



Analysis

Rubber Boom, Land Use Change and the Implications for Carbon Balances in Xishuangbanna, Southwest China



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ABSTRACT

Rubber farming expansion in Xishuangbanna, in the Upper Mekong region of Southwest China, has resulted in profound land use change and led to the severe degradation of the local environment. This study explores the dynamics of land use change as a result of the rubber boom, examines the factors influencing the heterogeneity in farmers' land allocations for rubber farming, and assesses the implications of this change for the local environment in terms of carbon balances. The analyses use a comprehensive household survey data set of 612 smallholder rubber farmers in Xishuangbanna. The historical data illustrate the trajectory of rubber expansion and land use change over the past three decades. The model of smallholder land allocation for rubber farming suggests its determinants include ethnicity, experience in rubber farming, household wealth, elevation, and several explanatory variables at the village level. A net loss in carbon stocks at the aggregate level was found due to the expansion of rubber plantations. The rubber farming expansion of smallholders outside the natural reserves in Xishuangbanna has led to a carbon loss of approximately 21 Mg/ha/year over the past three decades. The findings complement discussions on the future of the rubber-based land use system and its sustainability in Xishuangbanna and other rubber-growing areas in the Mekong region.

1. Introduction

Over the last three decades, Xishuangbanna Dai Autonomous Prefecture (XSBN), in the upper Mekong region, Southwest China, has experienced widespread and dramatic land-use changes such as deforestation, agricultural expansion and the conversion of secondary vegetation into monocultures, in particular, rubber plantations (Ahrends et al., 2015; Xu et al., 2005; Zhang et al., 2015). Since the 1980s, motivated by the combination of the domestic protection of rubber prices, the introduction of the Household Responsibility System, and the introduction of new technologies, smallholder rubber farming has been expanding rapidly in Xishuangbanna (Xu et al., 2005). By 2004, the total area devoted to rubber plantations in XSBN was 2.59 million mu,¹ with an annual dry rubber production of approximate 0.17 million tons, while by 2014, the total area covered by rubber plantations was 4.55 million mu, with dry rubber production of 0.29 million tons. Currently, > 50% of rubber plantations in XSBN are operated by smallholders (Min et al., 2017a). Min et al. (2017b) showed

that the share of rubber plantations in the total household land area was approximately 80%, but there were heterogeneous farmers in XSBN. Similarly, the increasing expansion of natural rubber farming can also be seen in other countries in the Mekong region, such as Laos, Myanmar, and Vietnam (Fox and Castella, 2013; Liu et al., 2013; Manivong and Cramb, 2008; Min et al., 2018). The establishment of rubber plantations also caused rapid and extensive changes in land-use patterns (Gerber et al., 2009). Unfortunately, due to the constraint of data availability, it remains unclear which types of land have been replaced by rubber plantations and how much.

The significant land use change with rubber expansion in XSBN had both positive and negative consequences (Hauser et al., 2015; Jiang et al., 2017). On the one hand, the rapid intensification of rubber farming has improved rural incomes (Fu et al., 2009; Min et al., 2017b). On the other hand, the shifting of traditional land-use patterns and forests towards specialized rubber plantations also implies a higher liability in terms of climatic and economic risks and has led to the large-scale destruction of ecologically important forest resources, thereby

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¹ 15 mu = 1 ha.

challenging the sustainability of land use in XSBN (Fu et al., 2009; Kassa et al., 2017; Qiu, 2009; Xu, 2006). Smallholder rubber farmers are also subject to potential economic risks due to potentially high sunk costs when investing in rubber (Min et al., 2017c). Particularly, the recent decline in rubber prices left smallholders vulnerable to a drop in income and the potential to again fall into poverty. Above all, the rapid expansion of rubber farming has triggered a series of negative effects on local ecosystems such as biodiversity, soil and water conservation (Hu et al., 2008; Liu et al., 2006; Xu, 2006; Yi et al., 2014), while the loss of agro-biodiversity may also have adverse implications for food and nutritional security (Fu et al., 2010).

Moreover, the impact of these significant changes in land use on landscape carbon sequestration has been demonstrated by researchers (Blagodatsky et al., 2016; de Blécourt et al., 2013; Li et al., 2008; Yi et al., 2014; Zhang et al., 2007). Although the cultivation of rubber trees on non-forested land could provide a carbon sink by sequestering carbon in biomass and indirectly in soils (Gnanavelrajah et al., 2008; Nizami et al., 2014; Wauters et al., 2008), the carbon sequestration ability of rubber trees is much lower than that of natural forest (de Blécourt et al., 2013; Jiang et al., 2017; Yang et al., 2016). Thus, although the conversion from traditional agriculture to rubber plantations may result in some improvements in carbon sequestration, the shift from forests to rubber plantation leads to a massive loss in carbon sequestration (de Blécourt et al., 2013). Yang et al.'s (2016) study of the Naban River Watershed National Nature Reserve in XSBN found that although a biosphere zoning strategy (i.e., experimental, buffer, core zones) and reforestation activities could enhance the carbon stocks, to date, rubber plantations had not compensated for carbon losses in the natural reserve due to deforestation. However, it is less clear what the effect of rubber expansion on the carbon balance outside the nature reserves in XSBN has been, considering the transition from the combination of forestland and traditional agriculture, including from swidden farming to rubber plantations, that has actually been taking place over recent decades.

The overall goal of this study is to gain a better understanding of the land use change under rubber expansion in XSBN and its implications for carbon balances. The focuses of analysis are on drawing the trajectory of land use change and the rubber expansion of smallholders and the trend of carbon balances over the past three decades in XSBN. Specifically, the analysis will trace how much land, in which years and of what types was converted into rubber. In addition, this study also tries to identify the factors determining the heterogeneity in land use allocation for rubber farming among smallholder rubber farmers in XSBN.

To achieve the above goal, first, this study uses representative household data from 612 smallholder rubber farmers collected through a comprehensive household and village survey conducted in 2013 in XSBN. The dataset includes detailed information on smallholders' land use situation, including historical land use, and therefore provides a unique opportunity to document the temporal patterns of land use transformation experienced by smallholder rubber farmers in XSBN. Second, a simple land use allocation model is established to assess the impacts of farmers' socioeconomic characteristics and geographical conditions on their decision regarding land use for rubber farming. Third, following the study of Yang et al. (2016), which evaluated carbon stocks using the *rapid carbon stock appraisal* method based on tree, plot, land use and landscape assessments, this study simulates the carbon balances of land use systems given the expansion of rubber farming in XSBN over the past three decades. Finally, we discuss the carbon balances stemming from the land use patterns of smallholder rubber farmers in the future under the context of current policy and land constraints.

This study can complement discussions on the future of a rubber-based land use system and its sustainability in XSBN and other similar rubber-growing areas in the Mekong region. Moreover, the findings add to those from studies on rubber plantations in XSBN (e.g., Fu et al., 2009; Xu et al., 2005; Xu, 2006; Zhang et al., 2015) by using a broader

empirical base and drawing conclusions on carbon balances (e.g., Blagodatsky et al., 2016; Li et al., 2008; Nizami et al., 2014; Wauters et al., 2008; Yang et al., 2016; Yi et al., 2014; Zhang et al., 2007).

The paper is organized as follows. The next section briefly introduces the data collection and statistically describes the trend in the land use change and the rubber expansion of smallholders in XSBN. Section 3 presents a simple model of smallholders' land allocation for rubber farming and estimation methods for carbon stocks considering the rubber-based land use change. Section 4 reports results, analyzes the determinants of smallholders' land use allocation for rubber farming and simulates the trend of carbon balances with the expansion of rubber plantations. Based on the findings of the analyses, the last section concludes and submits policy implications.

2. Data and Descriptive Statistics

2.1. Data Collection

In this study, we employ household survey data collected from a comprehensive socioeconomic survey of smallholder rubber farmers in XSBN carried out in March 2013. A modular household questionnaire was designed to collect detailed information on rubber farming and other socioeconomic conditions of smallholder rubber farmers. To understand the dynamics of rubber expansion among smallholders, information on planting time, area, density, and the crops in each plot before rubber was planted was collected from every household in the sample. Additionally, we collected plot level information including elevation, which is an important factor for rubber productivity.

A stratified random sampling approach (i.e., stratified by rubber planting area per capita and considering the distribution of rubber planting regions) was applied during the household survey to obtain a representative sample of smallholder rubber farmers in XSBN (Min et al., 2017b). First, 8 townships were stratified and randomly chosen from the rubber planting area in one city (Jinghong) and two counties (Menghai and Mengla) in XSBN: 2 townships were chosen from Menghai due to the relatively low intensity of rubber distribution there, while 3 townships were selected from both Jinghong and Mengla. Second, a total of 42 villages were drawn from the sample townships. Finally, we successfully administered 612 household questionnaires in 42 villages of 8 townships in XSBN. Our sample widely represents the various types of rubber planting regions in XSBN and broadly covered the geographical scope and elevation range of XSBN.

2.2. Sample Characteristics

Table 1 presents the socioeconomic characteristics of the 612 sample households and household heads. The household heads are relatively middle-aged, with an average age of 48. However, the household heads are in general low-educated, having received only approximately four years of education on average. A total of 5% of the population were of the Han majority, 58% represented the Dai minority, 11% the Hani minority and 26% other minorities. Each household has at least five family members. The households on average had been planting rubber for approximately 17 years. Household wealth is proxied by the total value of all non-land productive and consumptive assets (Teklewold et al., 2013). Accordingly, the average wealth is approximately 69.54 thousand yuan/person with a standard deviation of 81.07, reflecting the relatively large inequality of wealth among smallholder rubber farmers. The average farm size was approximately 13 mu, and nearly 85% are planted with rubber. All households are located in mountainous regions, with an average elevation of 756 m above sea level (MASL).

Regarding the characteristics at the village level, the average distance of sample villages to the nearest rubber processing factory is approximately 12.5 km. Approximately 26% of households were located in villages with special agricultural products, while

Table 1
Characteristics of households and household heads.

Variable	Definition and description	Mean	Std. Dev.
Household head			
Age	Age of household head (years)	47.98	10.52
Eduyears	Education of household head (years)	4.38	3.58
Ethnicity	Ethnicity of household head		
Han	Han ethnicity (1 = yes; 0 = otherwise)	0.05	0.21
Dai	Dai ethnicity (1 = yes; 0 = otherwise)	0.58	0.49
Hani	Hani ethnicity (1 = yes; 0 = otherwise)	0.11	0.32
Others	Other minorities, such as Yi, Bulang, and Jinuo (1 = yes; 0 = otherwise)	0.26	0.44
Household and farm			
HHsize	Number of household members	5.11	1.46
Experience	Duration of engaging in rubber cultivation (years)	17.21	8.69
Wealth	Value of household assets, including house(s), home appliances, and means of transportation (1000 yuan/person)	69.54	81.07
Land	Total area of household land (mu/person)	12.91	12.99
Rubber	Share of land planted with rubber	0.85	0.18
Elevation	Elevation of household site (meters above sea level (MASL))	756.11	160.27
Village level			
Factory	Distance to the nearest rubber processing factory (km)	12.51	17.46
Characteristic	Special agricultural products in the village (1 = yes; 0 = otherwise)	0.26	0.44
Green	Implemented “Grain to Green” project (1 = yes; 0 = otherwise)	0.42	0.49
Promotion	Promotion of rubber farming in the last 5 years (1 = yes; 0 = otherwise)	0.21	0.40
Subsidy	Subsidy for rubber farming in this year (1 = yes; 0 = otherwise)	0.46	0.50
Loans	Availability of interest-free loans (1 = yes; 0 = otherwise)	0.20	0.40
Observations		612	

Source: Authors' survey.

approximately 42% and 21% were located in villages that had, respectively, implemented the “Grain for Green” project and had promoted rubber farming in the last five years. In the observed year, 46% of households were located in villages that had received some subsidies for rubber farming, while approximately 20% of households were located in the villages where interest-free loans are available.

2.3. Descriptive Statistics

2.3.1. Land Use Change and Rubber Expansion (1981–2012)

Based on the collected data set, we aggregated the data on land use change for the total sample of smallholder rubber farms. Accordingly, the aggregated data provide a unique opportunity to trace the overall trajectory of land use change and rubber farming expansion of smallholder rubber farmers in XSBN. Unlike previous studies on rubber expansion and land use change in XSBN (Ahrends et al., 2015; Hammond et al., 2017; Xu et al., 2005; Smajgl et al., 2015; Yi et al., 2014; Zhang et al., 2015), this study shows the context of smallholder rubber farmers based on large-scale household survey data collected outside the nature reserve.

Fig. 1 shows the conversion of land use from various types to natural rubber from 1981 to 2012 for the 612 smallholder rubber farmers in XSBN. The results indicate that by 2012, nearly 2000 ha of land has

been gradually planted with natural rubber since 1981; accordingly, one household operates a rubber plantation of over 3 ha in 2012. Over half of rubber plantations were originally converted from the land planted with rice and other crops, including maize, beans and so on, while original forests and bush and grassland are also important sources of land for rubber plantations. Overall, the results of our survey provide clear evidence that the rubber boom has resulted in profound land use changes in XSBN.

Specifically, by 2012, over 328 ha of bush and grassland have been replaced by natural rubber, representing 17% of all rubber plantations, while the replaced original forests were approximately 300 ha, which almost account for 15% of all rubber plantations. Land planted with rice and other crops was the major source of new land for rubber plantations, respectively reaching 564 and 673 ha (29% and 35%). Only 4% of rubber plantations were originally planted with tea because tea is normally planted in regions with a relatively high elevation (over 800 MASL), which is inappropriate for the cultivation of natural rubber.

Fig. 2 further reveals the changing sources of land replaced by rubber over the past three decades. The pattern shows three periods: (i) during the 1980s, original forests were the major source of rubber plantations; (ii) during the 1990s, rice was the major source of rubber land; while (iii) after 2000, land planted with rice and other crops was converted to rubber plantations. In particular, during the third period, the speed of conversion from rice and other crops to rubber sharply increased and then decreased. In 2006, over 200 ha of land had been converted into rubber plantations, while this was only just over 10 ha in 2011. For various types of land use, this decreasing trend continued after 2006. We consider that the increasing concern for protecting the local ecological environment as well as the decrease in available suitable land for rubber in XSBN could be the reasons for this trend in land use change for smallholder rubber farmers.

2.3.2. Land Use Allocation for Rubber Farming in 2012

Although on average, nearly 85% of land area held by smallholder rubber farmers was allocated to rubber farming (Table 1), the shares of land planted with rubber in the total land area are heterogeneous among these smallholders. In Fig. 3, based on the cumulative distribution of the share of land planted with rubber in the total land area, it can be seen that the surveyed farmers tend to specialize primarily or entirely in rubber. Over 30% of smallholders allocated all of their land to rubber farming, while only 10% allocated < 50% of their land to rubber farming.

To better understand the correlations between the decision of small-scale rubber farmers regarding land allocation to rubber farming and the characteristics of the households and household heads, we trisect all households by the share of land planted with rubber in total land area and then compare the mean differences in characteristics between the three groups (Table 2). The results suggest that the mean values of most variables are significantly different among the three groups defined by the share of land planted with rubber in the total land area. These differences indicate the correlations between the decision about land allocation for rubber farming and these variables. Smallholders with less education tend to specialize in rubber farming. Smallholders belonging to the Dai and Hani ethnicities operate a relatively high share of land planted with rubber in the total land area; by contrast, Han and other minority farmers prefer to allocate less land to rubber farming. It seems that the share of land allocation for rubber farming is positively correlated with household wealth and experience in rubber farming but negatively associated with the land area and the elevation of the household's location.

Moreover, smallholders tend to allocate a smaller proportion of land to rubber farming if the village is located far from a rubber processing factory. If the located village has characteristic agricultural products or has implemented a “Grain for Green” project, the proportion of land allocated to rubber farming is low. Finally, some agriculture-related policies, such as the promotion of rubber farming over the past five

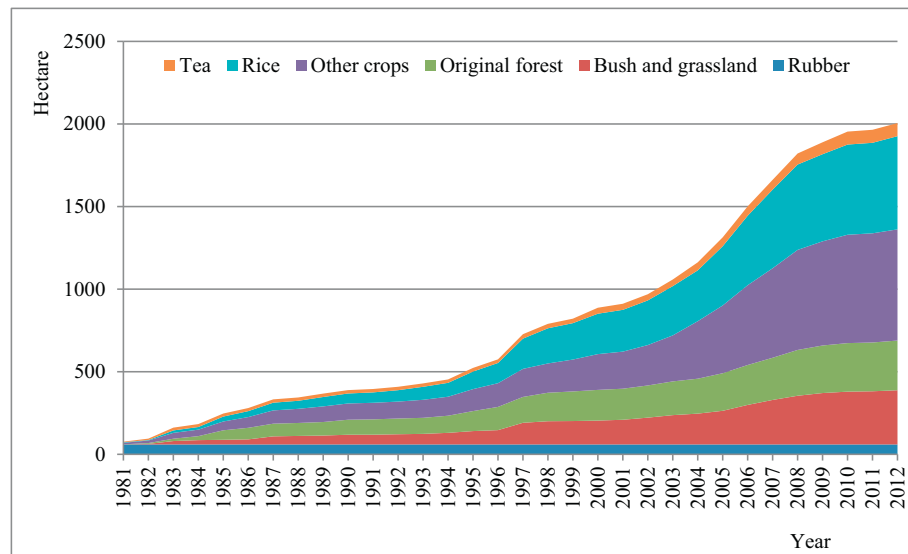


Fig. 1. The cumulative area dedicated to various land-use types replaced by rubber plantations.
Data source: Authors' survey.

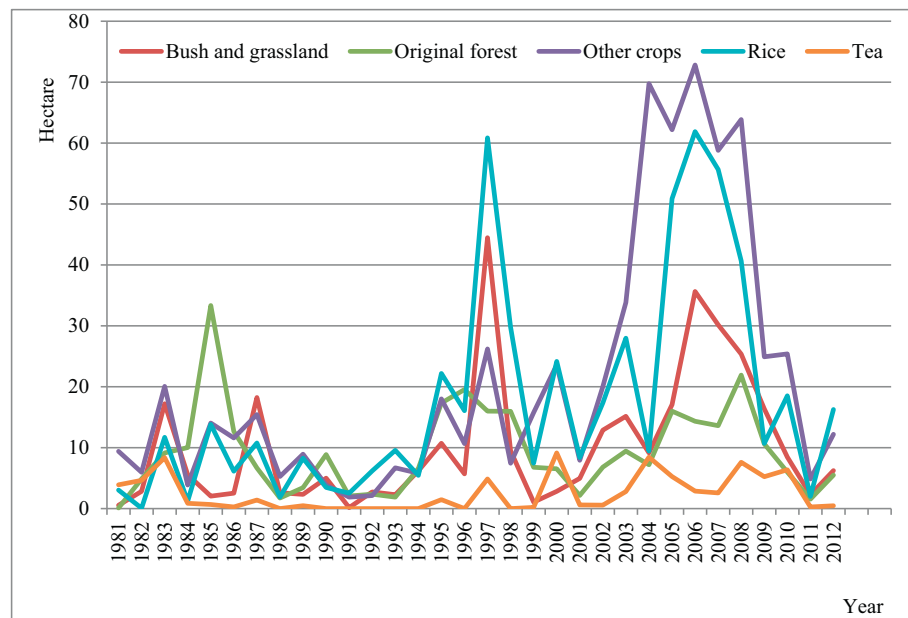


Fig. 2. Type of crops and corresponding area shifting to rubber land over time for the 612 smallholder rubber farmers in XSBN.
Data source: Authors' survey.

years, the provision of subsidies for rubber farming in 2012, and the availability of interest-free loans in the village can efficiently encourage smallholders to specialize in rubber farming. However, the above findings cannot be used to infer the determinants of land allocation to rubber farming, as the simple mean-comparison test does not control for confounding factors of these variables.

2.3.3. Carbon Stocks of Various Land Use Types

Turning to the question of the implications of land use change and rubber expansion for the local carbon balance, we summarize the total carbon stocks for various crops, forests and rubber plantations at different elevation levels in XSBN based on the studies of Li (2002) and Yang et al. (2016). As the initial soil organic carbon and below ground biomass generally depend on previous land use types, the estimated underground carbon stocks including root and soil (1–30 cm) may

result in relatively large variations for the total carbon stocks (Blagodatsky et al., 2016; Yang et al., 2016). As shown in Table 3, these data not only allow comparison and provide insights into the carbon sequestration capacities of various types of land use but also can be used as an initial evaluation of the carbon balance of a land use pattern.

In general, forest areas sequester atmospheric carbon and are an important factor in mitigating the effects of climate change (Lutz et al., 2016), while the change from forests to rubber will clearly decrease carbon stocks (Table 3). In contrast, the conversion from tea, rice, agricultural crops, bush and grassland to rubber plantations can slightly increase carbon stocks. In such situations, rubber trees actually provide some environmental services in terms of carbon stocks (Jaramillo-Giraldo et al., 2017). Hence, it is necessary to assess the balance of the overall landscape level in XSBN and the extent to which the rubber expansion of smallholder rubber farmers has affected the local carbon balance.

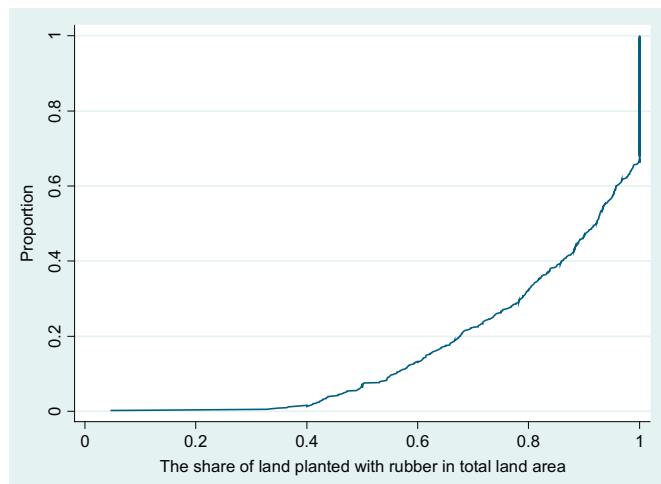


Fig. 3. Cumulative distribution of the share of land planted with rubber in total land area.

Data source: Authors' survey.

3. Methods

In this section, initially at the micro household level, we develop a Tobit model to examine the determinants of a farmer's land allocation to rubber farming. Second, to further assess the impacts of rubber expansion on the local environment in terms of carbon stocks in XSBN, we propose methods for simulating the carbon balances given rubber expansion at the aggregate level of the 612 surveyed smallholders over the past 30 years.

3.1. A Model of Smallholders' Land Allocation to Rubber Plantation

3.1.1. Conceptual Model

The decision behind a farmer's land use can be simply derived by

using the framework of maximizing expected utility or profit (e.g. Deininger and Jin, 2005; Kimura et al., 2011; Min et al., 2017b; Smale et al., 1994). Assume the profits from various land use portfolios can be calculated under a certain set of given conditions, then the optimal land use pattern is the option with maximum expected profits (Coxhead and Demeke, 2004; Hardie and Parks, 1997). In line with previous studies, we propose constructing a conceptual model to express the land use strategies of smallholder rubber farmers. Suppose a farmer chooses a land allocation $D(l_1 \dots l_j)$ that maximizes the expected profits (E_D); then the maximization problem can be written as follows:

$$\begin{aligned} \text{Max } E_D &= E_1 [l_1 \times f(\bar{P}_1, \bar{C}_1, Z)] + \sum_{j(j \neq 1)} E_j [l_j \times f(\bar{P}_j, \bar{C}_j, Z)] \\ \text{s. t. } \sum_j l_j &\leq L; l_j \geq 0. \\ \sum_j l_j \times \bar{C}_j &\leq W; \bar{C}_j \geq 0 \end{aligned} \quad (1)$$

where E_j represents the expected profits of the j th farm crop; l_j denotes the land area allocated to the j th farm crop; and $j = 1$ refers to rubber farming. L denotes the total land area. \bar{P}_j and \bar{C}_j indicate the expected price and the expected unit input costs of the j th farm crop, respectively. W denotes the wealth constraints for the expected total input costs of all crop farming. Z represents a vector of the socioeconomic characteristic variables of smallholder rubber farmers, which may affect farmers' land use decisions (Nguyen et al., 2017).

By maximizing function (1), we conceptually derive the optimal choice (E^*) for land allocation, which can be expressed as:

$$D^*(l_1, \dots, l_j) = f(\bar{P}_1, \bar{C}_1, \bar{P}_j, \bar{C}_j, W, L, Z) \quad (2)$$

Following the study of Min et al. (2017b), the expected output prices \bar{P}_j and expected unit inputs \bar{C}_j are assumed to be the nominal observed market prices and the nominal input costs of each type of crop farming. Thus, \bar{P}_j and \bar{C}_j can be eliminated in function (2) as \bar{P}_j and \bar{C}_j can be treated as a constant for farmers in cross-sectional data. Accordingly, the conceptual model of a farmer's land use status (D^*) can be expressed as a reduced-form function of household wealth (W), land constraints (L) and household socioeconomic characteristics (Z):

$$D^*(l_1, \dots, l_j) = f(W, L, Z) \quad (3)$$

Table 2

Mean differences in characteristics among the three quantile groups divided by the share of land planted with rubber in total land area.

Variable	Mean value			Expected sign
	Quantile 1 (0 < Rubber ≤ 0.8)*	Quantile 2 (0.8 < Rubber < 1)	Quantile 3 (Rubber = 1)	
Household head				
Age	48.15	47.50	48.30	
Eduyears	4.79	4.39	3.94**	–
Ethnicity				
Han	0.07	0.03**	0.04*	–
Dai	0.38	0.61***	0.75***	+
Hani	0.07	0.13**	0.15**	+
Others	0.48	0.23***	0.07***	–
Household and farm				
HHsize	4.97	5.19	5.19	
Experience	12.99	16.87***	21.90***	+
Wealth	48.89	67.31***	93.05***	+
Land	14.94	14.86	8.78***	–
Elevation	864.13	747.88***	654.01***	–
Village level				
Factory	17.53	13.75**	6.07***	–
Characteristic	0.39	0.22***	0.18***	–
Green	0.62	0.50**	0.15***	–
Promotion	0.16	0.22	0.24**	+
Subsidy	0.41	0.51**	0.47	+
Loans	0.04	0.21**	0.35***	+
Observations	204	209	199	

Reference group.

* Indicates 10% significance level of the mean-comparison test.

** Indicates 5% significance level of the mean-comparison test.

*** Indicates 1% significance level of the mean-comparison test.

Table 3
Carbon stocks in different land use types in XSBN (unit: Mg C/ha \pm S.E.)

Land cover	Total carbon stocks (Tree above ground + Understory + Necromass + Root + Soil (1–30 cm))
L1: Lowland forest (< 800 MASL)	309 \pm 91
L2: Highland forest (> 800 MASL)	256 \pm 38
L3: Bush and grassland	96 \pm 12
L4: Agricultural Crops	84 \pm 15
L5: Rice#	56 \pm 4
L6: Tea	101
L7: Rubber plantation (< 800 MASL)	124 \pm 14
L8: Rubber plantation (> 800 MASL)	91 \pm 5

Data Source: Yang et al. (2016) and # Li (2002).

where the vector Z includes the characteristics of the household head, household size, experience in rubber farming, elevation of household site, and the characteristics of the village, which are assumed to determine farmers' land use decisions by affecting their agricultural ability (Deininger and Jin, 2005). For the sake of simplicity, household wealth W , land size L and the vector Z in model (3) are further co-expressed as a vector X in the following analysis.

3.1.2. Empirical Model

To empirically capture the factors determining the heterogeneity in smallholders' land allocation to rubber farming, we propose establishing a multivariate regression model of smallholders' decision to allocate land to rubber farming and meanwhile define the dependent variable (y) as the share of rubber land area in the total land area of the household. Theoretically, y should be between 0 and 1 and therefore is a doubly censored dependent variable. Thus, the proposed model can be specified as a Tobit model, which was originally developed by Tobin (1958) and further introduced in detail by numerous studies, such as McDonald and Moffitt (1980), Cong (2000), Greene (2003) and Wooldridge (2013). Accordingly, the model of smallholders' land allocation to rubber farming can be expressed as:

$$y_i^* = X_i\beta + \epsilon_i \quad (4)$$

$$y_i = \begin{cases} 0 & \text{if } y_i^* \leq 0 \\ y_i^* & \text{if } 0 < y_i^* < 1 \\ 1 & \text{if } y_i^* \geq 1 \end{cases} \quad (5)$$

where subscript i represents the i th household. y^* is the latent variable of y , while X is a vector of explanatory variables representing the characteristics of the household head and household (see Table 1). The coefficients β are the parameters to be estimated. ϵ is an independent and identical error term assumed to be normally distributed ($\epsilon \sim N(0, \sigma^2)$).

Because all those in the sample were operating rubber plantations in 2012, the dependent variable y cannot take the value of zero. Thus, the Eq. (5) is adjusted as:

$$y_i = \begin{cases} X_i\beta + \epsilon_i & \text{if } 0 < X_i\beta + \epsilon_i < 1 \\ 1 & \text{if } X_i\beta + \epsilon_i \geq 1 \end{cases} \quad (6)$$

Then, the log-likelihood function for the employed Tobit model can be built up as:

$$\ln L = \sum_{0 < y_i < 1} \ln \frac{1}{\sigma} \varphi \left[\frac{y_i - X_i\beta}{\sigma} \right] + \sum_{y_i = 1} \ln \left[1 - \Phi \left(\frac{1 - X_i\beta}{\sigma} \right) \right] \quad (7)$$

where $\varphi(\cdot)$ and $\Phi(\cdot)$ are the univariate standard normal distribution and density functions, respectively. Hence, the parameters β can be estimated with the maximum likelihood estimation approach (MLE).

According to McDonald and Moffitt (1980) and Cong (2000), there are four forms of marginal effects to be calculated after the estimation of a Tobit model.

$$\beta = \partial E(y_i^*) / \partial X_i \quad (8a)$$

$$\beta_b = \partial E(y_i) / \partial X_i \quad (8b)$$

$$\beta_c = \partial E(y_i | 0 < y_i < 1) / \partial X_i \quad (8c)$$

$$\beta_d = \partial P(0 < y_i < 1) / \partial X_i \quad (8d)$$

where the coefficients β are the marginal effects on the latent dependent variable, β_b denote the marginal effects on the unconditional expected value of the observed dependent variable, β_c are the marginal effects on the conditional expected value of the dependent variable (conditioned on being uncensored), and β_d represent the marginal effects on the probability of being uncensored.

3.2. The Simulation of Carbon Stocks Considering Rubber Expansion

Due to uncertainties in estimating deforestation rates and the available biomass in secondary forests, estimations of the changes in carbon stocks as a result of deforestation are ambiguous (Li et al., 2008). To more clearly understand this phenomenon, a relatively reliable and accurate evaluation of carbon sequestration and emissions at the landscape level is particularly needed (Blagodatsky et al., 2016). Using the rapid carbon stock appraisal (RaCSA) method based on tree, plot, land use and landscape assessments and integrating field sampling with remote sensing and GIS technology, Yang et al. (2016) estimated the relationship between carbon stocks and the ages of rubber plantations and then calculated the time-average carbon stock at the median time of rotation length for lowland and highland plantations, respectively 17.5 and 12.5 years. These results provide an important reference for assessing the carbon stocks of rubber plantations under limited information.

This study attempts to use two methods to assess the carbon balance from rubber expansion in XSBN: 1) making use of the average carbon stocks of various crops, forest and rubber plantations considering the different elevations in Table 1; and 2) further taking into account the age of the rubber trees in each year. Assume B_t , F_t , C_t , R_t , and T_t hectares of bush and grassland, original forest, agricultural crops, rice, and tea, respectively, have been converted to rubber plantations in year t ; thus, the area devoted to rubber plantations increases by $(B_t + F_t + C_t + R_t + T_t)$. Suppose that α is the share of forest located below 800 MASL, while β is the share of other crops (bush and grassland, agricultural crops, rice, and tea) located below 800 MASL.

Following the first method, the decrease in carbon stocks due to deforestation in year t and the increase in carbon stocks from the correspondingly established rubber plantations can be respectively expressed as:

$$\text{Carbon_Forest (Decrease)}_t = L1 \times \alpha F_t + L2 \times (1 - \alpha) F_t \quad (9a)$$

$$\text{Carbon_Forest (Increase)}_t = L7 \times \alpha F_t + L8 \times (1 - \alpha) F_t \quad (9b)$$

where $L\#$ represent the carbon stocks in different land use types (Table 3). Similarly, the changes in carbon stocks as rubber plantations replace other crops can be expressed as:

$$\text{Carbon_Others(Decrease)}_t = L3 \times B_t + L4 \times C_t + L5 \times R_t + L6 \times T_t \quad (10a)$$

$$\begin{aligned} \text{Carbon_Others(Increase)}_t &= L7 \times \beta (B_t + C_t + R_t + T_t) \\ &+ L8 \times (1 - \beta) (B_t + C_t + R_t + T_t) \end{aligned} \quad (10b)$$

Thus, the changes in the carbon stocks by year T can be derived as:

$$\text{Carbon_Forest(Decrease)}_T = \sum_t^T \text{Carbon_Forest(Decrease)}_t \quad (9a')$$

$$\text{Carbon_Forest(Increase)}_T = \sum_t^T \text{Carbon_Forest(Increase)}_t \quad (9b')$$

$$\text{Carbon_Others(Decrease)}_T = \sum_t^T \text{Carbon_Others(Decrease)}_t \quad (10a')$$

$$\text{Carbon_Others(Increase)}_T = \sum_t^T \text{Carbon_Others(Increase)}_t \quad (10b')$$

Hence, by year T , the decrease in carbon stocks as forest and other crops are replaced by rubber plantations and the increase in carbon stocks from the correspondingly established rubber plantations can be specified as:

$$\text{Carbon(Decrease)}_T = \text{Carbon_Forest(Decrease)}_T + \text{Carbon_Others(Decrease)}_T \quad (11a)$$

$$\begin{aligned} \text{Carbon(Increase)}_T &= \text{Carbon_Forest(Increase)}_T \\ &+ \text{Carbon_Others(Increase)}_T \end{aligned} \quad (11b)$$

Accordingly, the comparison shown in the formula (12) between the results of formulas (11a) and (11b) can reflect the carbon balances from rubber expansion in XSBN by the year T .

$$\begin{cases} \text{Carbon loss}_T & \text{if } \text{Carbon(Decrease)}_T > \text{Carbon(Increase)}_T \\ \text{Carbon balance}_T & \text{if } \text{Carbon(Decrease)}_T = \text{Carbon(Increase)}_T \\ \text{Carbon surplus}_T & \text{if } \text{Carbon(Decrease)}_T < \text{Carbon(Increase)}_T \end{cases} \quad (12)$$

However, above calculation formulas regarding carbon stocks of rubber plantation just used the unit average carbon stocks of rubber plantations ($L7$ and $L8$) directly and did not take into account the heterogeneous carbon stocks of rubber tree by the age structure of the plantation. If the actual average age of rubber plantations is significantly different from that in the study of Yang et al. (2016), the calculation results of formula (11b) might be biased.

For the second method, we employ the yearly carbon stocks of rubber plantations instead of the unit time-average carbon stocks to assess the carbon stocks of rubber expansion. According to the equations between age and aboveground carbon stock of rubber trees as well as the underground carbon stock of rubber trees (Yang et al., 2016), we can further calculate the carbon stocks of rubber tree in the age a (L_a) below 800 MASL and the carbon stocks of rubber tree in the age a (L'_a) above 800 MASL. Thus, the increase in carbon stocks from the established rubber plantations in the year t can be revised as:

$$\text{Carbon_Forest(Increase)}'_t = L_{ta} \times \alpha \times F_{ta} + L'_{ta} \times (1 - \alpha) F_{ta} \quad (9c)$$

$$\begin{aligned} \text{Carbon_Others(Increase)}'_t &= L_{ta} \times \beta (B_{ta} + C_{ta} + R_{ta} + T_{ta}) \\ &+ L'_{ta} \times (1 - \beta) (B_{ta} + C_{ta} + R_{ta} + T_{ta}) \end{aligned} \quad (10c)$$

The changes in carbon stocks by year T can be further written as:

$$\text{Carbon_Forest(Increase)}'_T = \sum_a^A \sum_t^T \text{Carbon_Forest(Increase)}'_t \quad (9c')$$

$$\text{Carbon_Others(Increase)}'_T = \sum_a^A \sum_t^T \text{Carbon_Others(Increase)}'_t \quad (10c')$$

Hence, the modified carbon stocks of rubber plantations by year T should be the addition of formulas (9c') and (10c').

$$\begin{aligned} \text{Carbon(Increase)}'_T &= \text{Carbon_Forest(Increase)}'_T \\ &+ \text{Carbon_Others(Increase)}'_T \end{aligned} \quad (11b')$$

Because every year there are some newly established rubber plantations (Fig. 1), by accounting for the heterogeneous carbon stocks of rubber trees of different ages, the second assessment method is assumed to be superior to the first. Thus, the gap between the results of formulas (11b) and (11b') shows the estimation bias of the carbon stocks of rubber expansion due to ignoring the heterogeneity in the carbon stocks of rubber trees of different ages, while the comparison between the results of formulas (11a) and (11b') can more accurately reflect the carbon balances from rubber expansion in XSBN by year T .

4. Results and Discussion

4.1. Correlation Between the Expansion of Smallholder Rubber Farming and the Price of Natural Rubber

In a land allocation model using a cross-sectional data, the price of natural rubber is normally assumed to be constant and eliminated; however, it is undeniable that theoretically, the price of natural rubber is an essential determinant of rubber expansion. Fig. 4 shows the fluctuation trend of the price index of natural rubber from 1981 to 2012. By comparing Figs. 2 and 4, visually, the overall fluctuation in the price index of natural rubber is similar with the expansion of rubber farming shown in Fig. 2, particularly, around the three expansion peaks. Table 4 further presents the correlation between the expansion of natural rubber and the price of natural rubber. The results indicate that the expansion of rubber farming among smallholders in XSBN may not be determined by the price of natural rubber in the current year but instead is significantly correlated with the price of natural rubber lagging 2 or 3 years.

4.2. Determinants of Smallholders' Land Use for Rubber Farming

Based on the household survey data, a Tobit model for smallholders' land allocation to rubber farming was estimated. The results are shown in Table 5. Of the 612 smallholders in the sample, 199 households (33%) allocated all land to plant rubber, while 413 households (67%) planted both rubber and other crops. The F-statistic is 27.73 and significantly different from zero, confirming the joint explanatory power of these independent variables on smallholders' land allocation to rubber. Moreover, most independent variables have statistically significant impacts on the share of rubber plantations in the total household land area, further confirming the validity of the model specification.

While the household head's age and education level do not have a significant effect on smallholders' land use decisions around rubber farming, the Dai and Hani minority farmers tend to allocate a greater share of land to rubber farming than the Han majority. This result is reasonable as various ethnic farmers vary in histories, cultures, and knowledge; accordingly, their decision making and agricultural practices may also differ (Colfer et al., 1989; Brush and Perales, 2007; Montalvo and Reynal-Querol, 2005; Stichnoth and Van der Straeten, 2013). Consistent with the study of Min et al. (2017b), smallholders with a longer experience in rubber farming are likely to specialize in rubber farming. However, unlike the insignificant impact of household wealth on the share of rubber plantations in total land area found in the results of Min et al. (2017b), our results show that this impact is statistically significant and positive, suggesting that household wealth is an important influencing factor for land allocation (Walker et al., 2002). Although land constraints are an essential determinant of farmers' decisions on land use (Browder et al., 2004), the estimation results indicate that land size has no significant effect on smallholders' land use for rubber. Moreover, the elevation of the household site is an essential variable in the analysis of land use (Nelson and Geoghegan, 2002). As the elevation of the household site increases, smallholders tend to allocate a lower share of land to rubber farming due to the limitations of the minimum temperature needed for the growing

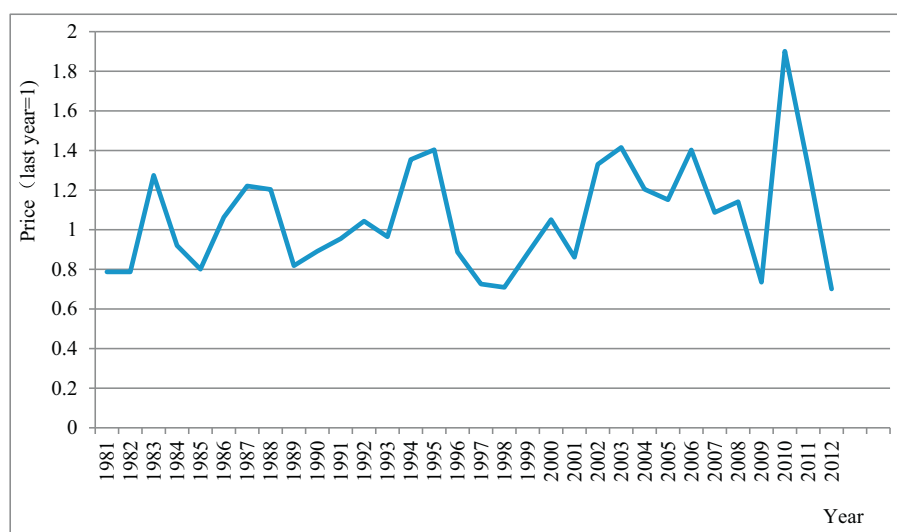


Fig. 4. Fluctuation trend of the price index of natural rubber from 1981 to 2012.
Data source: Singapore Commodity Exchange.

Table 4
Correlation coefficient matrix between the expanding area of natural rubber and the price index of rubber farming.

Expanding area of rubber from...	The price index of natural rubber				
	lag 0 year	lag 1 year	lag 2 year	lag 3 year	lag 4 year
Bush and grassland	0.157	0.067	0.316 [*]	0.544 ^{***}	0.269
Original forest	−0.079	−0.034	0.363 ^{**}	0.281	−0.003
Rice	0.328	0.232	0.384 ^{**}	0.348 [*]	0.238
Tea	0.136	0.073	0.391 ^{**}	0.526 ^{**}	0.229
Other crops	0.231 [*]	−0.089	0.120	0.141	0.117
All types of crops	0.195	0.037	0.305 [*]	0.513 ^{***}	0.265

Data source: Authors' calculation.

* Indicates 10% significance levels.

** Indicates 5% significance levels.

*** Indicates 1% significance levels.

environment of natural rubber.

Furthermore, consistent with the descriptive statistics in Table 3, the impacts of all explanatory variables at the village level on smallholders' land allocation for rubber farming are statistically significant with the expected signs. Smallholders living nearer a rubber processing factory normally allocate more land for rubber plantations. The existence of characteristic agricultural products and the implementation of the "Grain for Green" project in the village hinder smallholders' allocation of land to rubber farming, as they might be alternative income sources for rubber farmers. The results in Table 5 also indicate that promotions and subsidies for rubber farming as well as the availability of interest-free loans play significant roles in helping farmers to specialize in rubber farming.

The marginal effects of those significant variables on the share of land allocation to rubber farming are further calculated and reported in Table 5. For example, compared with other ethnicities, the Dai and Hani smallholders, on average, have a 23.73% and 12.64% higher probability of fully specializing in rubber farming, respectively. For the uncensored samples ($0 < y_i < 1$), Dai and Hani smallholders respectively tend to allocate 5.59% and 2.98% more land to rubber farming than smallholders of other ethnicities. From the perspective of the entire sample, smallholders on average allocate 7.96% and 4.24% more land to rubber farming if they belong to Dai and Hani minorities. The implementation of the "Grain for Green" project in the village also has relatively large marginal effects on the share of land allocated to rubber farming. Compared with the farmers in villages that did not implement

the "Grain for Green" project, farmers in a "Grain for Green" village have a 21.72% higher probability of fully specializing in rubber farming. The implementation of a "Grain for Green" project in the village leads farmers to allocate 7.29% (5.11%) less land to rubber farming on average for the whole sample (for the uncensored sample).

Apart from the explanatory variable "distance to the nearest rubber processing factory", the other explanatory variables at the village level appear to have larger marginal effects on the share of land allocated to rubber farming than the variables at the household and farm levels. These results imply that smallholder rubber farmers' land use allocation is mainly affected by implementations of some external projects. Hence, the policy design related to rubber farming should take into account project intervention at the village level.

4.3. Carbon Balances of Rubber Expansion

Based on the derived formulas (11a), (11b) and (11b'), we further calculate the carbon losses due to the reduced forest and other types of land (11a) and the increased carbon stocks from the newly established rubber plantations. The latter have been calculated by employing two methods: using the time-average carbon stocks of rubber plantations (11b) and then further taking into account the age of rubber trees in each year (11b'). Accordingly, Fig. 5 shows the trend in carbon balances of rubber-based land use change among smallholder rubber farmers in XSNB. The blue line represents the calculated results of formula (11a), the red dashed line denotes the estimation results of formula (11b), and the simulated results of formula (11b') are shown by the red line.

The first estimation method (the comparison between the blue line and the red dashed line) shows that the replacement of forest and the other land with rubber can lead to a certain loss of carbon stock in the first two decades (before 2003), the newly established rubber plantations could result in a carbon balance in approximately 2003, while since 2003, the rubber expansion has been gaining an increasing carbon surplus. By 2012, the carbon losses due to the replaced forest and the other land of the 612 smallholder rubber farmers in our samples were approximately 216,163 Mg, while the increased carbon stocks from the newly established rubber plantations reached 240,338 Mg, resulting in a carbon surplus of approximately 24,175 Mg.

However, as we discussed when describing the methods in Section 3.2, one of the limitations of the calculation results using the time-average carbon stocks of rubber plantations is that they do not take into account the specific age of the rubber plantations. Because every year some new rubber trees are planted, the existence of relatively large

Table 5
Estimation results and marginal effects of the Tobit regression for smallholders' land use for rubber farming.

Variable	Tobit regression		Marginal effects		
	Coef. (β)	Robust Std. Err.	Unconditional Expected Value (β_u)	Conditional on being Uncensored (β_c)	Probability Uncensored (β_d)
Household head					
Age	−0.0004	0.0007			
Eduyears	−0.0003	0.0025			
Ethnicity					
Han	0.0200	0.0581			
Dai	0.1180**	0.0218	0.0796	0.0559	−0.2373
Hani	0.0628**	0.0302	0.0424	0.0298	−0.1264
Others#					
Household and farm					
HHsize	0.0018	0.0057			
Experience	0.0033**	0.0013	0.0022	0.0016	−0.0067
Wealth	0.0002*	0.0001	0.0002	0.0001	−0.0005
Land	−0.0005	0.0011			
Elevation	−0.0005***	0.0001	−0.0003	−0.0002	0.0010
Village					
Factory	−0.0011*	0.0006	−0.0007	−0.0005	0.0022
Characteristic	−0.0364*	0.0202	−0.0246	−0.0172	0.0733
Green	−0.1080***	0.0196	−0.0729	−0.0511	0.2172
Promotion	0.0334*	0.0198	0.0226	0.0158	−0.0672
Subsidy	0.0406**	0.0187	0.0274	0.0192	−0.0817
Loans	0.0438**	0.0221	0.0295	0.0207	−0.0881
_cons	1.1578***	0.0840			
F(16, 596)		27.7300***			
Pseudo R2		0.9953			
Observations		612			

Note: 0 left-censored observations, 413 uncensored observations, 199 right-censored observations at Rubber = 1; # reference group.

* Represents the significance level at 10%.

** Represents the significance level at 5%.

*** Represents the significance level at 1%.

areas of immature rubber likely leads to the overestimation of carbon sequestrations by rubber plantations using the first method.

As shown in Fig. 5, the result from the second estimation method, which takes into account the actual age of the rubber plantations (red line) not only confirms that the first method (red dashed line) indeed overestimates the stock sequestrations of rubber plantations but also reveals that rubber expansion in XSBN has actually led to major carbon losses over the past three decades. By 2012, the modified carbon stocks of the rubber plantations for the 612 smallholder rubber farmers in our sample were approximately 173,934 Mg, suggesting that rubber

expansion led to a substantial carbon loss of 42,229 Mg. On average, rubber expansion among smallholder rubber farmers outside the conservation region in XSBN has led to a carbon loss of approximately 21 Mg/ha/year over the past three decades.

If we assume that smallholder rubber farmers would not have changed their land use patterns since 2012, then we can further project the trends in carbon stocks out to 2018. As shown in Fig. 5, the carbon losses due to the replaced forest and the other land (the blue line) will be constant every year into the future, while the carbon stocks from the established rubber plantations appear to grow at a relatively high

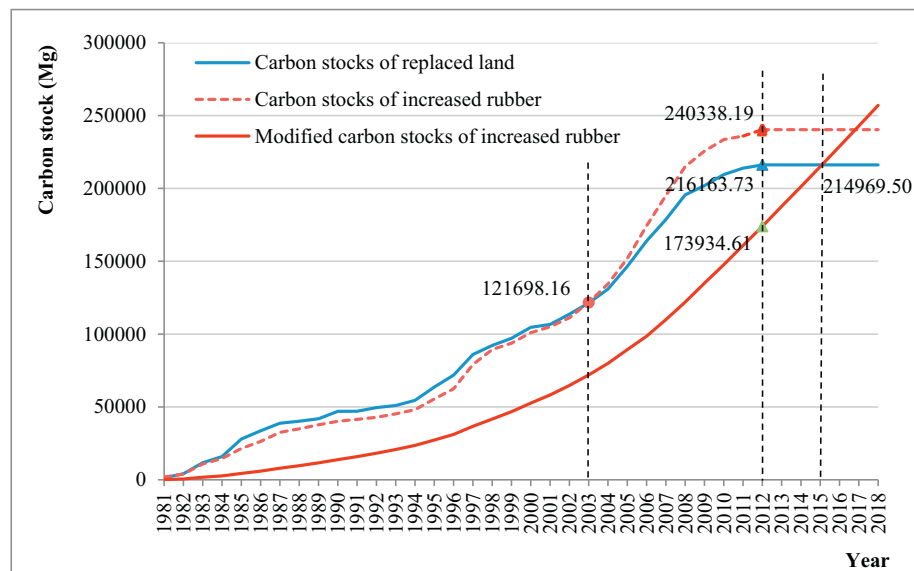


Fig. 5. The trend in aboveground carbon stocks of replaced land, increased rubber plantations and modification by the age of the rubber trees for the 612 smallholder rubber farmers in XSBN. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

speed, meaning that an increasing number of immature rubber trees will grow older. Hence, the carbon stocks from rubber expansion might compensate more for carbon losses over time. It is simulated that, in 2015, the increased carbon stocks from rubber plantations would for the first time go beyond the decreased carbon stocks from deforestation and land use change. Subsequently, smallholder rubber plantations in XSBN could result in net carbon surplus every year.

However, for smallholder rubber farmers, although the carbon balance between the established rubber plantation and the replaced land in XSBN would first be achieved by 2015, smallholder rubber plantations do not appear to become a vital carbon sink due to the limitation of rotations for rubber trees. According to the study of Nizami et al. (2014), a 40 year rotation length showed the maximum production and carbon stocks in Xishuangbanna. Thus, the increasing slope of the red line actually might slow down as more rubber trees enter the rotation at an age of 40 years. This implies that the carbon surplus of the established rubber plantations will begin to decrease in 2020, so that the decreased carbon stocks from deforestation and land use change and increased carbon stocks from rubber plantations might be close to a balance over time. By that time, the capacity of the carbon sink of smallholder rubber plantations relative to the replaced forest and land may be almost equal.

5. Concluding Remarks

This study shows the dynamics of rubber-based land use changes implemented by smallholder rubber farmers during recent decades. By 2012, over 60% of smallholder rubber plantations in XSBN were established by replacing rice and other crops, while approximately 15% of these rubber plantations were established by clearing virgin forests. The results complement empirical evidence that rubber expansion has resulted in a significant land use change for smallholders in XSBN and led to deforestation. Additionally, the expansion of smallholder rubber farming is correlated with the price of natural rubber lagged by 2–3 years.

Using a land use allocation model at the micro household level, we find that smallholders' decisions to allocate land for rubber farming are associated with their ethnicity, their experience in rubber farming, household wealth, the elevation of household site and several village-level variables including the distance to the rubber processing factory, operation of characteristic agriculture, implementation of a "Grain for Green" project, the promotion of rubber farming, the provision of a subsidy for rubber farming, and the availability of interest-free loans. In particular, the results of the marginal effects suggest that the policy and project variables related to rubber at a village level play a dominant role in farmers' land allocation decisions. These new findings help gain a better understanding the expansion of smallholder rubber farming in XSBN.

By simulating the carbon balances following rubber farming expansion among the surveyed smallholder rubber farmers over the past three decades in XSBN, the findings highlight the need to simulate the carbon stocks of rubber trees by taking into account the age of the rubber trees. In doing so, we find that the losses of carbon stocks due to rubber expansion are much higher than those estimated using the time-average carbon stocks of rubber plantations. The net loss of carbon stocks among smallholder rubber plantations outside the natural reserves in XSBN over the past three decades is estimated to be approximately 21 Mg/ha/year. In 2015, a carbon balance between smallholder rubber plantations and the replaced land was achieved for the first time. However, due to the rotation of rubber trees, the net gains in carbon stocks may only last until 2020. Furthermore, the results also indicate that overall, the rubber plantations outside of the natural reserves in XSBN cannot compensate for the carbon losses due to the reduction in forest and other types of land; this finding is generally consistent with a previous study based on rubber land in the nature reserve areas of XSBN (Yang et al., 2016). Considering the relatively large carbon surpluses by reforestation from rubber plantations, we

recommend carbon-trading schemes as a potential means to restore the natural environment threatened by rubber farming, while payment for ecosystem service schemes may also support the maintenance of ecosystem services (Klasen et al., 2016).

In recent decades, the rapid emergence of rubber farms is the hallmark of a larger land-cover transition that has been sweeping through Montane Mainland Southeast Asia (Ziegler et al., 2009). Particularly in the Greater Mekong Subregion (GMS), including Laos, Myanmar, Thailand and Vietnam, the expansion of smallholder rubber farming and its economic and environmental consequences have attracted widespread attention (Fox and Castella, 2013; He and Martin, 2016; Xu et al., 2014). While this study is limited to XSBN, our findings provide a good reference for the trajectory of smallholder rubber expansion, land use change and the carbon stocks of rubber plantations in the other similar rubber-growing areas in the GMS (Min et al., 2017b). Moreover, the methods used in this study to identify smallholders' land allocation for rubber plantations and simulate the carbon stocks of rubber expansion provide a reference for similar studies and could be applied to other rubber planting areas.

Finally, we would like to point out two limitations of this study. First, due to the uncertainties surrounding soil organic carbon and below ground biomass (Yang et al., 2016), the estimates of the total carbon stocks in the study may be somewhat biased. A more accurate estimate for the underground carbon stocks should be implemented in future studies by actual measurement instead of simply referring to the parameters in previous studies. Second, to more comprehensively understand rubber-based land use change and its implications for carbon balances in the whole region of XSBN, a comparative analysis examining farms inside and outside the natural reserves is worth conducting.

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