	
Fixed effect of village	Controlled		Controlled	
Constant	0.156	0.140	0.841	0.774
Wald Chi^2	218.31***		3.40***	
Hausman test (FE vs. RE)		21.93		
Number of obs.	2580		2580	

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.

Table 5
TE of rubber production and comparisons by groups.

Categories	Mean	Std. Dev.	Min	Max
All samples	0.554	0.211	0.005	0.888
By year				
2012#	0.518	0.225	0.005	0.855
2014	0.586***	0.200	0.010	0.889
2018	0.557**	0.203	0.018	0.870
By land tenure certificate				
No certificates##	0.528	0.222	0.013	0.841
Farmland tenure certificate	0.537	0.214	0.018	0.889
Forestland tenure certificate	0.562***	0.201	0.005	0.876

Note: # and ## are reference groups of the two mean comparison tests; ***, ** and * represent the 1%, 5%, and 10% significance levels, respectively.

different land tenure certificates are shown in Fig. 1. These results confirm that positive TE accompanies land certification, consistent with previous findings, such as Holden et al. (2009). Meanwhile, the TEs of rubber farming between the plots with a farmland tenure certificate and a forestland tenure certificate were also significantly different at the 10% significance level. Hence, having an inconsistent land tenure certificate appears to have a significant effect on the TE of smallholder rubber farming. As the rubber plots with farmland and forestland tenure certificates confront different land use regulations, these two types appeared to have somewhat inequivalent effects on guaranteeing land tenure security and improving rubber productivity.

Moreover, the TE of rubber production increased from 2012 to 2018, particularly from 2012 to 2014. The result is reasonable. As smallholders seek higher yields in the face of relatively high rubber prices, the inputs of rubber farming were usually overused in 2012, leading to a loss of efficiency. In contrast, in 2014 and 2018, the low rubber prices made

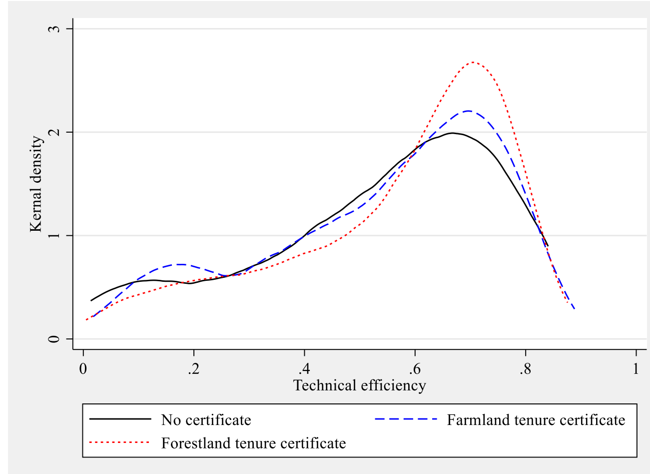

Fig. 1. Kernel density distributions of the technical efficiencies of rubber plots with different land tenure certificates.

farmers reduce their inputs. Accordingly, while the labor and operating capital inputs decreased by approximately 30%–50%, rubber yield did not significantly change and even slightly increased (Table 1).

The estimation results for the TE model of smallholder rubber farming also indicate that land quality and rubber tree age were significantly associated with the TE of smallholder rubber farming (Table 4). First, the average TE of rubber plantations with good quality conditions was significantly higher than that grown on poor land. Second, the first-order coefficients of the ages of the rubber trees were statistically positive, thus showing positive partial effects on TE. However, the quadratic terms of the ages of the rubber trees were significantly negative, thereby revealing nonlinear relations between the TE of smallholder rubber farming and the ages of the rubber trees.

Finally, the TE of smallholder rubber farming in XSBN was also significantly correlated with the age and education of the household heads. Due to labor constraints, an aging household head hinders the TE of smallholder rubber farming. A smallholder rubber farmer with a well-educated household head may also have a lower TE of smallholder rubber farming than a poorly educated household head. This finding is possible because a well-educated household head may engage in off-farm employment or self-employment instead of rubber farming.

6. Mechanism analysis

To explore the impact mechanism of land tenure status on the TE of smallholder rubber farming, a mediating effect analysis was further carried out in this study. First, we estimate the impact of the land tenure status of rubber plots on the TE of smallholder rubber farming. Second, a seemingly unrelated regression (SUR) was used to estimate the impacts of land tenure status on the inputs of labor and operating capital. Third, the TE of smallholder rubber farming was re-estimated by including land tenure status, inputs of labor, and operating capital. All statistics of F and Wald Chi^2 of the three regressions are significantly different from zero, validating the specifications of these empirical models. The result of Breusch-Pagan test of independence (26.598) indicate that all equations in the SUR are dependent, confirming the rationality of simultaneous regression for equations of labor and operating capital by using SUR.

The estimation results in Table 6 can be summarized as follows. First, land tenure status significantly affects the TE of smallholder rubber farming. Both farmland and forestland tenure certificates positively affect the TE of smallholder rubber farming. However, the different coefficient magnitudes of lt_1 and lt_2 suggest that an inconsistent (farm) land tenure certificate may lead to a loss of TE of smallholder rubber

Table 6
Seemingly unrelated regressions for the input factors of rubber production.

Variable	OLS		SUR				OLS	
	Efficiency		*ln(x1)*		*ln(x2)*		*Efficiency*	
	Coef.	Std.Err.	Coef.	Std.Err.	Coef.	Std. Err.	Coef.	Std. Err.
lt_1	0.049**	0.022	0.006	0.092	1.279***	0.489	0.048**	0.021
lt_2	0.060***	0.021	0.224***	0.087	1.218***	0.461	0.057***	0.020
$ln(x_1)$							0.012**	0.005
$ln(x_2)$							0.001	0.001
Plot-level variables	Controlled		Controlled		Controlled		Controlled	
Household-level variables	Controlled		Controlled		Controlled		Controlled	
Fixed effect of year	Controlled		Controlled		Controlled		Controlled	
Fixed effect of village	Controlled		Controlled		Controlled		Controlled	
Constant	0.374***	0.143	2.909***	0.654	3.407	3.467	0.337**	0.151
R^2	0.084		0.469		0.157		0.204	
F/Wald Chi^2	4.88***		2276.11***		481.77***		3.85***	
Breusch-Pagan test of independence (Chi^2)					26.598***			
Number of obs.	2580				2580		2580	

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.

farming compared to a forestland tenure certificate. Second, lt_1 has a significant and positive effect on the capital input of rubber farming, while lt_2 significantly and positively affects both the labor and capital inputs. This result suggests that issuing a forestland tenure certificate for rubber plots is more efficient for promoting the allocation of inputs in rubber farming. Moreover, compared with the reference group that did not have a land tenure certificate, the coefficients differed in magnitude between lt_1 and lt_2 for the inputs of labor and capital that were considered. This result reveals that an inconsistent land tenure certificate resulted in heterogeneous inputs of various factors of rubber farming. Third, only labor inputs significantly affect the TE of smallholder rubber farming, indicating that labor input is a mechanism through which forestland tenure certificates impact TE. Unfortunately, while farmland tenure certificates could affect capital inputs, farmland tenure certificates do not seem to have a significant impact mechanism on the TE of smallholder rubber farming.

7. Robustness check

To check the robustness of the main findings in this study, first, a pooled data analysis was applied to re-estimate the TE of smallholder rubber farming. As shown in Table 7, an OLS regression was employed to test the impacts of land tenure certificates on the TE of rubber production. To assist the robustness check, we also re-estimate the TE by dropping approximately 10% of samples with the lowest TE. Consistent with the estimation above, the TE model also controls for the variables at the plot level and household level and the fixed effects of year and village. Accordingly, as shown in Table 7, the estimation results using a full sample and a subsample consistently confirm that rubber farming with a farmland or forestland tenure certificate exhibited significantly higher TE than that without land tenure.

Table 7
Re-estimates of the TE model using the pooled data.

Variable	OLS regression		OLS regression (Subsample)	
	Coef.	Robust Std. Err.	Coef.	Robust Std. Err
lt_1	0.049**	0.022	0.034**	0.018
lt_2	0.060***	0.021	0.038***	0.016
Plot-level variables	Controlled		Controlled	
Household-level variables	Controlled		Controlled	
Fixed effect of year	Controlled		Controlled	
Fixed effect of village	Controlled		Controlled	
Constant	0.374***	0.143	0.645***	0.128
R^2	0.084		0.054	
F	4.88***		2.63***	
Number of obs.	2580		2329	

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.

Second, a quantile regression was employed to detect whether the impacts of farmland and forestland tenure certificates on the TE of smallholder rubber farming were stable at different quantiles. Fig. 2 displays the estimated coefficients of farmland and forestland tenure certificates at different quantiles. On the one hand, farmland and forestland tenure certificates always positively affect the TE of smallholder rubber farming, while the effect sizes are heterogeneous at different quantities. On the other hand, the variation in the impact of forestland tenure certificates on the TE of smallholder rubber farming (right side of Fig. 2) was greater than that of farmland tenure certificates (left side of Fig. 2).

Third, a PSM approach was further used to check the robustness by controlling for possible selection bias. While we argued that this study has no endogeneity issue due to confounding factors and/or reverse causality, it cannot be denied that endogeneity due to selection bias is a frequent issue in nonexperimental studies and may have affected the land tenure certification results in this study. The land tenure status of rubber farming in XSBN included three categories: a) no certificate, b) farmland tenure certificate, and c) forestland tenure certificate. Given that the PSM approach generally applies to matching two groups, we further treated the land tenure status by regrouping. Accordingly, the first column of Table 8 shows four different grouping schemes: PSM (1) and PSM (2) were used to quantify the differences in TE between the rubber plots without a land tenure certificate and the plots with a farmland (forestland) tenure certificate, respectively, and PSM (3) was used to test whether the TE was heterogeneous between the plots with a farmland and forestland tenure certificate.

Based on the calculated TEs from the translogarithmic production frontier, the PSM approach was applied to capture the impacts of land tenure status. PSM (1), PSM (2), and PSM (3) are implemented, while Table 8 presents the simulated average treatment effects on the treated (ATT) using a probit regression with the default single nearest-neighbor matching method. After correcting the potential selection bias, the ATT of PSM (1) is insignificant, indicating no significant difference in the TEs between the rubber plots with a farmland tenure certificate and those without a land tenure certificate. The values of ATT in PSM (2) and (3) are 0.029 and 0.026, respectively, which are significantly different from zero. In line with the main findings in this study, the TE of rubber plots with a forestland tenure certificate was higher than that of plots without a land tenure certificate and that of plots with a farmland tenure certificate. These results are in line with the main findings of this study, suggesting that, on the one hand, possible selection bias may not

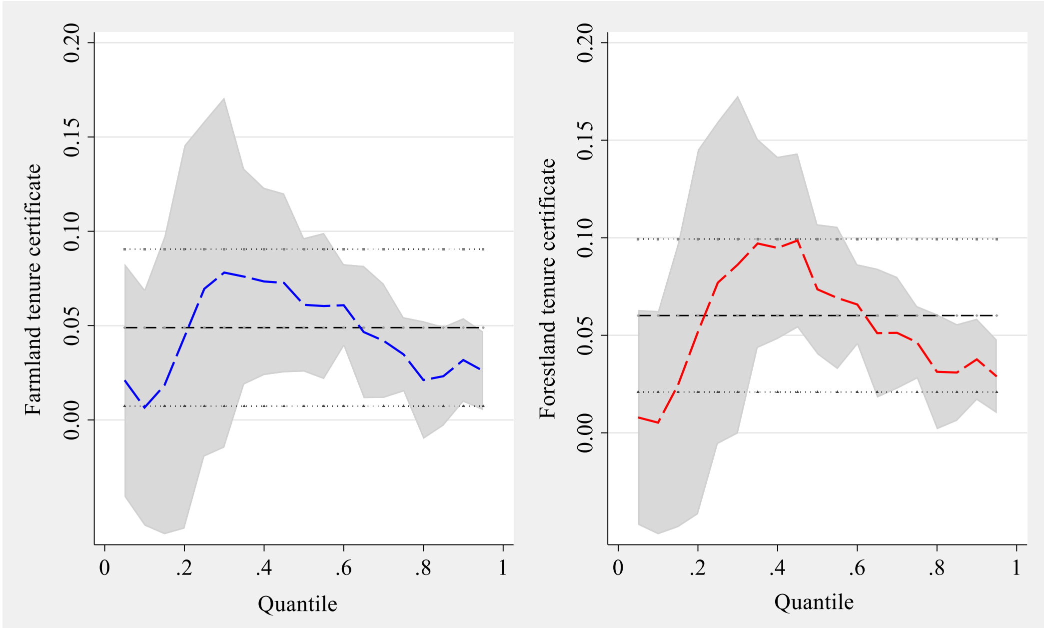

Fig. 2. Quantile regression results of the impacts of farmland/forestland tenure certificates on the TE of smallholder rubber farming.

Table 8
Estimated ATT of land tenure certificates on TE.

Dependent variable	Mean of TE	ATT
PSM (1)		
1 = Farmland tenure certificate	0.524	−0.006
0 = No certificate	0.530	
PSM (2)		
1 = Forestland tenure certificate	0.558	0.029**
0 = No certificate	0.529	
PSM (3)		
1 = Forestland tenure certificate	0.563	0.026**
0 = Farmland tenure certificate	0.537	

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.

significantly affect the estimation results of land tenure certificates on the TE of smallholder rubber farming; on the other hand, the results of PSM further confirm the robustness of the main findings.

8. Conclusions

This study underlines the phenomenon that actual land use is inconsistent with the issued land tenure certificate type in rubber plantations and estimates the impacts of inconsistent land tenure certificates on TE of smallholder rubber farming. The results showed that the TE of smallholder rubber plantations in XSBN ranged from 0.01 to 0.89, with an average of 0.554. Specifically, the average TEs for rubber plantations with farmland and forestland tenure certificates were 0.537 and 0.562, respectively, which were 0.09 and 0.34 higher than those without a land tenure certificate.

The findings of this study indicate that possessing a land tenure certificate could improve the TE of smallholder rubber farming in the study region, while an inconsistent land tenure certificate indeed significantly affects the TE of smallholder rubber farming. As forestland tenure certificates could better secure property rights for rubber plantations than farmland tenure certificates, the TE of smallholder rubber farming with forestland tenure certificates was greater than that with farmland tenure certificates. These results indicate that smallholder rubber farmers are indeed concerned with the security behind their tenure, such as the restrictions associated with different tenure types. Hence, we call for more studies on the inconsistency between land tenure certificates and actual land use. The study also confirms that the allocation of inputs is a mechanism through which inconsistent land tenure certificate affect the TE of smallholder rubber farming. Moreover, the TEs of smallholder rubber farming are heterogenous by year, land quality, rubber tree age, the age and education of the household heads. The main findings are also confirmed by a series of robustness check.

This study has important implications. Firstly, this study rises concerns on inconsistent land tenure certificates. Our findings show inconsistent land tenure certificates may hinder the TE of smallholder rubber farming compared to forestland tenure certificates. In recent years, with increasing concerns about food security, farmlands are no longer allowed to plant trees. Therefore, rubber plantations with farmland tenure certificates may confront a high risk of substitution by other crops, resulting in a series of related issues. Hence, more studies on the inconsistency between land tenure certificates and actual land use are worthy of concern. Secondly, this study provides empirical evidence for improving the TE of smallholder rubber farming in rubber planting areas, especially in the Mekong region, where the situation is similar to that in XSBN. Land certification is an efficient way to increase the TE of smallholder rubber farming. Nevertheless, in some areas, land tenure certificate issuing is already close to completion, and the policy options for promoting land tenure certificates are limited. Additionally, the TE of smallholder rubber farming could be considerably improved. A further optimization of factor inputs may promote the TE of rubber farming. Finally, there is a portion of rubber plantations with very low TE. Considering the intention of environmental protection in subtropical regions, a return of rubber plantations with a marginal or low TE to green areas is also recommended.

Finally, we would like to present a main limitation of this study. The representation of this study is limited as it only investigated the inconsistent land tenure certificates of rubber plantations in XSBN, southwest China. In fact, there are many forestlands in China, while it is unclear whether there are the inconsistent land tenure certificates in other forest regions of China. Hence, it is recommended to expand the study area in future studies.

CRediT authorship contribution statement

Shi Min: Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft. **Junfei Bai:** Data curation, Investigation, Validation, Writing – review & editing. **Xiaobing Wang:** Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – review & editing. **Hermann Waibel:** Data curation, Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (72103072; 72333003; 71761137002), National Social Science Foundation of China (22&ZD084; 22&ZD079), and the Fundamental Research Funds for the Central Universities (11041910122; 2662021JC003).

Appendix

Table A.1
Differences between farmland tenure certificate and forestland tenure certificate.

Categories	Farmland tenure certificate	Forestland tenure certificate
Duration of the tenancy	30 years	70 years
Restrictions in primary land use		
Crops	Allowed	Not allowed
Temporary trees	Allowed	Allowed
Economic trees	Not allowed	Allowed
Renewal terms	Renewed upon maturity	Renewed upon maturity
Ownership	Village collective	Village collective
Eligibility	Contract/operation rights	Contract/operation rights
Penalty upon change in uses	Restore land use/detention, fines/criminal responsibility	Restore land use/detention, fines/criminal responsibility

Table A.2
Differences in variables between the rubber plantations with different land tenure certificates.

Variables		(a) No certificate	(b) Farmland tenure certificate	Diff (a-b)#	(c) Forestland tenure certificate	Diff (a-c)#	Diff (b-c)#
p_1	Plot area	16.278	11.875	4.402***	11.542	4.735***	0.333
p_2	Slope of land	0.933	0.913	−0.021	0.896	0.037	0.017
p_3	Condition of land (poor)#	0.022	0.035	−0.013	0.059	−0.036*	−0.024**
p_4	Condition of land (general)	0.511	0.617	−0.106**	0.596	−0.085*	0.022
p_5	Condition of land (good)	0.467	0.348	0.119**	0.345	−0.121***	0.003
r_1	Rubber variety (a)	0.459	0.471	−0.012	0.492	−0.033	−0.021
r_2	Rubber variety (b)	0.111	0.124	0.013	0.081	−0.030	0.043
r_3	Rubber variety (c)	0.252	0.129	0.122***	0.128	−0.128***	0.002
r_4	Rubber variety (other)#	0.178	0.276	−0.098**	0.299	0.121***	−0.024
r_5	Age of rubber tree	16.281	17.960	−1.678**	18.225	−1.943***	−0.266
r_6	Density of rubber tree	32.651	35.650	−3.000**	35.099	−2.449**	0.552
h_8	Elevation (above sea level)	752.785	708.606	44.18***	698.641	54.143***	9.96**

Note: # mean-comparison tests; ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.

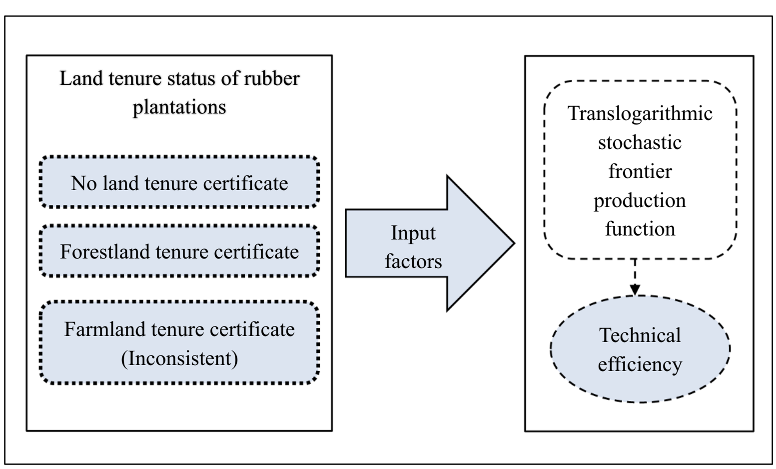

Fig. A.1. Impact of land tenure status on the TE of smallholder rubber farming.

References

Ahrends, Antje, Hollingsworth, Peter M., Ziegler, Alan D., Fox, Jefferson M., Chen, Huafang, Yufang, Su, Jianchu, Xu., 2015. Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. Glob. Environ. Chang. 34, 48–58. https://doi.org/10.1016/j.gloenvcha.2015.06.002.

Aigner, Dennis, Knox Lovell, C.A., Schmidt, Peter, 1977. Formulation and estimation of stochastic frontier production function models. J. Econ. 6 (1), 21–37. https://doi.org/10.1016/0304-4076(77)90052-5.

Aliyu, Abdulrahman, Latif, Ismail Abd., Shamsudin, Mad Nasir, Nawi, Nolila Mohd, 2017. Factors affecting technical efficiency of rubber smallholders in Negeri Sembilan, Malaysia. J. Malaysia Agric. Sci. 9 (5), 226–232. https://doi.org/10.5539/jas.v9n5p226.

Alwarritzia, Widya, Nansekib, Teruaki, Chomei, Yosuke, 2015. Analysis of the factors influencing the technical efficiency among oil palm smallholder farmers in Indonesia. Procedia Environ. Sci. 28, 630–638. https://doi.org/10.1016/j.proenv.2015.07.074.

Amos, T.T., 2007. An analysis of productivity and technical efficiency of smallholder cocoa farmers in Nigeria. J. Soc. Sci. 15 (2), 127–133. https://doi.org/10.1080/09718923.2007.11892573.

Anderson, Terry L., Lueck, Dean, 1992. Land tenure and agricultural productivity on Indian reservations. J. Law Econ. 35 (2), 427–454. https://doi.org/10.1086/467261.

Battese, George E., 1992. Frontier production functions and technical efficiency: a survey of empirical applications in agricultural economics. Agric. Econ. 7 (3–4), 185–208. https://doi.org/10.1016/0169-5150(92)90049-5.

Brush, S.B., Perales, R., Hugo., 2007. A maize landscape: ethnicity and agro-biodiversity in Chiapas Mexico. Agric. Ecosyst. Environ. 121 (3), 211–221. https://doi.org/10.1016/j.agee.2006.12.018.

Bureau of Statistics of Xishuangbanna Dai Autonomous Prefecture, 2017. Xishuangbanna Dai autonomous prefecture national economic and social development statistics bulletin. http://www.xsbn.gov.cn/214.news.detail.dhtml?news_id=38130 (Accessed 1 Sep 2018.).

Chand, Narendra, Kerr, Geoffrey N., Hugh, Bigsby, 2015. Production efficiency of community forest management in Nepal. Forest Policy Econ. 50, 172–179. https://doi.org/10.1016/j.forpol.2014.09.001.

Chapman, E.C., 1991. The expansion of rubber in southern Yunnan, China. Geogr. J. 157 (1), 36–44. https://doi.org/10.2307/635142.

Chen, Jiandong, Yinyin, Wu, Song, Malin, Zhu, Zunhong, 2017. Stochastic frontier analysis of productive efficiency in China's Forestry Industry. J. For. Econ. 28, 87–95. https://doi.org/10.1016/j.jfe.2017.05.005.

Coelli, Tim J., 1995. Recent developments in frontier modelling and efficiency measurement. Aust. J. Agric. Res. Econ. Battese 39 (3), 219–245. https://doi.org/10.1111/j.1467-8489.1995.tb00552.x.

Colfer, C. Pierce, Colfer, Barbara J., Newton, Herman, 1989. Ethnicity: an important consideration in Indonesian agriculture. Agric. Hum. Values 6 (3), 52–67. https://doi.org/10.1007/bf02217669.

Dawson, Philip J., Lingard, John, Woodford, Christopher H., 1991. A generalized measure of farm-specific technical efficiency. Am. J. Agric. Econ. 73 (4), 1098–1104. https://doi.org/10.2307/1242438.

Diaby, Moussa Ferrer, Valognes, Hélène, Fabrice, 2013. A social choice approach to primary resource management: the rubber tree case in Africa. Forest Policy Econ. 28.97 (2013), 8–14. https://doi.org/10.1016/j.forpol.2013.01.002.

Edirisinghe, Jagath, Wijesuriya, Wasana, Bogahawatte, C., 2010. Profit efficiency of smallholder rubber farmers in Kegalle, Kalutara and Ratnapura districts. J. Rubber Res. Inst. Sri Lanka 90, 64–77. https://doi.org/10.4038/jrrisl.v90i0.1831.

Fox, Jefferson, Castella, Jean Christophe, 2013. Expansion of rubber (*Hevea brasiliensis*) in mainland Southeast Asia: what are the prospects for smallholders? J. Peasant Stud. 40 (1), 155–170. https://doi.org/10.1080/03066150.2012.750605.

Fu, Yongneng, Brookfield, Harold, Guo, Huijun, Chen, Jin, Chen, Aiguo, Cui, Jingyun, 2009. Smallholder rubber plantation expansion and its impact on local livelihoods, land use and agrobiodiversity, a case study from Daka, Xishuangbanna, southwestern China. Int J Sust Dev World 16 (1), 22–29. https://doi.org/10.1080/13504500902753246.

Gao, Liangliang, Sun, Dingqiang, Huang, Jikun, 2017. Impact of land tenure policy on agricultural investments in China: evidence from a panel data study. China Econ. Rev. 45 https://doi.org/10.1016/j.chieco.2017.07.005.

Gavian, Sarah, Ehui, Simeon, 1999. Measuring the production efficiency of alternative land tenure contracts in a mixed crop-livestock system in Ethiopia. Agric. Econ. 20 (1), 37–49. https://doi.org/10.1016/S0169-5150(98)00067-X.

Giroh, D.Y., Adebayo, E.F., 2007. Analyzing the technical efficiency of rubber tapping in Nigeria. J. Agric. Soc. Sci. 3, 140–142. http://www.fspublishers.org.

Giroh, D.Y., Adebayo, E.F., 2009. Analysis of the technical inefficiency of rubber tapping in rubber research institute of Nigeria, Benin City, Nigeria. J. Hum. Ecol. 27 (3), 171–174. https://doi.org/10.1080/09709274.2009.11906207.

Giroh, Dengle Yuniyus, Moses, Joyce Daudu, Yustus, F.S., 2011. Technical efficiency and costs of production among small holder rubber farmers in Edo State, Nigeria. World Rural Obs. 3, 22–27. http://www.sciencepub.net/rural.

Holden, Stein Terje, Deininger, Klaus, Ghebru, Hosaena, 2009. Impacts of low-cost land certification on investment and productivity. Am. J. Agric. Econ. 91 (2), 359–373. https://doi.org/10.1111/j.1467-8276.2008.01241.x.

Huang, Wei, 2019. Forest condition change, tenure reform, and government-funded eco-environmental programs in Northeast China. Forest Policy Econ. 98, 67–74. https://doi.org/10.1016/j.forpol.2018.09.003.

Huang, Wei, Bruemmer, Bernhard, Huntsinger, Lynn, 2016. Incorporating measures of grassland productivity into efficiency estimates for livestock grazing on the Qinghai-Tibetan Plateau in China. Ecol. Econ. 122, 1–11. https://doi.org/10.1016/j.ecolecon.2015.11.025.

Huang, Wei, Bruemmer, Bernhard, Huntsinger, Lynn, 2017. Technical efficiency and the impact of grassland use right leasing on livestock grazing on the Qinghai-Tibetan Plateau. Land Use Policy 64, 342–352. https://doi.org/10.1016/j.landusepol.2017.03.009.

Jin, Songqing, Ma, Hengyun, Huang, Jikun, Ruifa, Hu, Rozelle, Scott, 2010. Productivity, efficiency and technical change: measuring the performance of China's transforming agriculture. J. Prod. Anal. 33 (3), 191–207. https://doi.org/10.1007/s11123-009-0145-7.

Kittilertpaisan, Jitti, Kittilertpaisan, Kallaya, Khatiwat, Phakhaphon, 2016. Technical efficiency of rubber farmers' in Changwat Sakon Nakhon: stochastic frontier analysis. Int. J. Finance Econ. Issues 6 (S6), 138–141. http://www.econjournals.com.

Lawin, Kotchikpa G., Tamini, Lota D., 2018. Tenure security and farm efficiency analysis correcting for biases from observed and unobserved variables: evidence from Benin. J. Agric. Econ. 70, 116–134. https://doi.org/10.1111/1477-9552.12275.

Liu, Wenjun, Huabin, Hu, Ma, Youxin, Li, Hongmei, 2006. Environmental and socioecono-mic impacts of increasing rubber plantations in Menglun township, Southwest China. Mt. Res. Dev. 26 (3), 245–253. https://doi.org/10.1659/0276-4741(2006)26[245:EASIOI]2.0.CO;2.

Lokonon, Boris O.K., Mbaye, Aly A., 2018. Climate change and adoption of sustainable land management practices in the Niger basin of Benin. Nat. Res. Forum 42 (1), 42–53. https://doi.org/10.1111/1477-8947.12142.

Longpichai, Onanong, Perret, Sylvain Roger, Shivakoti, Ganesh P., 2012. Role of livelihood capital in shaping the farming strategies and outcomes of smallholder rubber producers in southern Thailand. Outlook Agric. 41 (2), 117–124. https://doi.org/10.5367/oa.2012.0085.

Ma, Xianlei, Heerink, Nico, Feng, Shuyi, Shi, Xiaoping, 2017. Land tenure security and technical efficiency: new insights from a case study in Northwest China. Environ. Dev. Econ. 22 (3), 305–327. https://doi.org/10.1017/S1355770X1600036X.

Meeusen, Wim, van den Broeck, Julien, 1977. Efficiency estimation from cobb-douglas production functions with composed error. Int. Econ. Rev. 18 (2), 435–444. https://doi.org/10.2307/2525757.

Michler, Jeffrey D., Shively, Gerald E., 2015. Land tenure, tenure security and farm efficiency: panel evidence from the Philippines. J. Agric. Econ. 66 (1), 155–169. https://doi.org/10.1111/1477-9552.12082.

Min, Shi, Huang, Jikun, Bai, Junfei, Waibel, Hermann, 2017a. Adoption of intercropping among smallholder rubber farmers in Xishuangbanna, China. Int. J. Agric. Sustain. 15, 223–237. https://doi.org/10.1080/14735903.2017.1315234.

Min, Shi, Huang, Jikun, Waibel, Hermann, 2017b. Rubber specialization vs crop diversification: the roles of perceived risks. China Agric. Econ. Rev. 9 (2), 188–210. https://doi.org/10.1108/CAER-07-2016-0097.

Min, Shi, Waibel, Hermann, Huang, Jikun, 2017d. Smallholder participation in the land rental market in a mountainous region of southern China: impact of population aging, land tenure security and ethnicity. Land Use Policy 68, 625–637. https://doi.org/10.1016/j.landusepol.2017.08.033.

Min, Shi, Huang, Jikun, Waibel, Hermann, XueqingYang, Georg Cadisch, 2019. Rubber boom, land use change and the implications for carbon balances in Xishuangbanna, Southwest China. Ecol. Econ. 156, 57–67. https://doi.org/10.1016/j.ecolecon.2018.09.009.

Murtaza, Ghulam, Thapa, Gopal Bahadur, 2017. Factors affecting technical efficiency of small - scale apple farms in Balochistan Plateau, Pakistan. J. Mt. Sci. 14 (4), 782–794. https://doi.org/10.1007/s11629-016-3937-z.

Mustapha, Nik Hashim Hik, 2011. Technical efficiency for rubber smallholders under RISDA's supervisory system using stochastic frontier analysis. J. Sustain. Sci. Manag. 6 (1), 156–168. https://jssm.umt.edu.my/files/2012/01/18.June11.pdf.

Newman, David H., Wear, David N., 1993. Production economics of private forestry: a comparison of industrial and nonindustrial forest owners. Am. J. Agric. Econ. 75 (3), 674–684. https://doi.org/10.2307/1243574.

Ouedraogó, Robert S., Sawadogo, Jean Pierre, Stamm, Volker, Thiombiano, Taladia, 1996. Tenure, agricultural practices and land productivity in Burkina Faso: some recent empirical results. Land Use Policy 13 (3), 229–232. https://doi.org/10.1016/0264-8377(96)84061-0.

Parichatnon, Surakiat, Maichum, Kamonthip, Peng, Ke-Chung, 2018. Measuring technical efficiency of Thai rubber production using the three-stage data envelopment analysis. Agric. Econ. 64 (5), 227–240 doi:10.17221/19/2016-AGRICECON.

Pitt, Mark M., Lee, Lung-Fei, 1981. The measurement and sources of technical inefficiency in the Indonesian weaving industry. J. Dev. Econ. 9 (1), 43–64. https://doi.org/10.1016/0304-3878(81)90004-3.

Place, Frank, 2009. Land tenure and agricultural productivity in Africa: a comparative analysis of the economics literature and recent policy strategies and reforms. World Dev. 37 (8), 1326–1336. https://doi.org/10.1016/j.worlddev.2008.08.020.

Place, Frank, Hazell, Peter, 1993. Productivity effects of Indigenous land tenure systems in sub-saharan Africa. Am. J. Agric. Econ. 75 (1), 10–19. https://doi.org/10.2307/1242949.

Place, Frank, Otsuka, Keijiro, 2002. Land tenure systems and their impacts on agricultural investments and productivity in Uganda. J. Dev. Stud. 38 (6), 105–128. https://doi.org/10.1080/00220380412331322601.

Poungchompu, S., Chantanop, S., 2015. Factor affecting technical efficiency of smallholder rubber farming in Northeast Thailand. Am. J. Agric. Biol. Sci. 10 (2), 83–90. https://doi.org/10.3844/ajabssp.2015.83.90.

Qin, Ping, Xu, Jintao, 2013. Forest land rights, tenure types, and farmers' investment incentives in China. China Agric. Econ. Rev. https://doi.org/10.1108/17561371311294829.

Ren, Guangcheng, Zhu, Xueqin, Heerink, Nico, Feng, Shuyi, 2020. Rural household migration in China – the roles of actual and perceived tenure security. China Econ. Rev. 63 https://doi.org/10.1016/j.chieco.2020.101534.

Sibhatu, Kibrom T., Steinhübel, Linda, Siregar, Hermanto, Qaim, Matin, Wollni, Meike, 2022. Spatial heterogeneity in smallholder oil palm production. Forest Policy Econ. 139 https://doi.org/10.1016/j.forpol.2022.102731, 102731.

Smith, Robert E., 2004. Land tenure, fixed investment, and farm productivity: evidence from Zambia's southern province. World Dev. 32 (10), 1641–1661. https://doi.org/10.1016/j.worlddev.2004.05.006.

Son, Tran Vo, Hung, Tim Coelli, Fleming, Euan, 1993. Analysis of the technical efficiency of state rubber farms in Vietnam. Agric. Econ. 9 (3), 183–201. https://doi.org/10.1016/0169-5150(93)90047-G.

Susaeta, Andres, Adams, Damian C., Carter, Douglas R., Gonzalez-Benecke, Carlos, Dwivedi, Puneet, 2016. Technical, allocative, and total profit efficiency of loblolly pine forests under changing climatic conditions. Forest Policy Econ. 72, 106–114. https://doi.org/10.1016/j.forpol.2016.06.021.

Suyanto, S., Tomich, Thomas P., Otsuka, Keijiro, 2001. Land tenure and farm management efficiency: the case of smallholder rubber production in customary land areas of Sumatra. Agrofor. Syst. 52 (2), 145–160. https://doi.org/10.1023/a:1010625019030.

Wang, Hui, Tong, Juer, Fubing, Su, Wei, Guoxue, Tao, Ran, 2011. To reallocate or not: reconsidering the dilemma in China's agricultural land tenure policy. Land Use Policy 28 (4), 805–814. https://doi.org/10.1016/j.landusepol.2011.01.006.

Wang, Na, Wolf, Joost, Zhang, Fu-suo, 2016. Towards sustainable intensification of apple production in China—yield gaps and nutrient use efficiency in apple farming systems. J. Integr. Agric. 15 (4), 716–725. https://doi.org/10.1016/S2095-3119(15)61099-1.

Xie, Yi, Gong, Peichen, Han, Xiao, Wen, Yali, 2014. The effect of collective forestland tenure reform in China: does land parcelization reduce forest management intensity? J. For. Econ. 20 (2), 126–140. https://doi.org/10.1016/j.jfe.2014.03.001.

Xu, Jianchu, 2006. The political, social, and ecological transformation of a landscape: the case of rubber in Xishuangbanna, China. Mt. Res. Dev. 26 (3), 254–262. https://doi.org/10.1659/0276-4741(2006)26[254:TPSAET]2.0.CO;2.

Xu, Jintao, Hyde, William F., 2018. China's second round of forest reforms: observations for China and implications globally. Forest Policy Econ. https://doi.org/10.1016/j.forpol.2018.04.007. S1389934118300297.

Xu, Jianchu, Fox, Jefferson, Vogler, John B., Yongshou, Fu, Peifang, Zhang, Lixun, Yang, Jie, Qian, Leisz, Stephen, 2005. Land-use and land-cover change and farmer vulnerability in Xishuangbanna prefecture in southwestern China. Environ. Manag. 36 (3), 404–413. https://doi.org/10.1007/s00267-003-0289-6.

Yao, Shujie, Liu, Zinan, 1998. Determinants of grain production and technical efficiency in China. J. Agric. Econ. 49 (2), 171–184. https://doi.org/10.1111/j.1477-9552.1998.tb01262.x.

Yi, Yuanyuan, Köhlin, Gunnar, Xu, Jintao, 2014. Property rights, tenure security and forest investment incentives: evidence from China's Collective Forest Tenure Reform. Environ. Dev. Econ. 19 (2014), 48–73. https://doi.org/10.1017/S1355770X13000272.

Yin, Runsheng, Newman, David, 1997. Long-run timber supply and the economics of timber production. For. Sci. 43 (1), 113–120. https://doi.org/10.1093/forestscience/43.1.113.

Yin, Runsheng, Yao, Shunbo, Huo, Xuexi, 2013. China's 67 forest tenure reform and institutional change in the new century: what has been implemented and what remains to be pursued? Land Use Policy 30 (1), 825–833. https://doi.org/10.1016/j.landusepol.2012.06.010.

Zhang, Daowei, Owiredu, Eric Aboagye, 2007. Land tenure, market, and the establishment of forest plantations in Ghana. Forest Policy Econ. 9 (6), 602–610. https://doi.org/10.1016/j.forpol.2005.12.001.

Zhang, Le, Kono, Yasuyuki, Kobayashic, Shigeo, Hud, Huabin, Zhoue, Rui, Qin, Yaochen, 2015. The expansion of smallholder rubber farming in Xishuangbanna, China: a case study of two Dai villages. Land Use Policy 42, 628–634. https://doi.org/10.1016/j.landusepol.2014.09.015.

Zhou, Nan, Cheng, Wenli, Zhang, Longyao, 2022. Land rights and investment incentives: evidence from China's Latest Rural Land Titling Program. Land Use Policy 117 (June 2022). https://doi.org/10.1016/j.landusepol.2022.106126, 106126.

Further-reading

Guo, Li, Scott, Rozelle, Brandt, Loren, 2014. Tenure, land rights, and farmer investment incentives in China. Agric. Econ. 19 (1–2), 63–71. https://doi.org/10.1016/S0169-5150(98)00046-2.

Min, Shi, Waibel, Hermann, Cadisch, Georg, Langenberger, Gerhard, Bai, Junfei, Huang, Jikun, 2017c. The economics of smallholder rubber farming in a mountainous region of Southwest China: elevation, ethnicity, and risk. Mt. Res. Dev. 37 (3), 281–293. https://doi.org/10.1659/MRD-JOURNAL-D-16-00088.1.