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Climate change and farmers' perceptions: impact on rubber farming in the upper Mekong region

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Abstract
This article examines the impact of farmers' perceptions of temperature change on implementing environmentally friendly agriculture practices on rubber plantations. Based on the data collected from 611 smallholder rubber farmers in Xishuangbanna Dai Autonomous Prefecture (XSBN) in the upper Mekong region, an endogenous switching probit model and an endogenous treatment effects model are applied to estimate the impacts of farmers' perceptions of temperature change on implementing environmentally friendly rubber plantations (EFRP) proxied by the intercropping system. While the real annual average temperature in XSBN has been increasing, only 59% of respondents perceived an increasing trend, whereas over 38% perceived no change. Farmers' perceptions of temperature change appear to hinge on their education and socioeconomic characteristics and the experience of shocks related to regional climate change. Improving farmers' perceptions of increasing temperature can significantly foster their practice of EFRP. Hence, policies that promote awareness of regional climate change can effectively encourage the implementation of mitigation practices.

Keywords Temperature change · Environmentally friendly agriculture · Rubber intercropping · Endogenous switching probit model

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1 Introduction

In recent decades, the land use changes that occur through the conversion of natural rainforest, secondary forest, jungle, farmland, or other land types to monoculture tree crop plantations such as natural rubber, oil palm, and coffee plantations have led debates about deforestation, environmental degradation, and sustainable development in developing countries, especially in Southeast Asia (Angelsen 1995; Qiu 2009; Wicke et al. 2011; Zhou 2008; Ziegler et al. 2009). Notably, the conversion from forests to tree crops has significantly increased carbon emissions (Carlson et al. 2012; Fearnside 1997; Min et al. 2019), while the accumulation of carbon dioxide and other greenhouse gases is likely to lead to global warming and other substantive climate changes (Nordhaus 1992). Evidence from monoculture plantations of natural rubber, oil palm, and coffee has consistently confirmed that the massive expansion of these tree crops has greatly affected the regional climate (He and Zhang 2005; Hergoualc'h et al. 2012; Laurance et al. 2010; Qiu 2009; Zhou 2008).

Farmers' perceptions of the regional climate reflect their judgments and awareness of climate change and may affect their adaptation and mitigation behaviors (Hou et al. 2015). While the literature on adaptations makes it clear that perception is a necessary prerequisite for adaptation (Maddison 2007), some farmers who do not perceive climate change might also implement agricultural practices that help mitigate climate change. Hence, a better understanding of farmers' perceptions of climate change has been widely viewed as a crucial mechanism in the process of improving adaptation (Hou et al. 2017; Shi et al. 2015; Yu et al. 2013), which may determine the validity of policies or programs designed to cope with climate change. Temperature is a popular metric for summarizing the state of the climate, while surface air temperature change is a primary measure of climate change (Hansen et al. 2006; Lee et al. 2015). However, occasionally, farmers' perceptions of mean temperature are inconsistent with the meteorological record data (Hou et al. 2015; Lee et al. 2015; Maddison 2007). This incorrect (inconsistent) perception of temperature change may lead to inappropriate adaptation to, mitigation of, or responses to production or the natural ecosystem (Dawson et al. 2011). Counterfactual evidence by Di Falco et al. (2011) clearly indicates that farmers who adapted to climate change would have experienced a loss in food products if they had not adapted.

In the Greater Mekong region, the ecological environment and regional climate have been largely influenced by local human activities, notably, the expansion of monoculture rubber plantations (Qiu 2009; Ziegler et al. 2009). A typical case is the rapid expansion of natural rubber plantations in Xishuangbanna Dai Autonomous Prefecture (XSBN) in the southern Yunnan Province of China (Min et al. 2019), which is located in the upper Mekong region and is one of China's few tropical rainforest areas. Apart from the consequences of deforestation, biodiversity loss, loss of water, and soil erosion (Hu et al. 2008; Min et al. 2018), the impact of monoculture rubber farming on the regional climate has also been observed (Qiu 2009; Zhou 2008). For instance, He and Zhang (2005) found that since the 1960s, the average temperature of rubber planting areas in XSBN has increased at a rate of 0.01 °C/year to 0.04 °C/year, while there has been no change in other non-rubber planting areas in Yunnan Province. Some smallholders have also experienced yield loss due to pest and diseases (e.g., powdery mildew) in rubber farming as a result of higher temperature. However, to date, smallholder rubber farmers' perceptions of temperature change in XSBN have not been well recorded due to a lack of relevant data.

Numerous studies have been conducted to investigate farmers' adaptation and mitigation behaviors related to climate change (e.g., Antle and Capalbo 2010; Di Falco et al. 2011; Hou et al. 2017). However, most of these studies focused on food crops, while the adaptation or mitigation actions taken by smallholders planting non-food agricultural products to cope with climate change in the local area have rarely been discussed. Environmentally friendly rubber plantations (EFRP), which the local government in XSBN has proposed in recent years (Min et al. 2017a), aim to reduce the negative environmental impacts of agricultural practice and help to cope with regional climate change to some extent (Min et al. 2018). Previous studies have reported that agroforestry, tree-based production systems could play a significant role in sequestering carbon and mitigating the atmospheric accumulation of greenhouse gases (Dawson et al. 2011; Verchot et al. 2007), thereby helping to mitigate climate change. For instance, Hergoualc'h et al. (2012) proposed mitigating the climatic impact of coffee monocultures through establishing coffee-based agroforestry systems. Therefore, as an essential component of EFRP, the establishment of a rubber-based agroforestry system, specifically through intercropping (Min et al. 2017a), is presumed to be a useful mitigation behavior for regional climate change.

Specifically, the program of EFRP was announced by the local government of XSBN in 2009, while the implementation guidelines of the program were formulated in 2013 (XSBN Biological Industry Office 2013). One of the core contents of this program introduces rubber intercropping systems which, on one hand, can increase biodiversity and green cover within rubber trees as well as improving the cooling function of rubber plantations; on the other hand, it may help improve smallholder rubber farmers' resilience of livelihoods. However, the implementation of EFRP has to face challenges of limited family labor, rising labor wages, and household financial constraints. To date, while the government of XSBN has implemented the pilot projects of EFRP in some rubber plantations, there is no any specific promotion or extension measures of EFRP for smallholders in addition to calling for them to adopt it. The adoption rates of EFRP by smallholder rubber farmers in XSBN are also unclear.

Given the significant impact of farmers' perceptions of climate change on their adaptive and mitigation behaviors (Li et al. 2017; Swe et al. 2015; Woods et al. 2017), a research question is raised: whether and to what extent farmers' perceptions of regional climate change in terms of temperature change affect the implementation of the EFRP model on their farms. The answers to these questions not only contribute to the further implementation of the EFRP model but are also critical to better understanding farmers' perceptions and mitigation behaviors related to regional climate change in rubber planting areas in the upper Mekong region. Additionally, the study complements the empirical evidences supporting policymakers' regional climate change mitigation plans and investments in rubber planting areas.

The overall goal of this study is to investigate smallholder rubber farmers' perceptions of temperature change in XSBN and examine the impacts of these perceptions on the implementation of the EFRP model as proxied by the intercropping system. The scope of this study is limited to temperature change and the rubber intercropping system because they are the primary factors for regional climate change and EFRP implementation, respectively, in XSBN. To our knowledge, in the existing literature, no empirical study has investigated how rubber farm management has adjusted to regional climate change. While this study is limited to southern China, the findings have valuable reference implications for other rubber planting areas in the Mekong region and other areas in Southeast Asia. More broadly, this study to some extent also provides a reference for the design of policies aiming to mitigate the climatic effect of the conversion from forests to monoculture tree crop plantations in related developing countries.

To achieve our goals, we employ cross-sectional data collected in 2015 from 611 smallholder rubber farmers in XSBN in the upper Mekong region of southern China. Based on the instrumental variable (IV) full information maximum likelihood (FIML) method, an endogenous switching probit (ESP) model along with a counterfactual analysis is applied to estimate the effects of smallholder rubber farmers' perceptions of temperature change on their adoption of the rubber intercropping system. An endogenous treatment effects model is used to estimate the adoption intensity of rubber intercropping.

The results show that monoculture was the dominant planting system of rubber plantations in XSBN in 2014. While the real average temperature per year has been increasing in XSBN over the past 15 years, only 59% of respondents perceive an increasing trend. The results of the average treatment effect on the treated (ATT) indicate that a household that perceives increasing temperature has a 18.8% higher probability of implementing rubber intercropping. The counterfactual results of the average treatment effect on the untreated (ATU) further suggest that if households that do not perceive increasing temperature perceived increasing temperature, they would have a 49.9% higher likelihood of implementing rubber intercropping. Smallholders who perceive increasing temperature averagely adopt rubber intercropping more 3.359 mu than those who do not perceive increasing temperature. Hence, farmers' perceptions of regional climate change can significantly affect their rubber farming practices.

The remainder of this article is organized as follows. Section 2 presents the data source and the descriptive statistics of farmers' perceptions of temperature change and the adoption of EFRP. Section 3 presents the conceptual framework and hypotheses. Section 4 develops the empirical estimations to analyze the impacts of farmers' perceptions of temperature change on the adoption of EFRP at the household and plot levels, respectively. Section 5 discusses the results and then concludes.

2 Data and descriptive statistics

2.1 Data source

The data used in this study are from a socioeconomic survey of smallholder rubber farmers in XSBN in March 2015. To ensure a representative sample of smallholder rubber farmers in XSBN, a stratified random sampling approach, taking into account the rubber planting area per capita and the distribution of rubber planting areas across townships, was applied in this study (Min et al. 2019). Firstly, all townships with rubber plantations in each county of XSBN were stratified by the planting area per capita. Afterward, two townships were stratified and randomly selected in Menghai due to the relatively low intensity of rubber distribution, while three townships were stratified and randomly selected in Jinghong and Mengla, respectively. Accordingly, the eight sample townships were selected as shown in Fig. 3 of Appendix A. Secondly, a similar sampling approach was used to select the sample villages in each township. Two sample villages were selected in each sample township of Menghai, while three sample villages were selected in each sample township of Jinghong and Mengla. A total of 42 villages were chosen. Thirdly, about 14 sample households were randomly selected from the village roster.[1] Finally, we interviewed a total of 611 households of smallholder rubber

[1] Based on the arrangement of each enumerator interviewing two households per day, the number of households per village ranged from 12 to 16.

farmers from 42 villages in 8 townships in XSBN that broadly represent the different types of smallholder rubber farming in XSBN.

In the household survey, we used a comprehensive household questionnaire, including detailed information on the characteristics of household members, households, land use, rubber farming, other farm and nonfarm activities, and several other modules relevant to rubber. We also designed a block of questions on regional climate change and farmers' mitigation behaviors. Within these modules, we recorded farmers' perceptions of trends in temperature, rainfall, extreme weather, and natural hazards in the past 15 years; the impacts of these changes on rubber farming; and farmers' mitigation behaviors related to these changes. Furthermore, a village questionnaire was used to interview village heads to collect basic information on the village, such as population, land, agriculture, employment, infrastructure, economic and environmental conditions, etc.

2.2 Farmers' perceptions of increasing temperature and their mitigation behaviors

The annual mean temperature for XSBN from 1970 to 2014 is shown in Fig. 1. While the yearly mean temperature is fluctuating, an overall increasing trend occurred throughout the study period. Notably, the annual mean temperature increased from 23.83 °C in 2000 to 24.96 °C in 2014. Accordingly, the mean temperature in XSBN has risen more than 1 °C in 15 years. Compared with the annual temperature change trend in Yunnan and 8 other provinces in China (Hou et al. 2015), the temperature increased faster in the rubber planting area than in other regions. The results confirmed that XSBN experienced a significant increasing temperature trend in recent decades.

Interestingly, while the real annual mean temperature in XSBN increased from 2000 to 2014, smallholder rubber farmers' perceptions of temperature change in the local area were heterogeneous (Table 1). Only 58% of the 611 smallholders perceived an increasing trend consistent with the actual recorded data in this period (2000–2014), while 38% of smallholders perceived that the temperature had not changed. The percentages of smallholder rubber farmers who reported perceiving "a decreasing trend" or who responded "do not know" were approximately 1% and 2%, respectively.

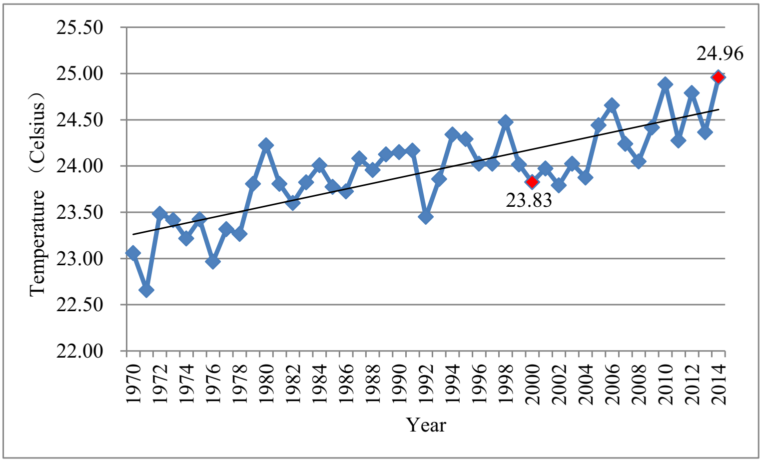

Fig. 1 The trend of average temperature per year from 1970 to 2014 in XSBN. Source: National Meteorological Information Center

While rubber intercropping is the primary component of EFRP, only 18% of smallholders had adopted rubber intercropping in 2014, while of total 3236 plots, 12.2% of rubber plots intercropped with other crops. This result indicates that monoculture was the dominant planting system on rubber plantations in XSBN (Min et al. 2017a, b). The crops intercropped with rubber at the plot level are summarized in Table 8 of Appendix A. The primary crop intercropped with rubber was tea, which occupied about 46.7% of 394 intercropping plots. Maize and coffee ranked second and third, accounting for 73 (18.53%) and 21 (5.33%) plots, respectively. The rest of crops intercropped with rubber also included banana, sorghum, hemp, fruits, and other economics forest tree. These intercropped crops increased agrobiodiversity as well as improved the cooling function of rubber plantation systems and reduced soil erosions by increasing green cover between monocultural rubber trees.

Smallholder farmers' implementation of the EFRP model was correlated with their perceptions of temperature change. Among the smallholders who perceive increasing temperature, approximately 21.57% had adopted rubber intercropping, which was significantly higher than the adoption rate of rubber intercropping in the other three groups (Table 1). Accordingly, we re-categorized all the smallholders into two groups: (1) those whose perceptions were consistent with the actual temperature record trends (smallholders who perceived increasing temperature in XSBN) and (2) those whose perceptions were inconsistent with the recorded trends (smallholders who did not perceive increasing temperature in XSBN). Overall, it seems that farmers' perceptions of increasing temperature could foster their adoption of the EFRP model in terms of rubber intercropping.

3 Conceptual framework and hypotheses

In this study, we focus on smallholder rubber farmers' decisions to adopt the EFRP which is proxied by rubber intercropping. The intercropping decision is assumed to be made for existing rubber plantations, i.e., after rubber trees were planted. The approaches to model adoption decisions normally include (1) using a static expected utility model to identify the determinants of adoption assuming that adoption will be beneficial and (2) conceptualizing adoption as a continuous optimization problem in which farmers have to make a choice about how much rubber land they want to devote to EFRP practices (Sunding and Zilberman 2001). Due to data constraints, the former approach is more widely used than the latter in previous adoption studies (Tang et al. 2016).

Table 1 Smallholder rubber farmers' perceptions of temperature change and their adoption of rubber intercropping

Categories	The proportion of households' perception on temperature	The average proportion of households with rubber intercropping by the different perception on temperature
Increase #	58.43%	21.57%
No change	38.30%	13.25%***
Decrease	1.31%	0.00%***
Do not know	1.96%	16.67%***

Source: Authors' calculation

#Reference group of the mean-comparison test; *** $p < 0.01$

Consistent with previous studies of technology adoptions (e.g., Herath and Hiroyuki 2003; Abdulai et al. 2011; Min et al. 2017a, b), this study employs the expected utility-maximizing framework to model the adoption of EFRP.[2] The farmer's total utility from rubber farming is assumed to include two components: (1) the utility derived from the profit of rubber farming and intercropping, which is affected by the weather condition during the crop season, and (2) the utility derived from improved environmental conditions when adopting rubber intercropping under the weather condition during the crop season. The farmer decides on the adoption of EFRP by taking into account the total utility derived from rubber farming. That is, if the adoption of EFRP can maximize the total utility of profit utility and environmental utility, the farmer would choose it.

Given that farmers' perceptions of climate change play a significant role in their adaptation and mitigating behaviors (Hou et al. 2017; Shi et al. 2015; Yu et al. 2013), the farmer's perception of temperature change can be incorporated into the adoption model of EFRP (Fig. 2). Intuitively, the farmer's perception of temperature change determines her/his prediction of weather condition in the coming cropping season (Bai et al. 2015). On the one hand, the increasing temperature is likely to increase the risk of pests and diseases (e.g., fungus diseases) in rubber farming and reduce the environmental utility of the farmer. On the other hand, the EFRP, proxied by rubber intercropping, to some extent, may mitigate the increase in temperature by lowering temperatures in rubber plantations. Thus, the farmers' perceptions of increasing temperature may affect their expected total utility comprising the utility from profit and the utility from environmental improvements and hereby influence the adoption of EFRP adoption decision. Therefore, the first hypothesis can be formulated as *farmers' perceptions of increasing temperature have a positive effect on their adoption of EFRP* (H.1).

The adoption of EFRP can be further categorized as three sub-adoption decisions (Fig. 2), while the first hypothesis can also be decomposed into three hypotheses. At the household level, there are two adoption decisions to be made, namely, (i) decision to adopt or not and (ii) the intensity of adoption. The former reflects the initial decision to adopt EFRP, while the latter indicates how much of the rubber area will be devoted to rubber intercropping. Like the first hypothesis, regarding the impact of farmers' perceptions of temperature change on the adoption of EFRP at the household level, we can formulate the following two hypotheses: *farmers' perceptions of increasing temperature increase the likelihood to adopt EFRP* (H.1.1) *and also positively affect the adoption intensity of EFRP* (H.1.2). At the plot level, the adoption of EFRP only consists of the decision to adopt or not, because for practical seasons farmers are likely to intercrop the entire rubber plot once they have decided to adopt the EFRP on a rubber plot. Thus, the third sub-hypothesis is at the plot level, namely, *farmers perceiving increasing temperature show a higher likelihood to adopt EFRP in their rubber plots* (H.1.3). Overall, the adoption analysis of EFRP at the household level provides a better understanding of how rubber farm management has adjusted to regional climate change, while the analysis at the plot level not only contributes to confirming the robustness of the findings from the household level but also provide evidence on the impacts of the variables at plot level including the area, land quality, and slope of a rubber plot on the adoption of EFRP.

[2] Alternatively, this study also established a theoretical framework based on conceptualizing adoption as a continuous optimization problem. The details are presented in Appendix B.

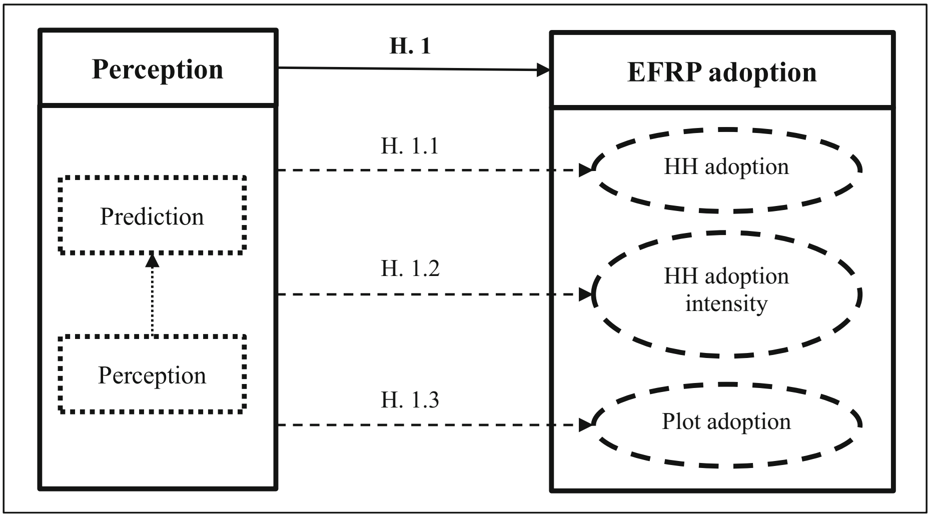

Fig. 2 The conceptual framework of EFRP adoption

4 Empirical specification

To better quantify the impact of farmers' perceptions of temperature change on the adoption of EFRP and test the proposed hypotheses, this section establishes a set of empirical models by further controlling for other variables that may influence farmers' perceptions and adoption decisions. Following the existing studies (Moser and Ekstrom 2010; Hou et al. 2017), farmers' climatic adaption behaviors follow a two-stage decision process: the first stage is with regard to farmers' perceptions of temperature change and the second stage involves adapting to adopt EFRP including adoption decision and adoption intensity given farmers' perceptions of temperature change.

Referring to the conceptual framework of EFRP adoption in Fig. 2, the empirical models are specified as follows:

$$Perception_i = \alpha_0 + \alpha_1 X_i + \alpha_2 IV_i + \mu_i \tag{1}$$

$$Adoption_i = \beta_0 + \beta_1 Perception_i + \beta_2 X_i + v_i \tag{2}$$

$$\mathrm{I}ntensity_i = \gamma_0 + \gamma_1 Perception_i + \gamma_2 X_i + \omega_i \tag{3}$$

$$Adoption\_plot_{ij} = \delta_0 + \delta_1 Perception_i + \delta_2 X_i + \delta_3 P_{ij} + \varphi_{ij} \tag{4}$$

where *i* and *j* represent the *jth* plot of the *ith* smallholder rubber farmers. Equation 1 represents the first stage regarding farmers' perception of temperature change, wherein the dependent variable, *Perception*, indicates whether the farmer *i* perceives a trend of increasing temperature (1 = yes, 0 = otherwise). Equations 2, 3, and 4 focus on the adoption behavior of EFRP at the second stage, wherein the dependent variables, *Adoption* and *Intensity*, in Eqs. 2 and 3, respectively, denotes the adoption decision (1 = yes, 0 = otherwise) and adoption intensity (the area of intercropped rubber plantations) of EFRP at the household level; Eq. 4 indicates the adoption decision ((1 = yes, 0 = otherwise) of EFRP at the plot level. X denotes a vector of independent variables reflecting the observed socioeconomic characteristics of the respondent, household, land, and village; P represents the variables regarding the nature of rubber plots. α, β, γ, and δ are vectors of corresponding parameters to be estimated, while μ, v, ω, and φ are error terms.

The IV in Eq. 1 is a vector of instrumental variables (IVs) and used to address the potential endogeneity in estimating the impact of farmers' perceptions of temperature on the adoption and adoption intensity of EFRP. The possible source of endogeneity can be summarized as follows. First, the endogeneity is due to the causality issue. That is, farmers' perceptions of increasing temperature may be endogenous in explaining their adoption behaviors, as farmers' rubber planting behavior in previous years could affect their perceptions of temperature change. Secondly, there may exist the sample selection bias arising from the fact that farmers who perceived increasing temperature change may systematically differ from those that did not perceive (Di Falco et al. 2011; Huang et al. 2015). Also, the unobserved heterogeneity of smallholder rubber farmers (e.g., cognitive ability) may affect both the perceptions of temperature change and the adoption of EFRP, resulting in inconsistent estimates of the impact of farmers' perceptions of temperature change on the adoption of EFRP.

4.1 Identification strategy

Equations 1 and 2 are used to capture the impact of farmers' perceptions of temperature change on the adoption of EFRP at the household level. Following previous studies (Lokshin and Glinskaya 2009; Lokshin and Sajaia 2011), we employ a two-stage ESP model accompanied by a counterfactual analysis to capture the impact of farmers' perceptions of temperature on the adoption of EFRP.[3] The ESP model comprised of Eqs. 1 and 2 can be estimated by the FIML method. The IVs in the selection equation of the ESP model contribute to controlling for the endogenous problem, while the ESP model also considers the unobservables that could simultaneously affect the farmer's perception of increasing temperature and the farmer's decision to adopt rubber intercropping. The application of the FIML method to simultaneously estimate the functions of these two decisions can yield consistent standard errors of the estimates (Lokshin and Sajaia 2011). Compared with other approaches such as the bivariate probit with endogenous regressors, the two regimes of outcome equations of the ESP model provide a better way to conduct counterfactual analysis. Treatment effects including the average treatment effect on the treated (ATT), the average treatment effect on the untreated (ATU), and the average treatment effect (ATE) can be further calculated.

Equations 1 and 3 are employed to assess the impact of farmers' perceptions of temperature change on the adoption intensity of EFRP at the household level. Following the study of Maddala (1983), we further use the endogenous treatment effects model (ETE).[4] Similar to the ESP model, the ETE model effectively controls for endogenous problems, while the estimation of the ETE model directly presents the impact of farmers' perceptions of temperature.

Equations 1 and 4 are used to estimate the impact of farmers' perceptions of temperature change on the adoption of EFRP at the plot level. Controlling for the nature of rubber plots, the results present the probability of adopting EFRP at a rubber plot with specified characteristics.

[3] The details of the setting of the ESP model and counterfactual analysis are presented in Appendix B.
[4] The details of the setting of the ETE model are presented in Appendix B.

Like the estimation of Eqs. 1 and 2, the adoption decision of EFRP at the plot level also employs the ESP model and a counterfactual analysis.

Finally, a falsification test is well used to check if IV fulfills the exclusion restrictions and justify its validation (Di Falco et al. 2011). Intuitively, the valid IV should significantly affect farmers' perceptions of temperature but does not directly affect the intercropping adoption of households that do not perceive increasing temperature. As extreme heat waves normally receive public attention (Hansen et al. 2012) and the perception of climate change appears to hinge on farmer experience related to climate change (Maddison 2007), we use the variable measure "whether the household experienced shocks of drought or extreme heat in the past year" as an IV to identify the perception of increasing temperature. Another potential IV is the quality change of forests in the village in the past 5 years. Intuitively, these two IVs are exogenous and meet the validity of IVs, while the results of falsification tests in Table 11 of Appendix C empirically validate these two IVs.

4.2 Explanatory variables

The detailed definitions and descriptive statistics of the variables used in this study are summarized in Table 2. Referring to previous studies (Di Falco et al. 2011; Li et al. 2017), we include the characteristics of the respondent, household, farm, and the local village as independent variables and control for the fixed effects of county. The characteristics of respondents including age, gender, educational attainment, and work status are important factors influencing farmers' perceptions of climate change and their adaptations (Maddison 2007; Hou et al. 2015). Due to the negative environmental effects of monocultural rubber plantations, farmers' perceptions of environmental change should be controlled in estimating farmers' perceptions of temperature and adaptative behaviors.[5] At household level, the number of family members, household wealth, the status of land endowment, and distance from the village to the county center may also play important roles in farmers' perceptions of climate change and the adoption of rubber intercropping (Hou et al. 2017; Min et al. 2017a, b). As XSBN is a minority and mountainous region, this study also includes the variable of ethnicity and elevation. Access to agricultural extension services may foster farmers' adoptions of rubber intercropping. At the same time, the variables at the village level, such as village size, the proportion of households with members participating in off-farm work, and the situation of community house, may affect farmers' perceptions of and adaptations to climate change. The instrumental variables include household experience in shocks of drought or extreme heat in the past year and the quality change of forests in the village in the past 5 years. The two IVs should be correlated with farmers' perceptions of temperature change but not directly related to their adoption of rubber intercropping.

Column 3 in Table 2 presents the mean values of these variables, while the rest of the columns in Table 2 report the differences in the mean values of all variables between the smallholder farmers that do and do not perceive an increasing temperature trend over the past 15 years and between the smallholders who did and did not adopt rubber intercropping. The differences in the mean values of most variables are statistically significant. In line with the results in Table 1, farmers' perceptions of increasing temperature were positively and significantly correlated with the adoption of rubber intercropping. Additionally, the information on the differences in mean values of all the variables provides an indication of the correlations

[5] Thank for the suggestion of the referee.

Table 2 Summary and descriptive statistics of the main variables

Variable	Definition and description	Mean	Perception mean		Diff. #	Intercropping		Diff. #
			1 = Yes	0 = No		1 = Yes	0 = No	
Temperature	Perception of increasing temperature (1 = Yes; 0 = Otherwise)	0.584				0.700	0.559	0.141***
Age	Age of respondent (Years)	41.092	41.073	41.118	− 0.045	40.445	41.234	− 0.788
Gender	Gender of respondent (1 = Female; 0 = Male)	0.311	0.294	0.335	− 0.041	0.382	0.295	0.086*
Ethnicity	Ethnicity of respondent (1 = Dai; 0 = Otherwise)	0.583	0.518	0.673	− 0.155***	0.600	0.579	0.021
Illiteracy	Education of respondent (1 = Illiteracy; 0 = Otherwise)	0.195	0.174	0.224	− 0.050*	0.118	0.212	− 0.094**
Primary	Education of respondent (1 = Primary school; 0 = Otherwise)	0.435	0.443	0.425	0.018	0.455	0.431	0.024
Middle	Education of respondent (1 = Middle school; 0 = Otherwise)	0.318	0.305	0.335	− 0.030	0.382	0.303	0.079*
High	Education of respondent (1 = High school and above; 0 = Otherwise)	0.052	0.078	0.016	0.062***	0.045	0.054	− 0.009
Occupation	Main occupation of respondent (1 = Farm work;0 = Otherwise)	0.853	0.356	0.331	0.025	0.355	0.343	0.012
Environment	Perception of environmental degradation (1 = Yes; 0 = Otherwise)	0.345	0.838	0.874	− 0.036	0.845	0.854	− 0.009
Hhsize	Number of family members	5.264	5.123	5.461	− 0.337***	4.973	5.327	− 0.355**
Land	Total land area (mu/person)	14.212	15.817	11.957	3.860***	11.931	14.713	− 2.782*
Rubber	% of rubber area in total land area	74.374	72.902	76.443	− 3.542*	72.741	74.733	− 1.992
Harvest	% of harvested rubber area in total rubber area	39.387	32.725	48.750	− 16.025***	28.715	41.730	− 13.015***
Services	Receive agricultural extension services (1 = Yes; 0 = Otherwise)	0.242	0.289	0.177	0.111***	0.391	0.210	0.181***
Wealth	Value of household assets (1000 Yuan/ person)	54.836	49.251	62.687	− 13.436***	51.989	55.461	− 3.472
Elevation	Elevation of household location (Meters above sea level)	756.839	780.625	723.408	57.217***	811.646	744.806	66.840***
Distance	Distance from the village to the county center (km)	73.774	77.115	69.079	8.036**	72.155	74.130	− 1.975
Vsize	Number of households in the village	85.074	81.185	90.539	− 9.355**	90.518	83.878	6.640
Off-farm	% of households with members participating in off-farm work	9.259	9.328	9.161	0.166	7.218	9.707	− 2.488*
House	Community house in the village (1 = Own; 0 = Otherwise)	0.908	0.916	0.898	0.018	0.873	0.916	− 0.043
Shocks (IV)	Whether the household experienced shocks of drought or extreme heat in the past year (1 = Yes; 0 = Otherwise)	0.157	0. 196	0.102	0.094***	0. 218	0.144	0.074*
Forest (IV)	Forest quality in the village in the past 5 years (1 = Decline; 0 = Otherwise)	0.481	0.532	0.409	0.123***	0.600	0.455	0.145***
Mengla	Mengla (1 = Yes; 0 = Otherwise)	0.408	0.403	0.413	− 0.010	0.236	0.445	− 0.209***
Jinghong	Jinghong (1 = Yes; 0 = Otherwise)	0.455	0.451	0.461	− 0.010	0.618	0.419	0.199***
Menghai	Menghai (1 = Yes; 0 = Otherwise)	0.137	0.146	0.126	0.020	0.146	0.136	0.010
Observations		611	357	254		110	501	

Source: Authors' survey

between these variables and farmers' perceptions of increasing temperature (or the adoption of rubber intercropping).

The adoption of rubber intercropping was also influenced by the nature and characteristics of specific rubber plots. The descriptive statistics of the variables at the plot level are reported in Appendix A Table 9. The results indicate that about 12.2% of rubber plots are intercropped with other crops. Referring to the study of Min et al. 2017a, b the variables at the plot level include the area, quality, and slope of rubber plots.

5 Results

5.1 The adoption decision of EFRP at the household level

Table 3 reports the estimates of the ESP model estimated by the FIML method with robust standard errors. The second column shows the estimated coefficients of selection Eq. 1 on whether farmers perceive an increasing trend in temperature over the past 15 years. The third and fourth columns present the intercropping adoption Eq. 2 for smallholders who do and do not perceive increasing temperature, respectively. The results of the Wald Chi^2 test of independent equations indicate that the simultaneous estimation of Eqs. 1 and 2 is not superior to the separate estimations. $\rho_{\mu 1}=-1.081$ is significant and negative, suggesting selection bias may skew the estimation results in a negative direction. The unobserved variables may lead to a selection bias that underestimates the impact of perceiving increasing temperature on the adoption of rubber intercropping.

5.1.1 Farmers' perception of temperature change

The results of the estimation of Eq. 1 suggest that the main influence factors for farmers' perceptions of temperature change (Table 3, column (2)). Firstly, both instrumental variables significantly affect farmers' perceptions of increasing temperature. Farmers who experienced shocks of drought and extreme heat in the past year are more likely to perceive increasing temperature. The decline in the forest quality of the located village can make farmers more likely to perceive increasing temperature. This result may be associated with the decreasing cooling function of forests due to the decline in forest quality in the village (Hamada et al. 2013). Compared with those who are illiterate, smallholder rubber farmers with a high school education or above tend to perceive increasing temperature, consistent with the reality. The number of family members and percentage of rubber in the harvesting phase negatively affect farmers' perceptions of increasing temperature. Farmers who own more land and those who receive agricultural extension services have a higher probability of perceiving increasing temperature. Additionally, wealthier farmers are less likely to perceive increasing temperature; this may be due to their location of a better environment or ownership of better-quality land. Another possible reason might be that wealthier farmers probably have more durable consumption assets and better living conditions, such as air conditioners or heating systems, which enable them to adapt to and focus less on temperature changes (Hou et al. 2015). At the village level, smallholder rubber farmers located in a village with a community house are found to be more likely to perceive increasing temperature. This result implies that the community house in a village may serve as a gathering place for farmers to exchange farming experiences and

Table 3 Estimation results of the endogenous switching probit model at the household level

Variables	Perception	Intercropping	
		Perception = 1	Perception = 0
Age	0.002	0.002	− 0.008
	(0.005)	(0.006)	(0.009)
Gender	0.004	0.093	0.185
	(0.120)	(0.155)	(0.208)
Ethnicity	− 0.200	0.395**	− 0.223
	(0.131)	(0.161)	(0.282)
Primary	0.194	0.111	0.551*
	(0.153)	(0.228)	(0.310)
Middle	0.064	0.202	0.558*
	(0.173)	(0.240)	(0.310)
High	1.127***	− 0.029	− 8.135***
	(0.368)	(0.385)	(0.824)
Occupation	− 0.179	0.297	0.096
	(0.157)	(0.196)	(0.282)
Environment	0.039	− 0.163	0.124
	(0.119)	(0.152)	(0.193)
Hhsize	− 0.099**	− 0.046	− 0.003
	(0.038)	(0.058)	(0.07)
Land	0.008**	− 0.012**	− 0.020*
	(0.004)	(0.005)	(0.011)
Rubber	0.002	0.003	0.005
	(0.003)	(0.003)	(0.005)
Harvest	− 0.009***	−0.001	− 0.006
	(0.002)	(0.003)	(0.005)
Services	0.308**	0.362*	0.095
	(0.137)	(0.185)	(0.293)
Wealth	−0.003**	0.001	0.004**
	(0.001)	(0.002)	(0.002)
Elevation	0.0004	0.002***	0.001
	(0.0005)	(0.001)	(0.001)
Distance	− 0.002	− 0.005**	− 0.0005
	(0.002)	(0.003)	(0.003)
Vsize	− 0.001	0.004**	0.002
	(0.001)	(0.002)	(0.002)
Off-farm	− 0.006	− 0.007	− 0.0166*
	(0.004)	(0.007)	(0.010)
House	0.609***	− 1.153***	− 0.276
	(0.210)	(0.315)	(0.343)
Shock (IV)	0.496***		
	(0.142)		
Forest (IV)	0.297***		
	(0.110)		
Counties	Controlled	Controlled	Controlled
Constant	0.131	− 1.356*	− 2.895***
	(0.570)	(0.819)	(1.088)
$\rho_{\mu 1}/\rho_{\mu 0}$		− 1.081***	− 0.784
		(0.377)	(0.799)
N		611	
Wald Chi2		91.37***	
Chi2 (Wald test of independent equations)		9.35***	

Robust standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

information, including those related to regional climate change, thereby enhancing farmers' perceptions of increasing temperature from social interactions.

5.1.2 Farmers' adoption of EFRP

We now turn to the estimation results for Eq. 2 by accounting for the endogenous switching in the adoption function of EFRP. The estimation results for the rubber intercropping adoption function among smallholders who perceive increasing temperature are almost completely different from that of the adoption function among smallholders who do not perceive increasing temperature (Table 3, columns 3 and 4). The differences in the coefficients of rubber intercropping adoption between the smallholders who perceive increasing temperature and those who do not illustrate the existence of heterogeneity in the sample.

For smallholder rubber farmers who perceive increasing temperature, the estimation results for rubber intercropping adoption are shown in column 3 of Table 3. Interestingly, once Dai ethnic farmers perceive increasing temperature, they have a higher probability of adopting rubber intercropping. Additionally, smallholders with small land sizes, who receive agricultural extension services, whose farms are at higher elevation, and whose farms are closer to the county center, tend to adopt the EFRP model in terms of rubber intercropping.

The estimation results for intercropping adoption among smallholders who do not perceive increasing temperature are reported in column 4 of Table 3. Compared with farmers who are illiterate, those with primary and middle school education levels are more likely to adopt rubber intercropping. However, farmers with a high school education level and above are less likely to adopt rubber intercropping. These results imply that the correlation between the possibility of adopting intercropping and farmers' education level is an inverted U-shaped curve. This finding is inconsistent with the study of Maddison (2007), which found a linear and positive impact of education on adoption of the adaptation measure. Additionally, the findings for the variable "household wealth" are in line with previous studies (Iqbal et al. 2006; Min et al. 2017a), suggesting that farmers are more likely to adopt intercropping with less financial constraints proxied by asset endowment.

The cumulative distributions of the predicted probabilities of adopting rubber intercropping between farmers who perceive increasing temperature and farmers who do not perceive increasing temperature are shown in Fig. 3 in the Appendix A. Visually, farmers who perceive increasing temperature have a higher probability of adopting rubber intercropping than others, illustrating that farmers' perceptions of increasing temperature are positively correlated with their likelihood of adopting rubber intercropping.

5.1.3 Counterfactual analysis

The first row in Table 4 presents the treatment effects of farmers' perceptions of temperature change on the adoption of the EFRP model. Regardless of ATE, ATT, and ATU, the impacts of farmers' perceptions of increasing temperature on the adoption of rubber intercropping are always significantly positive. In the counterfactual case (ATT), smallholder rubber farmers who perceive increasing temperature would have an 18.8% lower probability of adopting intercropping if they did not perceive increasing temperature. For another counterfactual case (ATU), smallholders who do not perceive increasing temperature would have 49.9% higher probability of adopting rubber intercropping if they perceived increasing temperature. Finally, in the counterfactual case (ATE), the effect of farmers' perceptions of increasing temperature on the adoption of rubber intercropping by a farmer randomly selected from the population is 31.9%. These results confirm that farmers' perceptions of increasing temperature can encourage farmers to implement the EFRP model, particularly among smallholders who do not actually perceive an increasing temperature trend.

The simulated results of ATT, ATE, and ATU according to several observable characteristics also reveal the heterogeneity in the effects of perceiving increasing temperature on the adoption of rubber intercropping (Table 4). First, the poorest smallholders have the largest positive ATT, ATU, and ATE for the adoption of rubber intercropping. This finding confirms that for the farmers perceiving increased temperature, less wealthy farmers are more likely to adopt rubber intercropping because the intercropped crops may provide additional income sources or household food consumption options. Likewise, for the probability of rubber intercropping, the positive ATT, ATU, or ATT decreases with the scale of the farm. In other words, for smallholders with the smallest land size, the impacts of perceiving increasing temperature on the adoption of rubber intercropping are always the largest. This may be because intercropping can be an intensification strategy for the farmers with less land to work with.

Interestingly, for smallholders receiving agricultural extension services, ATT, ATU, and ATT are always the highest. Particularly, from the perspective of ATU, smallholders who receive agricultural extension services but do not perceive increasing temperature have a 66.6% higher probability of adopting rubber intercropping if they perceive the increasing temperature trend. Moreover, the largest positive ATT, ATU, and ATE for the probability of adopting rubber intercropping are found for smallholders in villages without a community house. This result implies that enhancing farmers' perceptions of increasing temperature in villages without a community house would have a larger impact on the adoption of rubber intercropping.

Table 4 Simulated effects of farmers' perceptions of increasing temperature on rubber intercropping by characteristics

Variables	Average treatment effect on the treated (ATT)#	Average treatment effect on the untreated (ATU)	Average treatment effect (ATE)
All samples	0.188***	0.499***	0.319***
By the characteristics of households, farms, and villages			
Household wealth			
1st quantile	0.230***	0.516***	0.333***
2nd quantile	0.180***	0.494***	0.305***
3rd quantile	0.148***	0.489***	0.319***
Land size			
1st quantile	0.234***	0.550***	0.388***
2nd quantile	0.190***	0.480***	0.314***
3rd quantile	0.150***	0.449***	0.254***
Receiving agricultural extension services			
Yes	0.306***	0.666***	0.408***
No	0.141***	0.463***	0.290***
Community house			
Yes	0.181***	0.476***	0.303***
No	0.266***	0.700***	0.474***

Source: Authors' calculation

#*t* test; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

5.2 The adoption intensity of EFRP at the household level

Table 5 reports the estimation results of the endogenous treatment effects model. Farmers' perceptions of increasing temperature and their adoption intensity of rubber intercropping are estimated simultaneously. The results on the perceptions of temperature in column 2 of Table 5 are consistent with those in Table 3. Column 3 in Table 5 shows the estimation results of the adoption intensity of rubber intercropping. In line with the significant and positive treatment effects in Table 4, the impact of farmers' perceptions of increasing temperature on the adoption intensity of rubber intercropping is significantly positive. For smallholders perceiving increasing temperature, on average, they adopt 3.359 mu more intercropping than those who did not perceive increasing temperature.

Moreover, the adoption intensity of rubber intercropping is also significantly affected by elevation, village size, and the community house. Smallholders living in a place with higher elevation, in a bigger village, or in a village without a community house tend to adopt more rubber plantations for intercropping.

5.3 The adoption decision of EFRP at the plot level

An endogenous switching probit model including the variables at plot level is further employed to detect the impacts of the variables at the plot level on the adoption of rubber intercropping and further check for the robustness of the results regarding the impact of farmers' perceptions of temperature change. Table 6 reports the results estimated by using the data at the plot level, showing the significant impacts of the variables at plot level, including area, land quality, and slope of a plot on farmers' perceptions of temperature. For the smallholders without perceiving increasing temperature change, plot area also has a significant and positive effect on the adoption of rubber intercropping.

Based on the estimation results of Table 6, we further simulate the treatment effects of farmers' perceptions of increasing temperature on the probability of intercropping adoption at the plot level and compare these treatment effects by heterogeneities of the characteristics including household wealth, land size, access to agricultural extension services, and community house. As shown in Table 7, the treatment effects including ATT, ATU, and ATE at the plot level are lower than those at the household level. Moreover, the correlations between treatment effects and the variables of household wealth, land size, access to agricultural extension services, and community house are similar to those revealed by Table 4. In addition to the sizes of treatment effects, the results in Tables 4 and 7 are almost consistent. Hence, the main findings of this study have also been confirmed at the plot level.

5.4 Robustness check

Firstly, a probit model with a discrete endogenous regressor and a tobit model with a discrete endogenous regressor using a two-step regression approach are further employed to check for the impacts of farmers' perceptions of regional climate change on the adoption and adoption intensity of the EFRP model. In the first step, a probit regression with robust standard errors is estimated for farmers' perceptions of increasing temperature. The proposed IV "whether the household experienced shocks of drought and extreme heat in the past year" and "forest quality of the village in the past 5 years" are also included. In the second step, the predicted probability of perceiving increasing temperature from the first step of the regression is included

Table 5 Results of endogenous treatment effects model at the household level

	Perception	Adoption intensity
Perception		3.359*
		(2.022)
Age	0.001	− 0.047
	(0.005)	(0.060)
Gender	0.029	− 0.682
	(0.122)	(0.983)
Ethnicity	− 0.229*	− 0.680
	(0.129)	(1.358)
Primary	0.184	1.413
	(0.153)	(1.322)
Middle	0.067	1.028
	(0.174)	(1.415)
High	1.082***	− 2.224
	(0.367)	(1.906)
Occupation	− 0.205	− 0.138
	(0.160)	(1.156)
Environment	0.030	− 1.372
	(0.118)	(1.003)
Hhsize	− 0.104***	0.911
	(0.039)	(0.618)
Land	0.008*	0.047
	(0.004)	(0.050)
Rubber	0.002	0.031
	(0.003)	(0.026)
Harvest	− 0.009***	− 0.025
	(0.002)	(0.027)
Services	0.314**	1.784
	(0.135)	(1.192)
Wealth	− 0.003**	0.024
	(0.001)	(0.016)
Elevation	0.0003	0.019**
	(0.0004)	(0.008)
Distance	− 0.002	− 0.002
	(0.002)	(0.016)
Vsize	− 0.001	0.027**
	(0.001)	(0.011)
Off-farm	− 0.006	− 0.038
	(0.004)	(0.031)
House	0.642***	− 3.630*
	(0.209)	(1.862)
Shock (IV)	0.516***	
	(0.157)	
Forest (IV)	0.237*	
	(0.124)	
Counties	Controlled	Controlled
Constant	0.241	− 17.86**
	(0.573)	(8.943)
N	611	
Log likelihood	− 2848.36	
Chi-squared	43.11***	

Robust standard errors in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

in the probit model for rubber intercropping adoption and the tobit model for the adoption intensity of rubber intercropping to control for potential endogeneity, while a bootstrap procedure with 2000 bootstrap iterations is used to further adjust the standard errors to obtain

Table 6 Estimation results of the endogenous switching probit model at the plot level

Variables	Perception	Intercropping	
		Perception = 1	Perception = 0
Plot area	0 .482**	0.001	0.008*
Land quality	(0.069)	(0.003)	(0.005)
Below average #			
Average	− 0.183*	0.236	− 0.143
	(0.102)	(0.161)	(0.196)
Above average	0.226**	− 0.049	0.046
	(0.107)	(0.166)	(0.225)
Land slope			
Slope = flat #			
0% < Slope ≤ 25%	− 0.287***	− 0.099	0.142
	(0.095)	(0.149)	(0.261)
25% ≤ Slope < 45%	− 0.413***	− 0.043	0.346
	(0.088)	(0.152)	(0.242)
Slope ≥ 45%	− 0.251***	− 0.102	0.111
	(0.091)	(0.139)	(0.244)
Shocks (IV)	0.482***		
	(0.069)		
Forest (IV)	0.270***		
	(0.055)		
Control for other variables	Yes	Yes	Yes
Constant	0.771***	− 2.665***	− 4.133***
	(0.285)	(0.489)	(0.728)
$\rho_{\mu 1}/\rho_{\mu 0}$		− 0.389*	− 0.420
		(0.209)	(0.315)
N		3236	
Wald Chi2		514.98***	
Chi2 (Wald test of independent equations)		5.37*	

#Reference group; robust standard errors in parentheses; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

more accurate cluster-robust inference. Accordingly, Table 10 of Appendix A reports the estimation results, which further confirm the significant and positive impact of perceiving increasing temperature on the adoption and adoption intensity of rubber intercropping.

Secondly, the heterogeneity in the effect of farmers' perceptions of temperature change based on unobserved characteristics is also investigated using the marginal treatment effect (MTE) framework under the estimation of endogenous switching probit model at the household level. The results are presented in Fig. 5 of Appendix D and not only suggest that smallholders who are more likely to perceive increasing temperature are more likely to adopt rubber intercropping but also confirm the presence of unobservable heterogeneity in the impacts of farmers' perceptions of increasing temperature on farmers' decisions to adopt rubber intercropping. Overall, the finding that perceiving increasing temperature can encourage farmers to implement the EFRP model in terms of rubber intercropping is solid and robust.

6 Concluding remarks

In recent years, the EFRP model has been proposed to mitigate the negative environmental effects of monoculture rubber plantations in XSBN. Using household survey data, this article investigates the impacts of farmers' perceptions of temperature change on their

Table 7 Simulated effects of farmers' perceptions of increasing temperature on rubber intercropping by characteristics based on the results at the plot level

Variables	Average treatment effect on the treated (ATT)#	Average treatment effect on the untreated (ATU)	Average treatment effect (ATE)
All samples	0.104***	0.172***	0.133***
By the characteristics of households, farms, and villages			
Household wealth			
1st quantile	0.117***	0.150***	0.128***
2nd quantile	0.098***	0.150***	0.120***
3rd quantile	0.095***	0.203***	0.150***
Land size			
1st quantile	0.118***	0.198***	0.157***
2nd quantile	0.101***	0.161***	0.128***
3rd quantile	0.094***	0.151***	0.114***
Receiving agricultural extension services			
Yes	0.189***	0.310***	0.226***
No	0.069***	0.142***	0.103***
Community house			
Yes	0.096***	0.150***	0.119***
No	0.188***	0.384***	0.272***

Source: Authors' calculation

implementation of the EFRP model. The results reveal that farmers' perceptions of temperature change are determined by the experience of shocks related to regional climate change and their socioeconomic characteristics, while perceiving increasing temperature can encourage farmers to adopt the EFRP model in terms of intercropping. Farmers' perceptions of temperature change appear to be a mechanism through which regional climate change impacts farmers' mitigation behavior.

The findings from this study have several policy implications. First, there is a need to improve farmers' perceptions of increasing temperature to promote the implementation of the EFRP model among smallholders in XSBN. Second, enhancing perceptions of temperature among smallholders with specific characteristics can more efficiently encourage farmers to adopt EFRP. Improving perceptions of increasing temperature among smallholders who have less wealth and small land size, receive agricultural extension services, live in a higher elevation region, reside in a village close to the county center, or reside in a village without a community house can greatly promote the adoption of rubber intercropping when compared with the counterfactual cases. Additionally, the provision of agricultural extension services and the establishment of a community house in a village could also contribute to improving farmers' perceptions of increasing temperature. Hence, focusing solely on increasing farmers' perceptions of regional climate change to increase climate resilience may be limited; policies must jointly consider both improving the targeted farmers' perceptions of regional climate change and conducting other agricultural programs as mitigation strategies. Finally, the program of EFRP should be promoted by implementing measures that target the specific smallholder rubber farmers, for instance, training smallholders the EFRP program by the agricultural extension services.

Just as farmers have been confronted with increasing regional temperatures in the rubber planting region and are concerned with the sustainability of smallholder rubber farming in the upper Mekong region, we believe that the findings of this study have somewhat reference implications for rubber planting, particularly for other areas of the Mekong region such as

Laos, Thailand, and northern Vietnam. Moreover, considering the fact that the massive expansion of other tree crop plantations such as oil palm and coffee monocultures may also lead to regional climate change in the planting regions, improving local farmers' perceptions of regional climate change is likely to play a role in promoting tree crop-based agroforestry systems, which to some extent can mitigate the change of regional climate.

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Appendix A tables and figures

Table 8 Crops intercropped with rubber at the plot level

Categories	Number of plots	Percent
Perennial crops		
Tea	184	46.70%
Coffee	21	5.33%
Banana	5	1.27%
Fruits and other economic forest trees	18	4.57%
Annual crops		
Maize	73	18.53%
Sorghum	20	5.08%
Upland rice	4	1.02%
Hemp	3	0.76%
Vegetables	3	0.76%
Cotton	2	0.51%
Millet	1	0.25%
Groundnuts	1	0.25%
Other crops	59	14.97%
Total	394	100%

Table 9 Summary and descriptive statistics of the variables at the plot level

Variable	Definition and description	Mean	Std. dev.
Intercrop (plot)	Intercrop on a rubber plot (1 = Yes; 0 = Otherwise)	0.122	0.327
Plot area	Area of a rubber plot (mu)	13.651	17.046
Land quality	Soil quality of a rubber plot		
Below average	(1 = Yes; 0 = Otherwise)	0.065	0.246
On average	(1 = Yes; 0 = Otherwise)	0.617	0.486
Above average	(1 = Yes; 0 = Otherwise)	0.318	0.466
Land slope	Land slope of a rubber plot		
Slope = Flat	(1 = Yes; 0 = Otherwise)	0.092	0.288
0% < Slope ≤ 25%	(1 = Yes; 0 = Otherwise)	0.205	0.404
25% ≤ Slope < 45%	(1 = Yes; 0 = Otherwise)	0.388	0.487
Slope ≥ 45%	(1 = Yes; 0 = Otherwise)	0.315	0.465
Observations		3236	

Source: Authors' survey

Table 10 Probit regressions for farmers' perceptions of increasing temperature and the adoption of rubber intercropping at the household level

	Perception of increasing temperature	Adoption of rubber intercropping	Area of rubber plantations with intercropping (tobit)
$\widehat{P}$		3.077^{***} (0.940) [0.667]	104.348^{***} (39.422) [18.786]
Shock (IV)	0.505^{***} (0.157)		
Forest (IV)	0.242^{*} (0.124)		
Control for other variables	Yes	Yes	Yes
Constant	0.252 (0.573)	-4.447^{***} (1.117)	-195.593^{***} (57.011)
N	611	611	611
pseudo R^2	0.134	0.181	0.060
Log likelihood	−359.12	−235.96	−703.443
Wald Chi^2	87.84^{***}	49.21^{***}	43.45^{***}

Robust standard errors in parentheses in the first column; bootstrap standard errors in parentheses in the second column; marginal effects in square brackets; $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

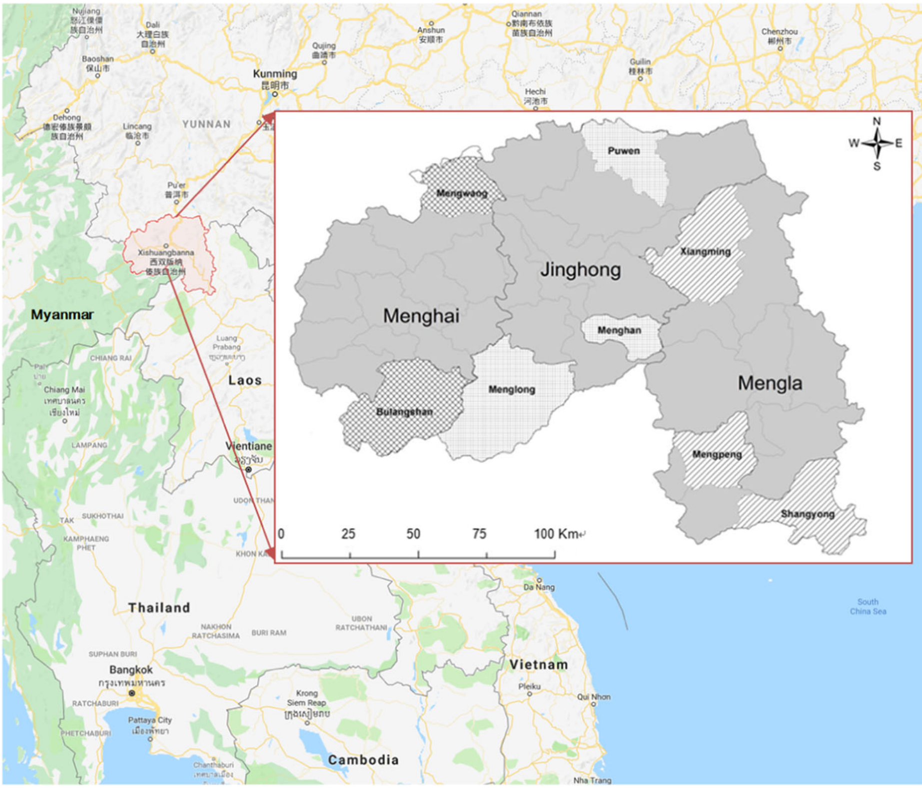

Fig. 3 The location of XSBN and the distribution of sample townships

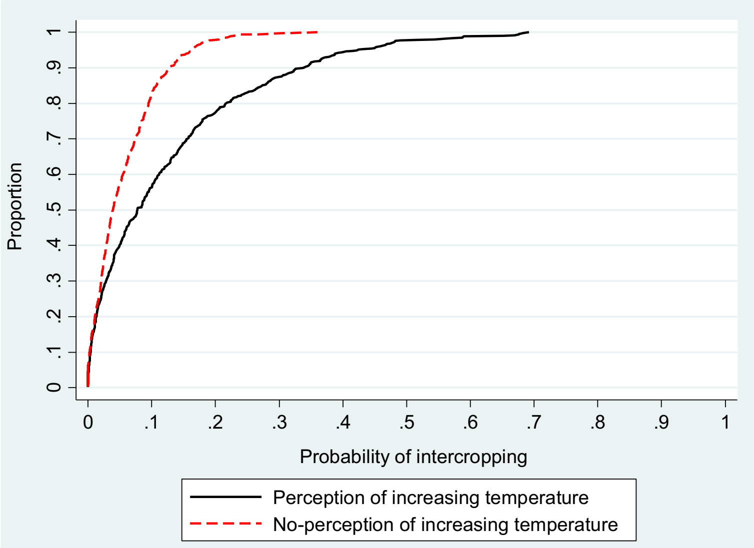

Fig. 4 Cumulative distribution of probabilities of adopting rubber intercropping between farmers who perceive increasing temperature and farmers who do not perceive increasing temperature

Appendix B Models

Theoretical framework

In this study, we focus on smallholder rubber farmers' decisions to adopt the EFRP which is proxied by rubber intercropping. This decision is assumed to be made by the farmer after the decision of land allocation for rubber farming has been completed. The farmer's utility from rubber farming is assumed to include two components: (1) the utility derived from the profit of rubber farming and intercropping, which is affected by the weather condition during the crop season, and (2) the utility derived from improved environmental conditions when adopting rubber intercropping under the weather condition during the crop season. Thus, the farmer should determine the proportion of the rubber plantation to allocate for intercropping to maximize the total utility from rubber farming.

Specifically, the expected profit of rubber farming and intercropping (π) is assumed to be determined as follows:

$$\begin{gathered}\pi = \int [\mathbf{y} - c(\mathbf{x})] f(\mathbf{y}) d\mathbf{y} \\ s.t. \;\; \sum_{i=1}^{2} x_i = 1\end{gathered} \tag{5}$$

where the vector $\mathbf{x} = (x_1, x_2)$, where x_1 and x_2 represent the proportions of rubber plantations allocated for intercropping and monoculture rubber plantations, respectively. L is defined as the planting area of natural rubber available to the farmer. $\mathbf{y}$ ($\mathbf{y} = \mathbf{y}(\mathbf{x}| L)$) is a vector of outputs corresponding to $\mathbf{x}$ given the planting area of rubber (L), while $c(\mathbf{x})$ is the cost function corresponding to $\mathbf{x}$. $f(\mathbf{y})$ is the farmer's subjective probability density function for $\mathbf{y}$, which can be assumed to be solely related to the weather condition (w_t) in the coming crop season (Bai et al. 2015). It is assumed that all smallholder rubber farmers in XSBN face the same market prices of rubber, intercrops, and inputs in the observation year; therefore, the price variables are omitted in the profit function (5).

Moreover, we further assume that the environmental utility of the farmer's rubber farming depends on the planting area of natural rubber (L), the proportions of intercropping and monoculture rubber plantations ($\mathbf{x}$), and the weather condition (w_t). Thus, the environmental utility can be expressed as

$$\mathrm{U(E)} = h(\mathbf{x}, L, w_t) \tag{6}$$

By combining the profit function (5) and the environmental utility function (6), the farmer's utility maximization problem can be written as

$$\max_{\mathbf{x}} \mathrm{U} = \max_{\mathbf{x}} [\mathrm{U}(\pi) + \mathrm{U(E)}]\, s.t. \ \textstyle\sum_{i=1}^{2} x_i = 1 \tag{7}$$

where U indicates the total utility from rubber farming, while U(π) denotes the utility from the profit of rubber farming and intercropping.

As farmers do not know the weather condition in the coming crop season (w_t), they make the decision on $\mathbf{x}$ based on their predictions of the weather condition. Here, we assume that farmers' predictions of weather condition in the coming crop season ($\widehat{w}_t$) rely on the real weather condition in previous years and their perceptions of weather condition change in previous years. Thus, $\widehat{w}_t$ can be expressed as

$$\widehat{w}_t = g(w_{t-1}, P) \tag{8}$$

where w_{t-1} denotes the real weather condition in previous years, while P represents farmers' perceptions of the weather condition change in previous years.

By incorporating the weather condition prediction function (8) into the utility maximization problem (7), the optimal choice of $\mathbf{x}$ can be conceptually derived as

$$\mathbf{x}_t^{\,*} = z(P, L) \tag{9}$$

where the real weather condition in previous years (w_{t-1}) is omitted as there is an implicit assumption that all rubber farmers faced the same weather condition in previous years. Given that temperature is a primary measurement of weather condition, the perception of a change in weather condition (P) can, to some extent, be proxied by the perception of temperature change (P'). Then, the optimal proportion of rubber plantations allocated for intercropping can be expressed as

$$x_1^{\,*} = z'(P', L) \tag{10}$$

According to Eq. A6, two hypotheses could be simply derived as follows. First, as $x_1^* > 0$ indicates that the farmer adopts intercropping, the hypothesis (1) is that the adoption of rubber intercropping is affected by the perception of temperature change (P'). Second, Eq. 10 shows the land allocated for rubber intercropping is a function of farmers' perceptions of temperature changes; thus, we propose the hypothesis (2) that farmers' perceptions of temperature change (P') also influence the adoption intensity of rubber intercropping.

Endogenous switching probit model and counterfactual analysis

According to Lokshin and Glinskaya (2009), a farmer's propensity to perceive increasing temperature can be expressed in a linear form as

$$P_i^* = \gamma Z_i + \mu_i \tag{11}$$

where subscript i represents the farmer. Z_i denotes a vector of independent variables reflecting the socioeconomic characteristics of the respondent, household, land, and located village, while γ is a vector of corresponding parameters to be estimated. μ_i is an error term. Therefore, the observed farmer's perception of increasing temperature (P_i) can be expressed as

$$P_i = \begin{cases} 1 & \text{if} \quad P_i^* \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

where $P_i = 1$ represents that the farmer perceives the trend in increasing temperature in the local area, while $P_i = 0$ denotes that the farmer does not perceive this trend.

The propensity of the farmer's household to adopt rubber intercropping as a mitigation behavior for the farmer's perception of increasing temperature is expressed as

$$A_{iP}^* = \beta_P X_i + v_{iP} \tag{13}$$

where the subscript P denotes the two regimes presented in Eq. 12. X_i is a vector of variables regarding the characteristics of the respondent, household, land, and village, while $\beta_P$is a regime-specific vector of the parameters to be estimated; v_{iP} is a regime-specific error term.

Hence, by combining Eqs. 12 and 13, the observed mitigation behavior regarding rubber intercropping can be written as follows:

$$A_{i1} = \begin{cases} 1 & \text{if} \quad A_{i1}^* \geq 0 \\ 0 & \text{otherwise} \end{cases} \qquad (P = 1) \tag{14a}$$

$$A_{i0} = \begin{cases} 1 & \text{if} \quad A_{i0}^* \geq 0 \\ 0 & \text{otherwise} \end{cases} \qquad (P = 0) \tag{14b}$$

where Eqs. 14a and 15b indicate whether the farmer adopts rubber intercropping under the conditions of $P = 1$ and $P = 0$, respectively.

According to previous studies (Lokshin and Glinskaya 2009), the error terms (μ_i, v_{i0}, v_{i1}) from Eqs. 12, 14a, and 14b are assumed to be jointly normally distributed with a zero-mean vector and correlation matrix:

$$\Omega_{\mathrm{m}} = \begin{pmatrix} 1 & \rho_{\mu 0} & \rho_{\mu 1} \\ & 1 & \rho_{01} \\ & & 1 \end{pmatrix} \tag{15}$$

where the terms $\rho_{\mu 0}$ and $\rho_{\mu 1}$ are the correlations between v_{i0}, v_{i1}, and μ and ρ_{01} is the correlation between v_{i0} and v_{i1}. However, as A_{i1} and A_{i0} are never observed simultaneously, the joint distribution of (v_0, v_1) is not identified; accordingly, ρ_{01} cannot be estimated. Hence, following the study by Lokshin and Sajaia (2011), we further assume that γ is estimable only up to a scalar factor ($\rho_{01} = 1$); therefore, this model can be identified by nonlinearities in its functional form. Following the study by Lokshin and Glinskaya (2009), we can express the log likelihood functions for the simultaneous system of Eqs. 12, 14a, and 14b as follows:

$$\ln(\xi) = \sum_{P_i \neq 0; A_i \neq 0} \ln\left\{\Phi_2\left(\beta_1 X_i, \gamma Z_i, \rho_{\mu 1}\right)\right\}$$
$$+ \sum_{P_i \neq 0; A_i = 0} \ln\left\{\Phi_2\left(-\beta_1 X_i, \gamma Z_i, -\rho_{\mu 1}\right)\right\} + \sum_{P_i = 0; A_i \neq 0} \ln\left\{\Phi_2\left(\beta_0 X_i, -\gamma Z_i, -\rho_{\mu 0}\right)\right\}$$
$$+ \sum_{P_i = 0; A_i = 0} \ln\left\{\Phi_2\left(-\beta_0 X_i, -\gamma Z_i, \rho_{\mu 0}\right)\right\} \quad (16)$$

where Φ_2 is the cumulative function of a bivariate normal distribution. Accordingly, function (20) can be estimated by the FIML method. The ESP model takes into account the unobserved variables that could simultaneously affect the farmer's perception of increasing temperature and the farmer's decision to adopt rubber intercropping. The application of the FIML method to simultaneously estimate the functions of these two decisions can yield consistent standard errors of the estimates (Lokshin and Sajaia 2011).

The impact of a farmer's perception of increasing temperature on the adoption of rubber intercropping can be defined as treatment effects, including the effect of treatment on the treated (TT), the effect of the treatment on the untreated (TU), and the treatment effect (TE). Following previous studies (Lokshin and Glinskaya 2009; Lokshin and Sajaia 2011), the formulas of these treatment effects are given as:

$$\mathrm{TT}(x) = \Pr(A_1 = 1 | P = 1, X = x) - \Pr(A_0 = 1 | P = 1, X = x) \quad (17)$$

$$\mathrm{TU}(x) = \Pr(A_1 = 1 | P = 0, X = x) - \Pr(A_0 = 1 | P = 0, X = x) \quad (18)$$

$$\mathrm{TE}(x) = \Pr[A = 1 | X = x] - \Pr[A = 0 | X = x] \quad (19)$$

Furthermore, the average treatment effect on the treated (ATT), the average treatment effect on the untreated (ATU), and the average treatment effect (ATE) can be obtained from Eqs. 17, 18, and 19 by averaging TT(x), TU(x), and TE(x) over the sample, respectively. ATT reflects the average difference between the predicted probability of adopting intercropping by a household that perceives increasing temperature and the predicted likelihood of adopting intercropping for the household had they not perceive increasing temperature. ATU is the average expected effect of perceiving increasing temperature on the probability that households with observed characteristic X, which do not perceive increasing temperature, would adopt intercropping. ATE is the average impact of perceiving increasing temperature on the probability that a household randomly drawn from the households with characteristics x would adopt intercropping. Additionally, the ATT, ATU, and ATT for a subgroup of the households are the averages of TT(x), TU(x), and TE(x) for that subgroup (Lokshin and Sajaia 2011).

Endogenous treatment effects model

Following Maddala (1983), the adoption intensity of rubber intercropping can be expressed as a treatment effects model:

$$y_i = \beta X_i + \gamma P_i + \varepsilon_i \quad (20)$$

where the definitions of X_i and P_i are the same as in Eq. 13. β and γ are parameters to be estimated, while ε_i is an error term. Meanwhile, ε_i and μ_i (in Eq. 11) are assumed to be bivariate normal with zero and covariance matrix:

$$\begin{pmatrix} \varepsilon_i \\ \mu_i \end{pmatrix} \sim N\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}\begin{pmatrix} \sigma_\varepsilon^2 & \rho\sigma_\varepsilon \\ \rho\sigma_\varepsilon & 1 \end{pmatrix}\right] \tag{21}$$

where ρ is the correlation coefficient between ε_i and μ_i. According to Maddala (1983), the log likelihood for observation i can be written as:

$$\ln L_i = \begin{cases} \ln\Phi\left\{\dfrac{\tau Z_i + (y_i - \beta X_i - \delta)\rho/\sigma}{\sqrt{1-\rho^2}}\right\} - \dfrac{1}{2}\left(\dfrac{y_i - \beta X_i - \delta}{\sigma}\right)^2 - \ln\left(\sqrt{2\pi}\sigma\right) & P_i = 1 \\ \ln\Phi\left\{\dfrac{-\tau Z_i - (y_i - \beta X_i)\rho/\sigma}{\sqrt{1-\rho^2}}\right\} - \dfrac{1}{2}\left(\dfrac{y_i - \beta X_i}{\sigma}\right)^2 - \ln\left(\sqrt{2\pi}\sigma\right) & P_i = 0 \end{cases} \tag{22}$$

where $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution. Thus, Eqs 10 and 12 could be simultaneously estimated by maximum likelihood estimation.

Appendix C Test

The estimation results of a falsification test for the validity of the proposed two IVs are reported in Appendix Table 11. The results show that the proposed two instrumental variables significantly affect farmers' perceptions of increasing temperature. However, for farmers who do not perceive increasing temperature, the proposed two IVs have insignificant impacts on the adoption of rubber intercropping. The proposed two instrumental variables meet the exclusion restriction. Hence, the falsification test empirically confirms the validity of the proposed two instrumental variables to control for the endogeneity of farmers' perceptions of temperature change in explaining farmers' implementation of the EFRP model.

Table 11 Falsification test for the validity of the instrumental variable

Variables	Perception	Intercropping (Perception = 0)
Shocks (IV)	0.505***	0.129
	(0.157)	(0.366)
Forest (IV)	0.242**	0.488
	(0.124)	(0.307)
Control for other variables	Yes	Yes
Constant	0.252	− 3.117**
	(0.573)	(1.383)
N	611	250#
pseudo R^2	0.134	0.182
Log likelihood	− 359.15	− 79.77
Chi-squared	87.84***	35.54***

Robust standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

#4 observations are automatically dropped due to predicting failure

Appendix D Unobserved heterogeneity

The effect of perceiving increasing temperature on the adoption of rubber intercropping by households can vary by observed household characteristics X and unobservables μ (Lokshin and Glinskaya 2009). To account for the unobserved heterogeneity, we can further simulate the MTE:

$$\mathrm{MTE}(x, \mu) = \Pr\left(A_1 = 1 | X = x, \mu = \overline{\mu}\right) - \Pr\left(A_0 = 1 | X = x, \mu = \overline{\mu}\right) \tag{23}$$

The MTE identifies the effect of perceiving increasing temperature on households induced to adopt rubber intercropping because of perceiving increasing temperature (Heckman and Vytlacil 2001; Lokshin and Glinskaya 2009).

Based on the estimation results of ESR, the simulated MTE is 0.342, nearly equal to the ATE, and heterogeneity in the effects of perceiving increasing temperature based on unobserved characteristics is also found (Fig. 5). Following the MTE framework (Lokshin and Glinskaya 2009), Fig. 5 plots the MTE of perceiving increasing temperature on the adoption of rubber intercropping against the normalized values of unobservable component (μ) at the household means for Xs according to Eq. 14a and 14b. The estimates of the MTE for perceiving increasing temperature on the adoption of rubber intercropping are monotonically increasing in μ, indicating that smallholders who are more likely to perceive increasing temperature are also more likely to adopt rubber intercropping. Additionally, the MTEs of perceiving increasing temperature on the adoption of rubber intercropping are not flat, which confirms the presence of unobservable heterogeneity in the impacts of farmers' perceptions of increasing temperature on farmers' decisions to adopt rubber intercropping.

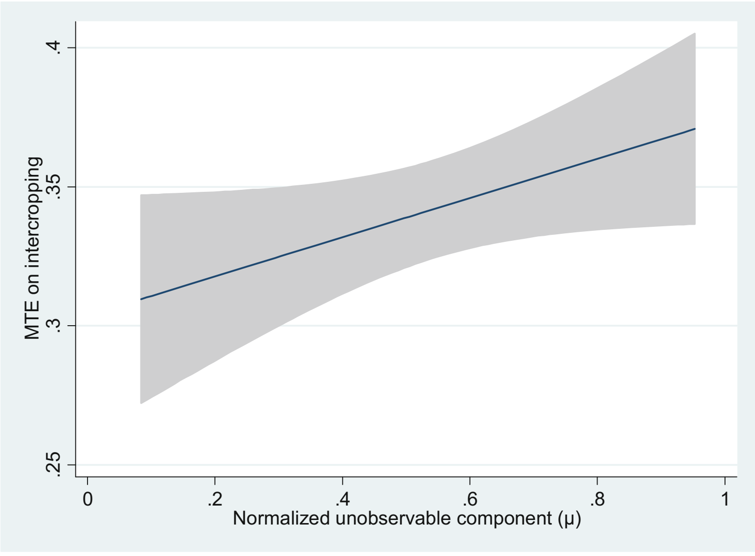

Fig. 5 Heterogeneities in the effects of perceiving increasing temperature on the adoption of rubber intercropping by unobserved component (95% confidence interval)

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