INTRODUCTION

For decades, cash tree crop expansion, such as rubber, palm oil, and cocoa expansion, in the tropical region of South Asia has tremendously transformed land-use patterns, implicating the local ecological environment, economy, and household welfare. For instance, although rubber expansion in Thailand, Vietnam, and southern China has brought about growth in household income and poverty reduction, it has also raised many issues, such as household food insecurity (Ecker, 2018), carbon imbalances (Min et al., 2019), soil and water erosion, and agrobiodiversity loss (Ahlheim et al., 2015; Liu et al., 2006). In Southeast Asia, such as Malaysia and Indonesia, palm oil has rapidly expanded, resulting in tropical deforestation (Fitzherbert et al., 2008; Vijay...
et al., 2016) and biodiversity loss (Butchart et al., 2004; Koh & Wilcove, 2008; Wilcove & Koh, 2010).

The expansion of cash tree crops has resulted in an agricultural transformation from subsistence production to market-oriented production. Farm commercialization typically involves the gradual replacement of integrated farming systems with the specialized production of few profitable cash tree crops. On the one hand, farm commercialization leads to a decline in farm production diversity and household food self-sufficiency (Ecker, 2018), as smallholders, to some extent, rely upon their own production for subsistence (Hawkes & Ruel, 2008; Sibhatu et al., 2015). On the other hand, farm commercialization also raises household incomes, and consequently, the reduced diversity of foods can be compensated for with market purchases. Hence, the expansion of cash tree crops plays an intricate role in household food security and dietary diversity.

As a typical case of cash tree crop expansion, Xishuangbanna Dai Autonomous Prefecture (XSBN), in the upper Mekong region, Southwest China, has experienced the conversion of secondary vegetation and traditional agriculture into monoculture with rubber plantations over the last three decades (Ahrends et al., 2015). Although rubber expansion in XSBN has remarkably improved smallholders’ incomes (Fox & Castella, 2013), it has also changed traditional land-use patterns, giving rise to the destruction of traditional farmland and ecologically important forest resources and thereby leading to great negative effects on agrobiodiversity (Fu et al., 2009; Hu et al., 2008). Fu et al., (2010) stated that rubber expansion-based land-use change may have adverse implications for food and nutritional security, but this study did not provide sufficient evidence. Overall, to date, few studies on the food-related issues of smallholder rubber farmers have been conducted, so the impacts of rubber expansion in XSBN on smallholders’ food and nutritional security remain unclear.

Dietary diversity is an important component of food security, reflects the quality of diets (FAO, IFAD, UNICEF, WFP, & WHO, 2020), and is highlighted by most countries’ dietary guidelines (Zhao et al., 2017). It is widely recognized that a more diversified diet tends to be associated with a higher nutritional adequacy and diet quality (Azadbakht & Esmailzadeh, 2011; Steyn et al., 2006). Furthermore, dietary diversity is also closely associated with human health, such as obesity (Jayawardena et al., 2013; Karimbeiki et al., 2018), metabolic syndrome (Zhao et al., 2018), and even mortality in elderly individuals (Lee et al., 2011). The focus on the dietary diversity of a specific group, such as smallholder rubber farmers, can have essential implications for understanding their food and nutrition status and corresponding policy design.

The objective of this study is to explore the impacts of rubber expansion on the household dietary diversity of smallholders. To achieve this aim, we first theoretically discuss two channels of the potential impact of rubber expansion on smallholders’ household dietary diversity, namely farm production diversity and household income. Then, representative household data of 611 smallholder rubber farmers collected through a comprehensive household survey conducted in 2015 in XSBN are used to empirically examine the relations between rubber expansion, farm production diversity, household income, and household dietary diversity. Additionally, to confirm the robustness of the main findings, a heterogeneity analysis is further implemented.

The results indicate that rubber expansion significantly improves household income but leads to lower farm production diversity. While rubber cultivation always has significant and positive effects on dietary diversity, it also indirectly impacts on dietary diversity by the two channels, namely farm production diversity and household income. In addition, through the analysis of heterogeneity, we find that rubber cultivation makes more contributions to the household dietary diversity of smallholders having relatively low household wealth and living in a village without a market. While the findings confirm the contribution of rubber cultivation to improving household income and nutrition, this study also notes the potential risks under the background of falling rubber prices.

This study contributes to supplementing the literature regarding the socioeconomic effects of rubber expansion in tropical areas by empirically analyzing the impacts of rubber farming on household dietary diversity and the likely mechanism. The findings not only have important policy implications for improving the food security and nutrition of smallholder rubber farmers in XSBN but also provide a better understanding of the welfare effects of cash tree crop expansion in tropical regions of South Asia. Finally, while this study is limited to the impact of rubber plantation on dietary diversity in Southern China, the findings also have broader implications, that is, this study reveals the success with poverty reduction under a scenario of rapid land-use changes from a diversified to a monoculture land-use system which has happened in many other places (e.g., natural rubber in the Mekong region and oil palm in Indonesia).

The rest of this paper is organized as follows. Section 2 illustrates the conceptual framework and empirical models of household dietary diversity under rubber expansion as well as the estimation strategy. After briefly introducing the study area and data collection procedure, in Section 3, descriptive statistics are presented for key variables and control variables. Section 4 presents the estimation results of the impacts of rubber cultivation on household dietary diversity and examines the possible intermediary variables, including farm production diversity and household income. The analysis of heterogeneous effects is also carried out in this section. The last section presents our summary and conclusions.
2 | METHODS

2.1 | Conceptual framework

To achieve the research objective, we draw on Figure 1 to explore the impacts of rubber expansion on the household dietary diversity of smallholders and account for two possible impact pathways, including farm production diversity and household income.

On the one hand, rubber expansion may affect land-use patterns and farm production diversity and thereby influences household dietary diversity. Agricultural transformation has led to the tremendous conversion of the majority of natural forests (Yi et al., 2014) and the shifting of agriculture to rubber monoculture plantations in XSBN. An analysis of satellite images showed that rubber plantations increased by 324% from 1988 to 2003 (Liu et al., 2006), with more traditional subsistence crops, such as rice, replaced by rubber plantations (Yi et al., 2014). It seems that rubber expansion may, to some extent, decrease the categories of crops that smallholders produce, which means reduced farm production diversity. Additionally, because farming households consume primarily what they produce themselves for subsistence (Jones et al., 2014), reduced farm production diversity may result in less diverse diets. Many studies have found that farm production diversity is positively associated with household dietary diversity (e.g., Ecker, 2018; Jones et al., 2014; Murendo et al., 2019). Hence, we could propose the first hypothesis:

3 | HYPOTHESIS 1: RUBBER PLANTATION MAY MAKE SMALLHOLDERS REDUCE THE TYPE OF THE CROPS THAT THEY PREVIOUSLY CULTIVATED; ACCORDINGLY, THE REDUCED FARM PRODUCTION DIVERSITY MAY FURTHER REDUCE HOUSEHOLD DIETARY DIVERSITY

On the other hand, rubber plantation may also play a role in household dietary diversity by improving smallholder income. Like farmers in other regions that have experienced the agricultural transformation from traditional subsistence agriculture to commercial agriculture based on high-value industrial crops, smallholder rubber farmers in XSBN have gained remarkably improved income (Fu et al., 2009). For example, from 1988 to 2003, the total net income of Menglun Township in XSBN increased from 0.49 million US dollars to 5.49 million US dollars (Jones et al., 2014). It is generally acknowledged that involvement in rubber cultivation generates significantly higher on-farm income and allows commercial crop smallholders to spend more money purchasing food, on average (Balde et al., 2019); then, the purchase of more diverse and nutritious foods from the market made possible by the higher cash income can improve dietary quality (Sibhatu & Qaim, 2018; Tian & Yu, 2015). Therefore, the second hypothesis can be expressed as:

4 | HYPOTHESIS 2: RUBBER PLANTATIONS CAN IMPROVE HOUSEHOLD INCOME, WHICH MAY FACILITATE SMALLHOLDERS’ ADOPTION OF MORE DIVERSIFIED DIETS THROUGH MARKET PURCHASES

In summary, given the opposite effects of rubber cultivation through the two pathways, namely farm production diversity and household income, on household dietary diversity, the total impact of rubber cultivation on household dietary diversity appears to be uncertain. Referring to the studies of Tian et al., (2019), hypothesis 1 reflects the substitution effect of rubber plantation on dietary diversity, while hypothesis 2 shows the expansion effect of rubber plantation on dietary. Thus, the total effects of rubber plantation on dietary needs to be tested together with the empirical tests for hypotheses 1 and 2.

4.1 | Empirical model

We further establish empirical models to examine the impacts of rubber farming on farm production diversity and household income:

\[
DI = \beta_0 + \beta_1 \text{RubberShare} + \sum_j \beta_j X_j + \sum_k \beta_k Z_k + \beta_4 \text{Township} + \varepsilon
\]

(1)
where \( CDI \) refers to the calculated Shannon index of crop diversity, which represents farm production diversity; \( RubberShare \) refers to the share of land used for rubber in the household, representing the rubber plantation and taking a value between 0 and 1; \( X_j \) is a series of independent variables at the individual and household levels that may play an important role in farm production choices, household income, and daily dietary diversity; \( Z_k \) is a series of independent variables at the village level that may also affect farm production choices, household income, and daily dietary diversity; and the vector \( Township \) represents a series of township dummy variables to control for potential heterogeneity. The vector \( \beta \) denotes the parameters to be estimated, while \( \epsilon_1 \) represents the error term. In equation (2), \( PNI \) refers to household net income per capita, which represents household income. The vector \( \theta \) denotes the parameters to be estimated, while \( \epsilon_2 \) represents the error term.

After examining the influence of rubber plantations on farm production diversity and household income, we attempt to determine whether the impact of rubber farming on household dietary diversity comes into effect through the pathway of farm production diversity and household income. First, model (3) is established as follows to investigate whether rubber plantations have a direct impact on household dietary diversity. Second, models (4) and (5) are established to examine the impacts of farm production diversity and household income on household dietary diversity, respectively. Third, key explanatory variables, namely rubber plantation, farm production diversity, and household income, are all incorporated into model (6). Thus, models (4), (5), and (6) can be used to examine whether farm production diversity and household income serve as intermediary variables when rubber plantations affect household dietary diversity.

\[
PNI = \theta_0 + \theta_1 RubberShare + \sum_j \theta_2 X_j + \sum_k \theta_3 Z_k + \theta_4 Township + \epsilon_2
\]

\[
HDDI = a_0 + a_1 RubberShare + \sum_j a_2 X_j + \sum_k a_3 Z_k + a_4 Township + \epsilon_3
\]

\[
HDDI = \gamma_0 + \gamma_1 RubberShare + \gamma_2 CDI + \sum_j \gamma_2 X_j + \sum_k \gamma_3 Z_k + \gamma_4 Township + \epsilon_4
\]

\[
HDDI = \rho_0 + \rho_1 RubberShare + \rho_2 CDI + \rho_3 PNI + \sum_j \rho_4 X_j + \sum_k \rho_5 Z_k + \rho_6 Township + \epsilon_5
\]

\[
HDDI = \delta_0 + \delta_1 RubberShare + \delta_2 PNI + \sum_j \delta_3 X_j + \sum_k \delta_4 Z_k + \delta_5 Township + \epsilon_6
\]

where \( HDDI \) represents the Shannon index of household dietary diversity; the vectors \( \alpha, \gamma, \delta, \rho, \) and \( \delta \) denote the parameters to be estimated; and \( \epsilon_3, \epsilon_4, \epsilon_5, \epsilon_6 \) represent the error terms in models (5), (6), (7), and (8), respectively.

### 4.2 Estimation strategy

Considering that the farm production decisions of small-holder farmers may be influenced by the plantation strategy they adopted in previous years, the estimation of the impacts of rubber farming on farm production diversity and household income may be endogenous. Therefore, an instrumental variable approach is employed to help overcome the possible endogeneity of the rubber plantation variable. In the literature, the cluster-effect instrumental variable, defined as the mean value of the corresponding values for peers, has been widely used to control for endogeneity (Benjamin, 1992; Ji et al., 2012; Min et al., 2017). Considering the existence of peer effects in agricultural knowledge transfer (Foster & Rosenzweig, 1995; Min et al., 2017; Patel et al., 2012), it is believed that the rubber plantation decisions of an individual are likely influenced by the decisions of his (her) neighbors through social interactions, knowledge sharing, and daily communication in the village. Thus, the mean value of the rubber planting ratio of other smallholders in the village can be used as an instrumental variable.

To test for the endogeneity of rubber plantations of smallholders and the validity of the instrumental variable, models (3) and (4) are estimated using two methods: ordinary least squares (OLS) regression and two-stage least squares (2SLS) regression. If the Wald test result significantly rejects the null hypothesis, \( RubberPercent \) is endogenous, and the
instrumental variable regression is superior to the OLS regression. Models (5), (6), (7), and (8) are estimated by 2SLS regression.

5 | DATA AND DESCRIPTIVE STATISTICS

5.1 | Study area and data sources

As shown in Figure 2, XSBN, our study area, is located in southern Yunnan Province, bordering Laos and Myanmar in the upper Mekong Basin. In the 1980s, authorities in Yunnan Province encouraged rubber plantations to stabilize forestlands and promote environmental conservation (Fox et al., 2014). Due to their high commercial value and economic interests, rubber plantations in XSBN expanded dramatically. By 2017, the rubber plantation area of XSBN was 304,946.7 hectares (XNESDSB, 2018), and rubber production increased from 39,493 thousand tons in 1988 to 298.3 thousand tons in 2017, with a growth rate of 655% (Statistical Bureau of Yunnan, 1989, 2018). XSBN is currently one of the most important natural rubber planting regions in China and contributes nearly half of the nation’s rubber production (Min et al., 2018). As long as the return on rubber farming remains attractive, smallholders remain motivated to expand rubber farms (Zhang et al., 2015).

A socioeconomic household survey of smallholder rubber farmers in XSBN was conducted in March 2015. Adopting a stratified random sampling approach, we investigated 611 smallholders from 42 villages in eight of the townships in XSBN. The data adopted in this study were collected through a comprehensive household questionnaire that includes detailed information on household characteristics, land use,
rubber farming activities, on-farm and off-farm activities, and expenditure on food and nonfood products, as well as other questions related to rubber. In the module on food expenditure, we asked farmers to report the average monthly per capita consumption on nine food categories, including vegetables, pork, poultry, beef, mutton, aquatic products, egg, and milk and dairy products.

### 5.2 Measurement of key variables

#### 5.2.1 Household dietary diversity

The dependent variable of interest is household dietary diversity, which is often applied as an indicator to measure dietary quality, nutrition intake, and food security. In practice, scholars have adopted various methods to measure household dietary diversity. For example, the household dietary diversity index (HDDI) has been widely used to indicate household nutrition status (Ritzema et al., 2019; Swindale & Bilinsky, 2006), while the potential food availability indicator (PFAI) has also been applied in previous studies to quantify the ability of a household to feed itself through both on-farm and off-farm activities (Frelat et al., 2016; Ritzema et al., 2017). Additionally, several researchers have employed the food consumption score (FCS) (Parvathi, 2018; Zanello et al., 2019), which is a weighted score calculated using the frequency of a household’s consumption of different food categories during the past few days before the survey. Given the data limitations, we follow Min et al., (2019) and Sharma and Chandrasekhar (2016) to calculate the HDDI using the Shannon index formula (Shannon & Weaver, 1949), the equation of the HDDI of the $i$th household’s food consumption can be expressed as:

$$HDDI_i = -\sum_{n_i} (\text{QuantityShare}_{n_i}) \ln (\text{QuantityShare}_{n_i})$$

where $\text{QuantityShare}_{n_i}$ denotes the share of the $n$th food category in the food consumption of the $i$th household. A higher HDDI value indicates greater dietary diversity.

Figure 3 shows the kernel density distribution of the Shannon index of smallholders’ food consumption representing household dietary diversity. The calculated results show that the mean value of the HDDI is 1.42, with a standard deviation of 0.23. Visually, the distribution curve is left-skewed, illustrating that the mean value of the HDDI is smaller than the mode, and the dietary diversity of most smallholders is above the average level.

#### 5.2.2 Farm production diversity

In terms of the measurement of farm production diversity, Hirvonen and Hoddinott (2017) used a simple count indicator to study the relationship between preschool children’s food consumption and household agricultural production; Huang and Tian (2019) also used a simple count indicator to discuss the influence of agricultural production diversity on the dietary pattern. Jones et al., (2014) and Ecker (2018) applied Simpson’s index to examine the impacts of farm production diversity on household dietary diversity, while scholars have also used the Margalef index to measure crop diversity on farms (Di Falco & Chavas, 2009; Margalef, 1968). The diversity index not only counts the number of crops but also considers the area of each crop. Consistent with the measurement of household dietary diversity, we still applied the Shannon formula to measure farm production diversity as the crop diversity index (CDI). Specifically, suppose that the count of the planted crops of the $i$th smallholder is $M_i$, then the equation for the CDI of the $i$th smallholder can be expressed as:

$$CDI_i = -\sum_{m_i} (\text{LandShare}_{m_i}) \ln (\text{LandShare}_{m_i})$$

where $\text{LandShare}_{m_i}$ denotes the share of the $m$th crop’s planting area of the total land area of the $i$th smallholder. When $M_i$ equals 1, the smallholder plants only rubber; accordingly, $CDI_i$ equals 0. A higher CDI value indicates greater crop diversity (farm production diversity).

Figure 4 reports the distribution histogram of the number of crop categories planted by smallholders, while Figure 5
presents the distribution histogram of the CDI as farm production diversity. From Figure 4, we can reach a preliminary understanding of the land use of smallholder rubber farmers: nearly 34% of smallholders plant only rubber, while approximately 33% of smallholders plant only one other crop in addition to rubber. The average number of planted crops is 2.13; in other words, smallholder rubber farmers in the XSBN plant, on average, only one other kind of crop in addition to rubber. Moreover, with the increase in the number of crop categories or the CDI value, the sample distributions tend to decrease. However, the CDI distribution is more balanced than the distribution of the simple count of crops because it accounts for the \( \text{LandShare}_m \).

5.3 | Summary of variables

Table 1 provides detailed definitions and statistics for all the variables used in the econometric analyses. The variables of interest, HDDI and CDI, have been introduced in the analysis above. The other variable we focused on is the household net income per capita (PNI) of smallholder rubber farmers. The PNI has a mean value of 10.026 thousand yuan and a large standard deviation (26.588 thousand yuan), implying a large income gap between different rubber smallholder farmers in XSBN. The median value of household net income per capita is 4.826 thousand yuan, which is smaller than the mean value, indicating that the household net income distribution is skewed to the right. The key independent variable \( \text{RubberShare} \) is defined as the share of land used for rubber in the household. The average value of the land share used for rubber in the household is 0.815, denoting a high average proportion of rubber planting, which is reasonable in the context of rubber expansion.

In addition to those critical variables, control variables regarding characteristics at the individual and household level \( (X_j) \) and village level \( (Z_k) \) are included in the models. In terms of variables at the individual and household level, the gender, age, education, and ethnicity of the household head are included because the household head often plays an important role in family decision-making (Huang et al., 2014). The average age and years of education of household
heads were approximately 48 and 4.5 years, respectively, and only 8% of the household heads were women. The land area per capita was 14.21 mu/person (1 mu = 0.067 ha). The average household population was five family members, of whom 18.5% were below 16 years old and 7.1% were 65 years old or older. Approximately 31.8% of households had no less than one family member engaged in off-farm activities. Household wealth is defined as values of household assets, including house(s), home appliances, and means of transportation, and the average value was 54.84 thousand yuan/person with a standard deviation of 49.78, reflecting the relatively large inequality of wealth among smallholder rubber farmers. The altitude of the household location is also controlled because smallholders located at higher altitudes probably plant more kinds of crops (Min et al., 2017).

In terms of variables at the village level, the average values of the village head’s age and tenure are 40.84 and 5.47 years, respectively. The average population of the villages is 388 persons. Considering that there may exist interactions such as borrowing and giving behaviors between villagers, the crop diversity of the village where the smallholder lives may affect his (her) household diet. Based on that, the CDI of the village is included in the models with a mean value of 0.881. Only 10% of villages had markets, and on average, 8% of the villagers worked outside the village in 2014. The average distance from

| Variable | Definition and description | Mean | Std. Dev. |
|----------|-----------------------------|------|-----------|
| CDI | Crop Diversity Index | 0.250 | 0.260 |
| PNI | Household net income per capita (thousand yuan/person) | 10.026 | 26.588 |
| HDDI | Household Dietary Diversity Index | 1.420 | 0.230 |

| Independent variables | Definition and description | Mean | Std. Dev. |
|-----------------------|-----------------------------|------|-----------|
| RubberShare | Share of land used for rubber in the household | 0.815 | 0.238 |
| HDfem | Whether the household head is female (1 = yes; 0 = no) | 0.080 | 0.272 |
| HDage | Age of the household head (year) | 47.730 | 10.650 |
| HDedu | Educational attainment of the household head (year) | 4.453 | 3.596 |
| HDdai | Whether the ethnicity of the household head is Dai (1 = yes; 0 = no) | 0.583 | 0.494 |
| HHarea | Per capita land area (mu/person) | 14.210 | 15.320 |
| HHchild | The proportion of children in the household | 0.185 | 0.151 |
| HHelder | The proportion of the elder in the household | 0.071 | 0.129 |
| HHpop | Household population (persons) | 5.264 | 1.477 |
| HHnonfarm | Whether there exists off-farm labor in the household | 0.318 | 0.466 |
| HHwealth | The value of household assets, including house(s), home appliances and means of transportation (thousand yuan/person) | 54.840 | 49.780 |
| HHaltitude | Altitude of the household location (meters above sea level (MASL)) | 756.800 | 165 |

| Z: Characteristics at the village level | Definition and description | Mean | Std. Dev. |
|--------------------------------------|-----------------------------|------|-----------|
| VDage | Age of the village head | 40.840 | 6.881 |
| VDayear | Tenure of the village head | 5.468 | 3.611 |
| Vpop | Population of the village where the respondent lives in (persons) | 388 | 222.400 |
| VCDI | Crop Diversity Index of the village | 0.881 | 0.480 |
| Vmarket | Whether the village has a market (1 = yes; 0 = no) | 0.100 | 0.300 |
| Vworkout | Percentage of villagers working outside the village in 2014 | 7.614 | 9.012 |
| Vdistown | The distance to the center of the township | 11.220 | 11.540 |
| Township | Township dummy variables | — | — |
| Observations | | 611 |  |
the village to the center of the township is 11.22 kilometers. To control regional heterogeneity, seven township dummy variables are also incorporated into the equations to be estimated.

6 | RESULTS AND DISCUSSION

6.1 | The impact of rubber farming on the CDI and PNI

Table 2 reports the estimation results of models (1) and (2), in which we examine the impact of rubber farming on farm production diversity (CDI) and household net income per capita (PNI), respectively. Each model is estimated by both OLS regression and 2SLS regression. As stated in the estimation strategy, the mean value of the rubber planting ratio of other smallholders in the village is used as an instrumental variable. We perform Hausman tests for the estimation results for model (1) and model (2). The results show that the Hausman test for model (1) does not reject the null hypothesis. The 2SLS estimation results of model (1) using an instrumental variable are not superior to the OLS estimation results. Thus, we prefer the results of the OLS regression of model (1) to analyze the impact of rubber farming on farm production diversity. Relatively, the Hausman test for model (2) rejects the null hypothesis at the 5% significance level, meaning that the estimation results of the 2SLS regression are preferred to those of the OLS regression for model (2).

Table A1 reports the results of the first-stage regression of the 2SLS estimation of models 1 and 2. The results not only confirm the significant impacts of the two proposed instrumental variables but also indicate several other variables which are significantly correlated with farm production diversity and household income. For example, the Dai ethnic group plant more diverse crops and have significantly higher household income than that of other ethnicities. These may be because that the Dai ethnicity is the majority in XSBN and therefore have somewhat advantages. Surprisingly, households with more areas of land appear to plant fewer types of crops and have a lower income. The possible reason is that most land owned are forest lands such that farmers can only obtain somewhat subsidies instead of planting crops and earning. Similar reason is also valid for the negative impacts of altitude on farm production diversity and household income, as most land in the higher altitude areas are covered by forests.

Specifically, the OLS estimation results of model (1) demonstrate that rubber plantations have a negative and significant impact on farm production diversity, which is represented by the CDI. Even in the results of the 2SLS regression, the estimated results of the rubber share are consistent with the OLS estimation results. Hence, for smallholders in XSBN, the expansion of rubber plantations can reduce the variety of crops planted. Moreover, not surprisingly, the proportion of children in the household has a significantly negative impact on farm production diversity at a 5% significance level. This is reasonable because raising children requires much energy, and a higher proportion of children prevents households from adopting a more diversified crop planting strategy. Consistent with the studies of Brush and Perales (2007) and Min et al., (2017), our results suggest that smallholders located at higher altitudes plant more diversified crops. The older the village head is, the more diversified the farm production of households. Additionally, the crop diversity of the village where the household lives has a significantly positive impact on the farm production diversity of the household. Thus, a village with more diversified crop production can promote household production of more crop varieties.

The results of model (2) illustrate that rubber plantations have a significantly positive impact on household net income per capita at the 10% significance level. This result provides empirical evidence that rubber cultivation in some extent contributes to improving the household income of smallholder rubber farmers. Furthermore, off-farm labor, altitude, crop diversity of the village, and the distance to the center of the township have a significant impact on household net income. Specifically, households with at least one family member engaging in off-farm employment have higher household income per capita than households with no off-farm employment. The altitude of the household location also leads to higher household net income per capita. The crop diversity of the village has a negative impact on household net income per capita at the 5% significance level. The likely reason is that the crop diversity of the village contributes to households diversifying their production, which consequently results in the decreased production of commercial crops and then reduces the household net income per capita. The distance to the center of the township has a negative impact on household net income per capita. Being located a long distance from the township can not only increase the transportation cost of smallholders but also reduce the probability of augmenting their income by way of finding off-farm occupations and selling their production.

6.2 | The impact of rubber farming on the HDDI

Models (3), (4), (5), and (6) are estimated to examine whether rubber plantations have an impact on household dietary diversity through farm production diversity and household income. These models are estimated by both OLS and 2SLS regressions, while the Hausman tests validate the results using 2SLS regression. The results of the OLS regressions and Hausman tests can be provided upon request. As shown in Table 3, from the estimation results of models (3), (4), (5), and (6), rubber plantations always have significant direct impacts on the HDDI. With the inclusion
| Variables            | Model (1): CDI | Model (2): PNI |
|---------------------|---------------|---------------|
|                     | OLS regression | 2SLS regression# | OLS regression | 2SLS regression# |
| (IV)RubberShare     | −0.582***     | −0.626***     | −1.214          | 6.599*            |
|                     | (0.033)       | (0.127)       | (0.921)         | (3.813)           |
| HDfem               | −0.038        | −0.036        | −0.006          | −0.311            |
|                     | (0.024)       | (0.024)       | (0.672)         | (0.711)           |
| HDage               | −0.0002       | −0.0002       | 0.010           | 0.016             |
|                     | (0.0007)      | (0.0007)      | (0.019)         | (0.020)           |
| HDedu               | −0.002        | −0.003        | 0.047           | 0.067             |
|                     | (0.002)       | (0.002)       | (0.056)         | (0.059)           |
| HDdai               | −0.035**      | −0.031        | −0.222          | −0.838            |
|                     | (0.017)       | (0.019)       | (0.483)         | (0.579)           |
| HHarea              | 0.0002        | 0.0001        | −0.017          | −0.009            |
|                     | (0.0005)      | (0.0005)      | (0.014)         | (0.015)           |
| HHchild             | −0.096**      | −0.093**      | −1.320          | −1.925            |
|                     | (0.047)       | (0.047)       | (1.320)         | (1.398)           |
| HHdrider            | −0.069        | −0.067        | 0.725           | 0.437             |
|                     | (0.052)       | (0.052)       | (1.485)         | (1.545)           |
| HHpop               | 0.006         | 0.006         | −0.044          | −0.061            |
|                     | (0.005)       | (0.005)       | (0.137)         | (0.142)           |
| HHnonfarm           | −0.002        | −0.002        | 2.843***        | 2.872***          |
|                     | (0.014)       | (0.014)       | (0.406)         | (0.421)           |
| HHwealth            | −0.0002       | −0.0002       | 0.002           | 0.002             |
|                     | (0.0001)      | (0.0001)      | (0.004)         | (0.004)           |
| HHalitude           | 0.0002***     | 0.0002***     | 0.001           | 0.004*            |
|                     | (0.00006)     | (0.00007)     | (0.002)         | (0.002)           |
| VDage               | 0.002**       | 0.002*        | 0.005           | 0.027             |
|                     | (0.001)       | (0.001)       | (0.034)         | (0.037)           |
| VDyear              | −0.003        | −0.003        | −0.061          | −0.102            |
|                     | (0.002)       | (0.002)       | (0.063)         | (0.068)           |
| Vpop                | −0.00006      | −0.00007*     | 0.001           | 0.002             |
|                     | (0.00004)     | (0.00004)     | (0.001)         | (0.001)           |
| VCDI                | 0.041**       | 0.043**       | −0.931          | −1.367**          |
|                     | (0.021)       | (0.021)       | (0.589)         | (0.644)           |
| Vmarket             | 0.012         | 0.013         | 1.065           | 0.802             |
|                     | (0.026)       | (0.026)       | (0.742)         | (0.779)           |
| Vworkout            | −0.0002       | −0.0002       | −0.011          | −0.013            |
|                     | (0.0009)      | (0.0009)      | (0.025)         | (0.026)           |
| Vdistown            | 0.0003        | 0.0005        | −0.050**        | −0.119***         |
|                     | (0.0008)      | (0.001)       | (0.024)         | (0.032)           |
| Township dummy variable | Controlled     | Controlled     | Controlled     | Controlled     |
| Constant            | 0.562***      | 0.596***      | 1.370           | −4.667            |
|                     | (0.088)       | (0.128)       | (2.494)         | (3.849)           |
| F statistic         | 45.54***      | 33.99***      | 4.83***         | 4.28***           |

(Continues)
of the CDI and PNI, the coefficients of rubber plantations also change. These results suggest that both CDI and PNI represent channels through which rubber plantations impact the HDDI. Nevertheless, the coefficient of rubber plantations is still nonsignificant even when the model controls for both the CDI and PNI, implying that there are also other potential impact channels.

In Table (2), we have determined that rubber plantations have a significantly negative impact on farm production diversity. The results of model (3) indicate that when farm production diversity is not controlled, rubber plantations have a significantly positive influence on the HDDI. Moreover, we can see that the impact of rubber farming on the HDDI increases when farm production diversity (CDI) is incorporated in model (4). It can be concluded that rubber plantations have an indirect impact on the HDDI through the CDI. That is, rubber plantations can reduce farm production diversity and negatively affect the HDDI, confirming the hypothesis 1.

From the above analysis of model (2), we also know that rubber plantations have significantly positive impacts on household income. However, it is found that the impact of rubber farming on the HDDI (in model (3)) decreases when household income (PNI) is incorporated in model (5). This indicates that household income plays a partial mediating role in the impact of rubber planting on the HDDI. Higher income can generally bring about more expenditure on a household's food consumption, and then, the dietary quality improves. Consequently, rubber plantations also can enhance the HDDI by increasing household income. Hence, the second hypothesis is confirmed too.

Furthermore, in regard to the control variables, the dummy variable Dai positively affects household dietary diversity at the 1% significance level. According to Liu (2007), because the Dai ethnic group lives in areas with lush plants, in addition to the food they produce, there are many edible wild fruits and vegetables; fish can also be caught to meet meat requirements. Therefore, the Dai ethnic group traditionally collects or hunts food from natural resources as a complementation for their diets, while this dietary culture of the Dai ethnic group helps the Dai adopt more diversified diets than other ethnicities.

Wealth also has a positive and significant impact on household dietary diversity. Different from household net income, the wealth variable measures the cumulative wealth of households in the form of assets. The results indicate that richer smallholders have more diversified diets and better dietary quality. The age of the village head has a negative impact on household dietary diversity at the 10% significance level. Additionally, a higher percentage of villagers working outside the village motivates smallholders to diversify their diets.

It is worth noting that the market variable at the village level has a positive and significant impact on household dietary diversity at the 10% significance level when the variable CDI is excluded in models 3 and 5. The nonsignificant impacts of the market variable on the HHDI in models 4 and 6 may be because smallholders extract food first from household farm production, followed by the village market; therefore, when the CDI is further controlled, the impacts of the village market become nonsignificant.

The significant impact of the village market is consistent with the findings of several studies. For instance, Sibhatu et al., (2015) use household-level data from Indonesia, Kenya, Ethiopia, and Malawi and find that market access has larger positive effects on dietary diversity than increased production diversity. Zanello et al., (2019) use data in Afghanistan and find that in the lean season, the market aspect becomes important for dietary diversity. Sibhatu and Qaim (2018) insist that market access is more important than farm diversification from a nutrition perspective. We further divide the households into two groups according to whether there is a market in the village in which they live. Then, the empirical cumulative distribution function of the predicted HDDI is drawn in Figure 6 to compare the dietary diversity of these two groups. Obviously, households living in villages with a market generally have more diversified diets than those in villages without a market. There are two main explanations for the role of markets in improving household dietary diversity. One is that much of the food diversity consumed in farmer households is purchased from the market (Sibhatu & Qaim, 2018), and even very poor and very remote rural households rely extensively on markets to satisfy their demand for diversified foods. The other is that the household can sell its
### TABLE 3
2SLS estimation results of models (3), (4), (5), and (6)

| Variables | HDDI | Model (3) | Model (4) | Model (5) | Model (6) |
|-----------|------|-----------|-----------|-----------|-----------|
| IV-RubberShare | | 0.766*** | 1.274*** | 0.731*** | 1.212*** |
| | | (0.213) | (0.376) | (0.205) | (0.359) |
| CDI | | 0.811*** | 0.769*** | | |
| | | (0.237) | | | |
| PNI | | | 0.005** | 0.005** | |
| | | | (0.002) | (0.003) | |
| HDfem | | 0.017 | 0.047 | 0.019 | 0.047 |
| | | (0.040) | (0.043) | (0.039) | (0.042) |
| HDage | | −0.0004 | −0.0002 | −0.0005 | −0.0003 |
| | | (0.001) | (0.001) | (0.001) | (0.001) |
| HĐedu | | 0.003 | 0.005 | 0.003 | 0.005 |
| | | (0.003) | (0.004) | (0.003) | (0.004) |
| HDdai | | 0.040 | 0.065** | 0.045 | 0.069** |
| | | (0.032) | (0.033) | (0.032) | (0.032) |
| HHarea | | 0.001 | 0.001 | 0.001 | 0.001 |
| | | (0.0008) | (0.0009) | (0.0008) | (0.0009) |
| HHchild | | 0.026 | 0.101 | 0.036 | 0.107 |
| | | (0.078) | (0.085) | (0.077) | (0.083) |
| HHelder | | 0.069 | 0.123 | 0.067 | 0.118 |
| | | (0.086) | (0.095) | (0.085) | (0.093) |
| HHpop | | −0.005 | −0.010 | −0.005 | −0.010 |
| | | (0.008) | (0.009) | (0.008) | (0.009) |
| HHHnonfarm | | −0.006 | −0.005 | −0.022 | −0.020 |
| | | (0.024) | (0.026) | (0.024) | (0.026) |
| HHwealth | | 0.001*** | 0.001*** | 0.001*** | 0.001*** |
| | | (0.0002) | (0.0003) | (0.0002) | (0.0003) |
| HHalatitude | | 0.0002 | 0.0003 | 0.0002 | 0.0002 |
| | | (0.0001) | (0.0001) | (0.0001) | (0.0001) |
| VDage | | −0.0007 | −0.003 | −0.0008 | −0.003 |
| | | (0.002) | (0.002) | (0.002) | (0.002) |
| VDyear | | −0.008** | −0.006 | −0.008** | −0.006 |
| | | (0.004) | (0.004) | (0.004) | (0.004) |
| Vpop | | −0.000007 | 0.000005 | −0.000002 | 0.000003 |
| | | (0.00007) | (0.00008) | (0.00006) | (0.00007) |
| VCDI | | −0.00006 | −0.035 | 0.007 | −0.026 |
| | | (0.036) | (0.044) | (0.035) | (0.042) |
| Vmarket | | 0.079* | 0.068 | 0.075* | 0.064 |
| | | (0.044) | (0.049) | (0.043) | (0.048) |
| Vworkout | | 0.002 | 0.002 | 0.002 | 0.002 |
| | | (0.001) | (0.002) | (0.001) | (0.002) |
| Vdistown | | −0.002 | −0.003 | −0.002 | −0.002 |
| | | (0.002) | (0.002) | (0.002) | (0.002) |

(Continues)
harvest in the market to generate agricultural income, which can further help enhance dietary diversity.

### 6.3 Heterogeneous effects

Given that the impacts of rubber farming, farm production diversity, and household income on household dietary diversity may vary by household wealth and the market status of the village, we further conduct a heterogeneity analysis. First, the whole sample is divided into three subsamples according to household wealth; then, model (6) is re-estimated for each subsample. As shown in Table 4, the impacts of rubber farming, farm production diversity, and household income are significant only for smallholders with low household wealth. It seems that households with low wealth are more susceptible than those with relatively medium and high wealth. Specifically, for smallholders with low household wealth, an increase in household income can significantly improve their dietary diversity. This may be because income improvement can contribute to a more significant marginal influence on the dietary diversity of low-income families, while relatively wealthy smallholders usually have various choices in regard to food consumption. Following the above explanation, it is reasonable that rubber plantations, as an effective way to bring about smallholders’ income, can have significantly positive effects on the HDDI of poor families rather than rich families. In addition, the results show that farm production diversity (CDI) is positively associated with the HDDI at the 10% significance level for smallholders with low household wealth. This finding reveals that farm production diversity plays a more important role in household dietary diversity for smallholders with low household wealth, while smallholders with more wealth tend to have more other channels to improve household dietary diversity.

Second, we attempt to examine the heterogeneity resulting from the existence of a market. As presented in Table 5, all three key variables have significantly positive effects on...
the HDDI when the village where the smallholder lives does not have a market. These effects turn out statistically non-significant for smallholders who live in villages with markets. This demonstrates that the existence of a village market hinders the effects of the three key dependent variables on the HDDI. This is consistent with the viewpoint that more emphasis should be placed on rural markets’ role to improve household dietary diversity.

### 6.4 Robustness check

In order to confirm the stability of the main findings of this study, we further conducted a robustness check by using alternative estimation approaches and alternative measures of key variables. The specific results are reported as follows.

Firstly, we employ a three-stage least square (3SLS) to re-estimate the established empirical models. The 3SLS regression results of models (1) and (2) show significant impacts of rubber cultivation on farm production diversity and household income (Table A3), consistent with the 2SLS regression results in Table (2). Table A4 reports the 3SLS regression results of models (3), (4), (5), and (6). While the significances of CDI and PNI are inconsistent with the results in Table (3), rubber cultivation always significantly impact on the HHDI. When the control variables adjust from model (3) to model (6), the change trends of estimated coefficients of rubber cultivation are consistent with those in Table (3). Hence, the main findings of this study do not change with the employed estimation methods.

Secondly, we alternatively use the number of types of crops grown and the number of food categories to measure the farm production diversity and dietary diversity, respectively. Then, we re-estimate the models (1), (3), (4), (5), and (6). The results are reported in Table A5 and A6 of appendix. The results indicate that rubber cultivation negatively impacts on farm production diversity (Table A5). While rubber cultivation always directly and positively affects the HDDI, it could also indirectly impact on the HDDI by the two channels including farm production diversity.
diversity and household income (Table A6). These results are consistent with those in Tables (2) and (3), confirming that the main findings of this study do not change with the measures of key variables.

7 | SUMMARY AND CONCLUSION

In the context of cash tree crop expansion and agricultural transformation in South Asia, especially southern China, rubber expansion has resulted in several economic and ecological problems. To better understand the impact of rubber farming on household dietary diversity, in this study, we use representative household survey data from 611 smallholder rubber farmers in XSN. Our empirical results indicate that rubber plantations lead to significantly lower farm production diversity, which has a significantly positive effect on household dietary diversity. Conversely, rubber planting can have a significantly positive influence on household dietary diversity when household income is taken as a mediating variable. These findings confirm the contributions of rubber expansion to the household income and nutrition of smallholders, thereby complementing the evidence of the welfare effects of cash tree crop expansion in tropical regions.

Moreover, the results indicate that Dai ethnicity smallholders tend to have a high HDDI, evidencing the healthy diet of the Dai ethnicity. Similar to the positive effects of household income on the HDDI, cumulative wealth also contributes to the improvement in the HDDI. Smallholders living in a village with a market appear to have a relatively high HDDI. Thus, enhancing market availability in a village is of great significance to ensure the food and nutrition security of smallholders (Sibhatu et al., 2015).

The heterogeneity analysis further suggests that the impacts of rubber farming, farm production diversity, and per capita net income on the HDDI are significant only for households having low wealth or living in a village without a market. These results emphasize that rubber plantations, farm production diversity, and household income are particularly important for improving the nutrition of poor smallholders and verify the significance of rural markets to household dietary diversity.

The potential threats of rubber price risks to household income, food security, and nutrition are worthy of notice. The positive effects of rubber plantations are based on the relatively high rubber price, which can make rubber farming profitable. In fact, since 2011, the price of natural rubber has been decreasing from a peak. While in 2014, rubber farming was still profitable and contributed to per capita net income, the persistent decline in the rubber price has made smallholder rubber farming unprofitable in recent years. Thus, although this study confirms the positive welfare effects of rubber expansion, the potential price risks must be considered.

Finally, we would like to point out the major limitation of this study, which regards the cross-sectional data used, the monthly average food consumption, and the absence of anthropometric data. Panel data with more detailed food consumption data and anthropometric data may contribute to establishing a more advanced nutrition model and providing more insights into the dynamic impacts of rubber farming on the household dietary diversity of smallholder rubber farmers.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data used in this study can be provided upon request.

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### APPENDIX A

**TABLE A1** The first-stage regression results of the 2SLS estimation of models 1 and 2

| Variables            | Model (1): CDI | Model (2): PNI |
|----------------------|----------------|----------------|
| IV-RubberShare       | 0.479***       | 0.479***       |
|                      | (0.077)        | (0.077)        |
| HDfem                | 0.029          | 0.029          |
|                      | (0.029)        | (0.029)        |
| HDage                | −0.0004        | −0.0004        |
|                      | (0.001)        | (0.001)        |
| HDedu                | −0.001         | −0.001         |
|                      | (0.002)        | (0.002)        |
| HDdai                | 0.043**        | 0.043**        |
|                      | (0.022)        | (0.022)        |
| HHarea               | −0.001*        | −0.001*        |
|                      | (0.001)        | (0.001)        |
| HHchild              | 0.052          | 0.052          |
|                      | (0.057)        | (0.057)        |
| HHelder              | 0.045          | 0.045          |
|                      | (0.065)        | (0.065)        |
| HHpop                | 0.003          | 0.003          |
|                      | (0.006)        | (0.006)        |
| HHnonfarm            | −0.007         | −0.007         |
|                      | (0.018)        | (0.018)        |
| HHwealth             | −0.0002        | −0.0002        |
|                      | (0.0002)       | (0.0002)       |
| HHaltitude           | −0.0002**      | −0.0002**      |
|                      | (0.0001)       | (0.0001)       |
| VDage                | −0.002         | −0.002         |
|                      | (0.001)        | (0.001)        |
| VDyear               | 0.003          | 0.003          |
|                      | (0.003)        | (0.003)        |
| Vpop                 | −0.00002       | −0.00002       |
|                      | (0.00005)      | (0.00005)      |
| VCDI                 | 0.031          | 0.031          |
|                      | (0.026)        | (0.026)        |
| Vmarket              | 0.008          | 0.008          |
|                      | (0.032)        | (0.032)        |
| Vworkout             | −0.0004        | −0.0004        |
|                      | (0.001)        | (0.001)        |
| Vdistown             | 0.002*         | 0.002*         |
|                      | (0.001)        | (0.001)        |
| Township Dummy variable | Controlled   | Controlled    |
| Constant             | 0.447***       | 0.447          |
|                      | (0.116)        | (0.116)        |
| F statistic          | 39.05***       | 39.05          |
| LM statistic         | 38.3***        | 38.3***        |
| Observations         | 611            | 611            |

**Notes:** ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses.
| Variables                  | HDDI                  |          |          |          |
|---------------------------|-----------------------|----------|----------|----------|
|                           | Model (3)             | Model (4) | Model (5) | Model (6) |
|                           | 0.479***              | 0.304*** | 0.490*** | 0.312*** |
|                           | (0.077)               | (0.063)  | (0.077)  | (0.063)  |
| CDI                       | −0.583***             |          |          | −0.581*** |
|                           | (0.034)               |          |          | (0.034)  |
| PNI                       | −0.003*               | −0.002   |          |          |
|                           | (0.002)               | (0.001)  |          |          |
| HDfem                     | 0.029                 | −0.003   | 0.029    | −0.003   |
|                           | (0.029)               | (0.024)  | (0.029)  | (0.024)  |
| HDage                     | −0.0004               | −0.0004  | −0.0003  | −0.0003  |
|                           | (0.001)               | (0.001)  | (0.001)  | (0.001)  |
| HDedu                     | −0.001                | −0.002   | −0.001   | −0.002   |
|                           | (0.002)               | (0.002)  | (0.002)  | (0.002)  |
| HDdai                     | 0.043**               | 0.009    | 0.041*   | 0.008    |
|                           | (0.022)               | (0.018)  | (0.022)  | (0.018)  |
| HHarea                    | −0.001*               | −0.001   | −0.001** | −0.001   |
|                           | (0.001)               | (0.0005) | (0.001)  | (0.0005) |
| HHchild                   | 0.052                 | −0.021   | 0.047    | −0.024   |
|                           | (0.057)               | (0.047)  | (0.057)  | (0.047)  |
| HHelder                   | 0.045                 | −0.010   | 0.048    | −0.009   |
|                           | (0.065)               | (0.053)  | (0.064)  | (0.053)  |
| HHpop                     | 0.003                 | 0.006    | 0.003    | 0.006    |
|                           | (0.006)               | (0.005)  | (0.006)  | (0.005)  |
| HHnonfarm                 | −0.007                | −0.005   | 0.003    | 0.001    |
|                           | (0.018)               | (0.014)  | (0.018)  | (0.015)  |
| HHwealth                  | −0.0002               | −0.0002  | −0.0002  | −0.0002  |
|                           | (0.0002)              | (0.0001) | (0.0002) | (0.0001) |
| HHaltitude                | −0.0002**             | 0.000003 | −0.0002**| 0.00001  |
|                           | (0.0001)              | (0.0001) | (0.0001) | (0.0001) |
| VDage                     | −0.002                | 0.0003   | −0.002   | 0.0003   |
|                           | (0.001)               | (0.001)  | (0.001)  | (0.001)  |
| VDyear                    | 0.003                 | 0.0001   | 0.003    | −0.0001  |
|                           | (0.003)               | (0.002)  | (0.003)  | (0.002)  |
| Vpop                      | −0.00002              | −0.0001  | −0.00002 | −0.00005 |
|                           | (0.00005)             | (0.00004)| (0.00005)| (0.00004)|
| VCDI                      | 0.031                 | 0.045**  | 0.027    | 0.042**  |
|                           | (0.026)               | (0.021)  | (0.026)  | (0.021)  |
| Vmarket                   | 0.008                 | 0.013    | 0.011    | 0.015    |
|                           | (0.032)               | (0.026)  | (0.032)  | (0.026)  |
| Vworkout                  | −0.0004               | −0.0003  | −0.0005  | −0.0004  |
|                           | (0.001)               | (0.001)  | (0.001)  | (0.001)  |
| Vdistown                  | 0.002*                | 0.002*   | 0.002    | 0.001    |
|                           | (0.001)               | (0.001)  | (0.001)  | (0.001)  |
| Township Dummy variable   | Controlled            | Controlled| Controlled| Controlled|
| Constant                  | 0.447***              | 0.631*** | 0.441*** | 0.627*** |
|                           | (0.116)               | (0.095)  | (0.116)  | (0.095)  |
| F statistic               | 39.05***              | 23.09*** | 40.71*** | 24.16*** |
| LM statistic              | 38.3***               | 23.28*** | 39.88*** | 24.35*** |
| Observations              | 611                   | 611      | 611      | 611      |

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses.
## TABLE A3 3SLS estimation results of models (1) and (2)

| Variables          | Model (1): CDI  | Model (2): PNI  |
|--------------------|------------------|------------------|
|                    | 3SLS regression# | 3SLS regression# |
| (IV) RubberShare   | −0.626***        | 6.599*           |
|                    | (0.127)          | (3.813)          |
| Other independent  | Controlled       | Controlled       |
| variables          | Township dummy   | Township dummy   |
|                    | variables        | variables        |
| Constant           | 0.596***         | −4.667           |
|                    | (0.128)          | (3.849)          |
| Chi2               | 924.67***        | 116.55**         |
|                    | (0.231)          | (0.220)          |
| Observations       | 611              | 611              |

*Notes:* ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses; the regression results for the share of land used for rubber in a household could be provided upon request.

## TABLE A4 3SLS estimation results of models (3), (4), (5), and (6)

| Variables          | HDDI                      |
|--------------------|---------------------------|
|                    | Model (3) | Model (4) | Model (5) | Model (6) |
| (IV) RubberShare   | 0.766***   | 0.796**   | 0.46***   | 0.791**   |
|                    | (0.213)    | (0.375)   | (0.205)   | (0.357)   |
| CDI                | 0.048      | 0.070     |
|                    | (0.231)    | (0.220)   |
| PNI                | 0.003      | 0.003     |
|                    | (0.002)    | (0.002)   |
| Other independent  | Controlled | Controlled | Controlled | Controlled |
| variables          | Township dummy variable   | Township dummy variable |
| Constant           | 0.753***   | 0.725      | 0.767***   | 0.725     |
|                    | (0.215)    | (0.350)   | (0.209)   | (0.335)   |
| Chi2               | 104.56***  | 152.13***  | 108.67***  | 149.93*** |
| Observations       | 611        | 611        | 611        | 611       |

*Notes:* ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses; the regression results for the share of land used for rubber in a household could be provided upon request.
TABLE A5  2SLS estimation results of models (1) using count variable

| Variables                      | Model (1): CDI_count 2SLS regression# |
|-------------------------------|----------------------------------------|
| (IV)RubberShare               | -1.165*** (0.602)                      |
| Other independent variables   | Controlled                             |
| Township dummy variables      | Controlled                             |
| Constant                      | 1.429*** (0.608)                       |
| F statistics                  | 26.37***                               |
| Observations                  | 611                                    |

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses; the regression results for the share of land used for rubber in a household could be provided upon request.

TABLE A6  2SLS estimation results of models (3), (4), (5) and (6) using count variables

| Variables                      | HDDI_count |
|-------------------------------|------------|
|                               | Model (3)  | Model (4)  | Model (5)  | Model (6)  |
| IV-RubberShare                | 3.354***   | 3.838**    | 3.244***   | 3.697***   |
|                               | (1.089)    | (1.249)    | (1.060)    | (1.209)    |
| CDI_count                     | 0.414      | 0.401***   | 0.401***   | 0.401***   |
|                               | (0.153)    | (0.149)    | (0.149)    | (0.149)    |
| PNI                           |            |            | 0.017      | 0.019      |
|                               |            |            | (0.012)    | (0.012)    |
| Other independent variables   | Controlled | Controlled | Controlled | Controlled |
| Township dummy variable       | Controlled | Controlled | Controlled | Controlled |
| Constant                      | 2.884***   | 2.291*     | 2.962***   | 2.400      |
|                               | (1.100)    | (1.258)    | (1.079)    | (1.228)    |
| F statistics                  | 3.53***    | 3.38***    | 3.46***    | 3.33***    |
| Observations                  | 611        | 611        | 611        | 611        |

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; standard errors are in parentheses; the regression results for the share of land used for rubber in a household could be provided upon request.