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Factors affecting farmers' adoption of and willingness to pay for biodegradable mulch films in China

Wei Yang [a,*], Jianling Qi [b,*], Yao Lu [b], Waranan Tantiwat [a], Jin Guo [c], Muhammad Arif [d]

[a] Faculty of Agribusiness and Commerce, Lincoln University, Commerce Building, Lincoln University, Christchurch 7647, New Zealand
[b] Yunnan Agriculture University, Kunming, Commerce Building, Heilongtan, Panlong District, Kunming, Yunnan Province 100191, China
[c] Agricultural Environmental Protection and Monitoring Center of Yunnan Province, Kunming 650201, China
[d] Department of Business Administration, Shaheed Benazir Bhutto University, Shaheed Benazirabad, Pakistan

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ABSTRACT

The technology of biodegradable mulch films (BDMs) is an environmentally-friendly substitute for polyethylene (PE) mulches in agricultural production. Given the technology is new to the market, it is not easy for farmers to adopt it. Additionally, farmers' decision on BDMs adoption is a multiple-stage process. To understand the decision process, this paper employs a double hurdle model to explore the factors affecting farmers' adoption and willingness to pay for BDMs using the sample data from China. The results show farmers follow a two-stage decision-making process, farmers have to overcome the first hurdle, i.e., adoption or non-adoption, and then decide how much they are willing to pay for BDMs. The role of technology-specific characteristics is more important than adopter-specific characteristics in the adoption of BDMs. Understanding the impact of factors on farmers' decision-making process can assist policymakers in designing programs, specifically tackling difficulties confronting farmers at different stages of decision-making.

1. Introduction

With the population growth and economic development, the global usage of plastic is rising significantly, and one of the main sources is plastic films used in agriculture for mulching (Jambeck et al., 2015). Different from the developed countries, where plastic mulch is mainly used with micro-irrigation, Chinese farmers use plastic mulch on a vast scale independent of micro-irrigation, but for water conservation, weed control, and higher production (Liu et al., 2014). So far, the use of plastic film mulching technology (mainly polyethylene (PE) mulches) in China has helped increase the yields of cash crops by 20% to 60% (Ingman et al., 2015), and its land area in plastic mulch has exceeded the world's total land area in micro-irrigation (Liu et al., 2014). However, the extensive use of plastic mulch films has caused severe environmental problems, because a large number of plastic mulch residues have not been appropriately recycled, directly leading to land and water pollution (Roy and Dutta, 2019). Particularly, in the high mountain areas of southwestern China, such as Sichuan and Yunnan province, the use of recycling machines is limited by the landscape, and thus recycling is associated with high labor demand and cost. Besides the geographical disadvantages, the plastic mulch film used in China is thinner than 0.008 mm which is significantly lower than the international standard (e.g., 0.02 mm in Europe and Japan) (Liu et al., 2014), making it more difficult to recycle the residues completely. According to a national survey in 2019, about one-third of plastic mulch films were left on the land, and 80% of plastic mulch films picked up from the land were either dumped without proper treatment or burned up (Yan and Liu, 2020). Consequently, although the usage of plastic mulch films has not been the largest compared to that of the northwestern area, the residues of plastic films in the southwestern provinces have been substantially high (Yan et al., 2016).

Therefore, besides encouraging farmers to adopt "best recycling practices", the Chinese government starts introducing biodegradable mulch films (BDMs) through demonstration farms, particularly in the

* Corresponding authors.
E-mail addresses: wei.yang@lincoln.ac.nz (W. Yang), qijianling@163.com (J. Qi).

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regions confronting the difficulty of recycling plastic film residues (e.g., southwestern China).[1] The BDMs can be introduced to soil at the end of the crop season and undergo the process of biodegradation by microorganisms, and no significant differences in crop yields between the use of PEs and BDMs. Meanwhile, there has been a change in crop choice from planting traditional food crops (e.g., rice and wheat) to cash crops, such as fruits and vegetables, mainly due to the high return of cash crops and policy supports from the central and local government (Huang et al., 2002). It is expected that the use of plastic films in southwestern China will continue to grow significantly (Yan et al., 2016). However, except for the demonstration farms operated by the government, few farmers have attempted to adopt BDM, mainly due to its high price which is about 3 times higher than PE films, and uncertainty about its efficiency that BDMs can be broken down easily and not having the expected functions (e.g., water conservation). It is, therefore, important to understand what drives or hinders farmers' adoption of the new technology, i.e., BDMs, to maintain crop production and productivity while reducing the environmental pollution of plastic film residues. Note that many smallholder farmers rely on subsidies for technology adoption in China (Ding et al., 2011; Yu and Jensen, 2010), and thus the adoption of BDMs may rely on the cost-effectiveness of the subsidy policy. Hence, prior to implementing any subsidy policy for the adoption of BDMs, policymakers need to know what determines farmers' adoption and willingness to pay for BDMs.

The existing studies show that farmers' adoption of sustainable practices and new technologies are contingent on a number of factors that are categorized into five broader categories, namely, farm- and farmer-specific characteristics, social and cultural norms, availability of support and resources, and perceived benefit. (e.g., Barham et al., 2015; Dumbrell et al., 2016; Mekonnen et al., 2020; Pannell et al., 2006; Weber, 2012). Farmers' adoption is also dependent on the types of practices and technologies, but the practice or technology itself has been under-emphasized (Pannell and Zilberman, 2020). A recent study by (de Oca Munguia and Llewellyn, 2020) states that more emphasis should be placed on analyzing the impact of technology characteristics in adoption analysis. Additionally, when targeting developing countries, the adoption analysis needs to consider the distinctive features when analyzing farmers' adoption decision-making (Pannell and Zilberman, 2020). For example, the majority of farms in developing countries are small-scale rather than large commercial farms (Llewellyn and Brown, 2020); the role of technologies in agricultural production is to enhance crops to further increase production and feed the poor people in developing countries (Huang et al., 2002). In that way, the impact of farm and farmer characteristics on adoption behavior may be dependent on the economic-historical context (Burton, 2014). Besides, farmers in developing countries usually lack an adequate understanding of new technologies due to the difficulty of accessing relevant information or training programs (Chen et al., 2013; Yang et al., 2021). Therefore, these two gaps addressed in the adoption literature lead us to consider the technology-specific characteristics and the distinctive features of the targeted region in China in analyzing the determinants of farmers' adoption of BDMs.

It was not until recent years that researchers attempted to address the issue of plastic pollution from agricultural production in China. The existing studies are from the field of agriculture and environmental science, mainly focusing on measuring the amount of residual mulch films for different crops and the impact on crop yields and greenhouse gas emissions. (e.g., (He et al., 2018; Zhang et al., 2016)). To our best knowledge, no study attempts to address plastic film pollution by understanding farmers' decision-making. Till now, the literature on the determinants of farmers' decision-making of sustainable agricultural practices in China has mainly focused on good management of fertilizer, pesticide, and water quality protection (e.g. (Pan et al., 2017; Sun et al., 2018; J. Wang et al., 2018; Wu and Hou, 2012)).

Therefore, this study aims to investigate determinants of farmers' choices of adoption and willingness to pay for BDMs in China by using a double hurdle model, where two mechanisms of decision-making (i.e., a direct rejection of technology and lack of resources) were used to capture zero willingness to pay (WTP) for BDMs. A sample of 1247 observations used in the study was sourced from a survey of farmers in Yunnan province, China, mainly because: 1) the usage of plastic mulch films is relatively high (Liu et al., 2014); 2) the central and local government starts promoting the use of BDMs. The contributions of this study are threefold. First, it addresses the importance of technology-specific characteristics and the impact on farmers' adoption of and WTP for the new technology, BDMs in our case. Second, the study considers farmers' adoption choices as a two-step process by using a double hurdle model, where farmers have to overcome the hurdle of whether or not to adopt and achieve the decision of how much to pay for the technology. Third, the results and findings of the study may contribute to the design of policy instruments in motivating the adoption of BDMs in China, for instance, to provide some insights into determining the value of substitutes for farmers' adoption of BDMs.

The rest of the paper is structured as follows. Section 2 specifies the conceptual analysis framework and econometric models used in the study. Section 3 presents the sample data and descriptive statistics of the variables used in the econometric models. The empirical results and findings are presented and discussed in Section 4, followed by the last section to conclude.

2. Method and data

2.1. Empirical analysis framework

The decision on whether or not to adopt a specific technology and how much to pay for that technology can be made jointly or separately (Gebremedhin and Swinton, 2003). Either way can cause the censored nature of farmers' WTP, with a large proportion of zeros presented in WTP. To deal with the zero-left censored WTP, the Tobit model (Tobin, 1958) and the extensions have been largely used to correct the problem of zero observations in a variety of research fields, in particular in analyzing consumer expenditure and demand (Gallet and List, 2003; Jones, 1989). This paper follows the analysis framework for zero-left censored WTP from consumer expenditure (Jones, 1989; Gillingham and Tsvetanov, 2019), and we conceptualize the sources of farmers' zero WTP for BDMs. As shown in Fig. 1, there are two main sources of zero WTP, including 1) direct rejection: the farmer directly rejects adopting BDMs due to the farmer's preferences over another mulching technology, for example, PE mulch films; 2) lack of resources: the farmer would like to adopt BDMs but cannot afford to pay it.

Therefore, the sources of zero WTP can be modeled as:

$$\begin{cases} Y_1^* = \beta_1^{\mathrm{T}} X_1 + \varepsilon_1 \\ Y_2^* = \beta_2^{\mathrm{T}} X_2 + \varepsilon_2 \end{cases}, \tag{1}$$

here the two equations represent the two decision mechanisms of zero WTP. Y_1^* and Y_2^* are latent variables representing farmers' adoption decisions and levels of WTP for BDMs; X_1 and X_2 represent the independent variables impacting the two decision mechanisms, associated with unknown vector coefficients β_1 and β_2; and $\varepsilon_1 \sim N(0,1)$ and $\varepsilon_2 \sim N(0,\ \sigma^2)$ are the random disturbances. Specially, for the technology rejection mechanism (first equation in Eq. (1)), if $Y_1^* < 0$, biodegradable

[1] Note that, although there are different types of mulching technologies (Anzalone et al., 2010), BDMs have been the most discussed mulching technology in the literature and in practice in China (Yan et al., 2016), (Ren, 2003, Yang et al., 2020, Li et al., 2017). Currently, the fully commercialised BDMs in China are starch-based biodegradable films, the percentage of weight loss from 0% in 0th month to 97.5% in the 3rd month – buried in soil and basically invisible with in 90 days (Liu et al., 2010).

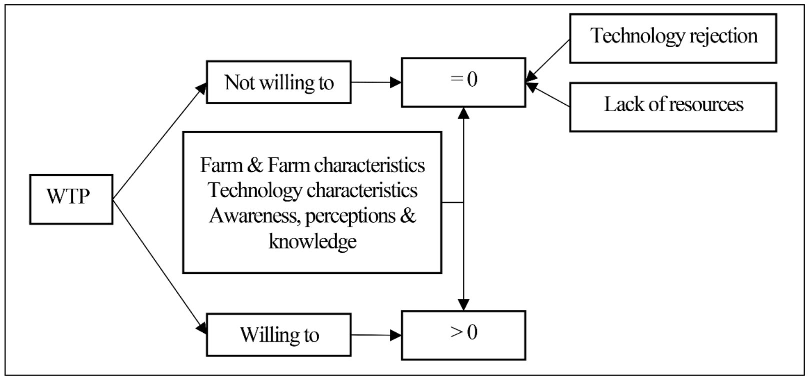

Fig. 1. The conceptual analysis framework of farmers' willingness to pay for BDMs.

mulching technology is not adopted as it is not considered by farmers as a relevant mulching technology. The second equation defines the levels of WTP for BDMs, and thus, if $Y_2^* < 0$, BDMs are not adopted because a negative WTP implied by resource constraints – labor, financial, and information support cannot be realized.

A double hurdle model is utilized to support the decision-making context conceptualized in Fig. 1. Originally formulated by John G, Cragg (Gragg, 1971), the double hurdle model is a parametric generalization of the Tobit model, in which two separate stochastic processes determine the decision to adopt and WTP for the technology (Jones, 1989; Yen and Jones, 1997). The model has been widely used in the literature on decision-making behavior across different research fields, such as marketing (consumer purchasing behavior) (Gao et al., 1995), economics (consumption analysis) (Jones, 1989), and social science studies (e.g., technology adoption) (Kaliba et al., 2020; Noltze et al., 2012). In the double hurdle model, Y_1^* and Y_2^* is used to model each decision process, and both hurdles have equations (shown in Eq. (1)) associated with the effects of the included factors as the independent variables. It assumes that farmers make two sequential decisions concerning adopting and WTP for a technology. First, the farmer decides whether or not to adopt the technology (the first hurdle). Second, the level of WTP that shall be used in purchasing the technology (the second hurdle). Hence, the first hurdle is a sample selection equation estimated with a Probit model and the second hurdle involves an outcome equation, which uses a truncated model to determine the WTP for BDMs. This second hurdle uses observations only from those respondents who indicated a positive WTP value of the use of a technology (Noltze et al., 2012; Martínez-Espiñeira, 2006).

The double hurdle model fits our problem of measuring crowding out because it allows for the fact that fixed costs may affect a farmer's adoption, but once the decision to adopt has been made, fixed costs may not affect the WTP decision. Each hurdle is conditioned by factors, such as farmer and farm characteristics (adopter-specific characteristics), technology-specific characteristics, and farmers' awareness, perceptions, and knowledge of the technology (shown in the middle of Fig. 1). Note that these independent variables may appear in both equations or either of one, and most importantly, a variable appearing in both equations may have opposite effects in the two equations (Jones, 1989; Yen and Jones, 1997).

Combining the log-likelihood function for zero and positive WTP observations, the sample likelihood function for this double hurdle model can then be written as (Jones, 1989):

$$\ln L = \sum_{i|Y_i=0} \ln L_i^- + \sum_{i|Y_i>0} \ln L_i^+, \quad (2)$$

where the first term estimates the status of Y_i (whether $Y_i = 0$ or $Y_i > 0$) capturing the contribution of a zero observation to the sample log-likelihood function and the second term estimates WTP (the exact value of Y_i, if $Y_i > 0$. Specifically,

$$\ln L_i^- = \ln\left(1 - \frac{\Phi\left(\beta_1^T X_{1i}, \frac{\beta_2^T X_{2i}}{\sigma}; \rho\right)}{\Phi\left(\frac{\beta_2^T X_{2i}}{\sigma}\right)}\right);$$

$$\ln L_i^+ = -\ln\sigma + \ln\Phi\left(\frac{e_i}{\sigma}\right) + \ln\Phi\left(\frac{\beta_1^T X_{1i} + \frac{\rho}{\sigma} e_i}{\sqrt{(1-\rho^2)}}\right) - \ln\Phi\left(\frac{\beta_2^T X_{2i}}{\sigma}\right), e = Y_i - \beta_2^T X_{2i}, \quad (3)$$

here, $\Phi(\bullet)$ denotes the probability density and cumulative distribution function of an N(0,1) random variable; and e is the "residual" of the fit representing the contribution of a positive observation to the log-likelihood function. Note the general model shown above nests several other formulations. We assume $\rho \neq 0$, indicating the adoption equation and WTP equation are correlated, i.e., ε_1 and ε_2 are not independent. However, it should be noted that the two-stage decision-making process may collapse if the assumption of $\rho \neq 0$ in the double-hurdle model does not stand. Hence, this limits the accuracy of the estimation of adoption probability and the associated WTP. Particularly, when $\rho = 0$, the double hurdle model may collapse to the independent Cragg model or the Tobit model nested within the independent Cragg model, with the further assumption that the adoption probability is 1. To avoid the collapse of the double-hurdle model, we need to conduct further test for the dependence of the adoption equation and WTP equation.

2.2. Data and variables

The study area of Yunnan province is located in the southwest of China, which has a strong agricultural focus. However, level land for agricultural production is scarce in Yunnan, with only 5% of the land under cultivation and more than 94% of the land categorized as mountainous areas (Ding et al., 2011). Given the geographical disadvantages, plastic mulch films have been extensively applied in Yunnan to help increase production and productivity. In addition, the types of crops planted in Yunnan determine the large use of plastic mulch films – besides having traditional food crops, such as rice, Yunnan's agriculture industry is well-known for its cash crops. In particular, the tobacco industry is the main "export" product and makes up a large part of the provincial GDP, and the flower industry takes up 50% of China's cut flower production. Additionally, in recent years, Yunnan has developed strong competitive potential in its fruit and vegetable industries due to its climatic and ecological advantages, and the high demand from the market further drives the expansion of planting areas of fruit and vegetable. The technology of plastic mulching helps maintain the high yield of tobacco and fruit and vegetable. Besides the difficulty of planting in upland plains and sloped hillsides, farmers find it hard to collect residual plastic mulch films. Hence, though not ranked at the top regarding the usage of PE films, the residues of plastic films in Yunnan have been substantially high (Yan et al., 2016). Being one of the BDMs "pilots", the local government has built demonstration farms to show and educate farmers regarding the utilization of BDMs. However, till now, the adoption rate of BDMs has almost been zero.

Data used in this study were collected through a survey from different crop growers in Yunnan province of China between July and November 2018.[2] The objectives of the survey are to analyze pollution sources of agricultural production and understand the current status of using plastic mulch films and farmers' adoption and pay for BDMs. The design of the questionnaires for the survey has undergone two stages. First, we conducted a pilot survey in three randomly chosen villages of Yunnan. 36 farmers were randomly chosen and interviewed by trained interviewers in person. The results of the pilot study provide a thorough understanding of the utilization of plastic mulch films in the context of Yunnan, and the initial questionnaire was tested and adjusted accordingly. Based on the results of the pilot study, a structured farm and household questionnaire was finalized and used in the second stage survey. Several trained interviewers were sent out to conduct face-to-face interviews with 1358 farmers randomly chosen from 128 villages out of 26 counties in Yunnan. This provides a final sample of 1247 valid questionnaires.[3] Specifically, we collected information about farmers' adoption and willingness to pay for BDMs, their perception and knowledge of the plastic mulching technology for both PE mulch films and BDMs, and farm and farmer characteristics (e.g., farm size, age, and income). Table 1 presents a descriptive and statistical summary of the variables included in the study.

There are two outcome variables (dependent variables), adoption and WTP, to be included in the two equations of the double hurdle model. Fig. 2 shows a clear pattern of the zero-left censored WTP, with 195 farmers chose not to adopt BDMs. The average per kg WTP for BDMs was found to be 13.7 China yuan among the farmers who are willing to adopt BDMs. Although 83% of farmers stated they are willing to adopt BDMs, when all the zeros (not willing) are included in calculating the average WTP, we got a lower per kg WTP of 11.6 China yuan.

The potential determinants of farmers' adoption and WTP are categorized into three groups of independent variables, including farm and farmer characteristics, technology-specific characteristics, and farmers' awareness, perception, and knowledge of plastic mulching technology. Farm and farmer characteristics include demographic factors, such as farmers' age, gender, ethnicity, education, and income level, as well as farm-related variables of farm type, farm size, and types of crops planted. Overall, as shown in Table 1, farmers in the sample are mainly male with a relatively low education level, and the majority of the farms are small-scale, with a large proportion of them planting tobacco and fruit and vegetables. Technology-specific characteristics are closely related to farmers' awareness and knowledge of BDMs. In our case, the efficiency of BDMs is highly valued by farmers followed by the attribute of price, and only a small proportion of farmers (21%) are aware of any forms of promotions for the adoption of BDMs. Note we included the variables that are related to PE mulches, given that BDMs are seen as an alternative technology to PE mulches to be adopted in the future. Although the majority of farmers notice the negative impact of PE mulches on the environment, about 61% of farmers have maintained the same level of PE usage and 28% have it increased in the past five years. This is mainly explained by their perceptions of the usefulness of plastic mulching technology in agricultural production, with approximately 96% of farmers seeing the technology as important. Lastly, getting a subsidy for recycling plastic residues and training opportunities may also affect their decisions on using BDMs.

Table 1
Descriptions and descriptive statistics of the variables.

Variables	Description	Mean	S.D.
Outcome variable			
Adoption	Farmers' choices of adopting degradable mulch films, =1 to adopt, = 0 not to adopt.	0.83	0.38
WTP	Farmers' willingness to pay for degradable mulch films in China yuan.	13.7	8.3
Independent variable[a]			
Age	Age of the farmer (owner/ manager) in years[b].	47.6	10.03
Male	Dummy variable representing gender =1 Male, = 0 Female.	0.75	0.43
Ethnicity	Dummy variable =1 Han, = 0 Others.	0.77	0.42
Education	The education level defined as schooling years.	6.84	3.54
Labor	The number of labors employed by the farm.	2.61	1.05
Farm type[c]	Dummy variable, =1 Small farm, =0 Others.	0.95	0.22
Farm size	Total planting area measured in Mu.	18.29	32.27
Household income	Total household income from all source measures in Chinese yuan (CNY).	63,252.7	245,753
% Agricultural Income	Percentage of household income from agriculture.	79	39
Main crop	Categorical variables representing the main crops planted.		
Food crop	=1 if mainly planting food crops, such as rice and wheat, =0 otherwise (set as the base).	0.21	0.42
Tobacco	=1 if mainly planting tobacco, =0 otherwise.	0.38	0.41
Fruit & vegetable	=1 if mainly planting fruits and vegetables, =0 otherwise.	0.37	0.28
Other crops	=1 if mainly planting other crops, such as flowers and trees, =0 otherwise.	0.04	0.11
Mulch usage	Categorical variables representing changes in PE film usage in the past five years,		
Mulch usage – decreased	=1, if the usage of PE films has decreased in the past five years, =0 otherwise (set as the base).	0.11	0.32
Mulch usage – same	=1, if the usage of PE films has had no change in the past five years, =0 otherwise.	0.61	0.60
Mulch usage – increased	=1, if the usage of PE films has increased in the past five years, =0 otherwise.	0.28	0.42
Recycle subsidy	The farmer receives subsidies for recycling plastic mulch films, =1 Yes, = 0 No.	0.34	0.47
Training	Farmer received training for film mulching technology, =1 Yes, = 0 No.	0.39	0.49
BDMs attributes	Categorical variables representing the most important attribute that affect farmers' choice of different plastic mulch films.		
BDMs – Price	=1 price is regarded as the most important attribute for purchasing plastic mulch films, = 0 otherwise (set as the base).	0.23	0.42
BDMs – Efficiency	=1 efficiency is regarded as the most important attribute for purchasing plastic mulch films, = 0 otherwise.	0.58	0.49
BDMs – Brand	=1 brand is regarded as the most important attribute for purchasing plastic mulch films, = 0 otherwise.	0.12	0.40
BDMs – others	=1 other attributes, such as quality, are regarded as the most important	0.07	0.24

(continued on next page)

[2] The survey of the study is approved by the human ethics committee of Yunnan Agricultural University in 2018.
[3] Note that 111 questionnaires were excluded as they are either incomplete or erroness.

Table 1 (*continued*)

Variables	Description	Mean	S.D.
	attribute for purchasing plastic mulch films, = 0 otherwise.		
BDMs Promotion	The farmer is aware of promotions for adopting BDMs from the government and/ or industry, 1=Yes, 0=No.	0.21	0.41
Damage to environment	Perceived negative impact of PE mulch films on the environment, =1 Yes and = 0 No.	0.79	0.41
Usefulness to agriculture	Categorical variables representing farmers' perception of the usefulness of plastic mulch film to agricultural production.		
Usefulness – not important	=1, plastic mulch film is regarded to be not important to agricultural production, =0 otherwise (set as the base)	0.04	0.23
Usefulness – important	=1, plastic mulch film is regarded to be important to agricultural production, =0 otherwise.	0.32	0.46
Usefulness – very important	=1, plastic mulch film is regarded to be very important to agricultural production, =0 otherwise.	0.64	0.56

Note:
[a] County effects are controlled and included as categorical variables (10 countries in total).
[b] The variables of farmer characteristics are about the owner (for small-scale farms) or owner/manager (for large farms) who make the primary decision-making of agricultural production of the farm.
[c] Small-scale farms are those with effective land areas less than 0.5 ha (7.5 mu).

3. Empirical results

For comparison purposes, we report the results from the double hurdle model and Tobit model regarding factors affecting farmers' WTP for BDMs in Table 2: the first two columns present results from the double hurdle model for adoption and WTP and the third column presents the results from the Tobit model. For the factors affecting WTP (the second and third columns), the coefficient estimates of the double hurdle model are different from those of the Tobit model at various degrees. Notably, for example, the main crop type – tobacco is found to have no effect on farmers' WTP for BDMs in the double hurdle model but is negatively significant in the Tobit model; for the variables of "main crop", statistically significant effects are detected in the Tobit model but not in the double hurdle model. The differences in the estimation results of the two models indicate the Tobit model cannot capture the technology selection mechanism shown in Fig. 1, where farmers first choose to adopt BDMs and then decide their WTP for the technology. Once they go over the first hurdle, some factors affecting the first hurdle may not affect the second hurdle of WTP. Note that the correlation coefficient ρ is positive and statistically significant, indicating the two hurdles are positively correlated, and thus the two selection mechanisms need to be considered jointly. In addition, the values of Loglik, AIC, and BIC support choosing the double hurdle model to estimate farmers' WTP for BDMs. Hence, our interpretation of the results is based on the double hurdle model: in hurdle 1, farmers decide whether or not to adopt BDMs, and if one chooses to adopt, hurdle 2 considers one's WTP associated with per kg BDMs.

For the variables of farm and farmer characteristics, the demographic factors, such as age, gender, and ethnicity, and farm characteristics, including farm size, farm type, and the number of labors, have no impact on farmers' adoption of BDMs. However, education is found to be an important determinant of both farmers' adoption and WTP. The positive effect of education indicates that farmers with higher education levels tend to be more likely to adopt BDMs and are willing to pay more for the use of BDMs. This finding is consistent with many existing studies on technology adoption for farmers across the developed and developing world (Dumbrell et al., 2016; Pannell et al., 2006; Ma et al., 2012). For other farm characteristics, income and the type of crop, are found to only influence farmers' adoption of BDMs. Farmers with higher household income are more likely to adopt BDMs, but they are less likely to adopt BDMs if the percentage of agricultural income increases. Intuitively, it is easier for farmers with higher household income to try out new technologies, given the high price of BDMs and the fixed cost associated with learning and training for the adoption of BDMs

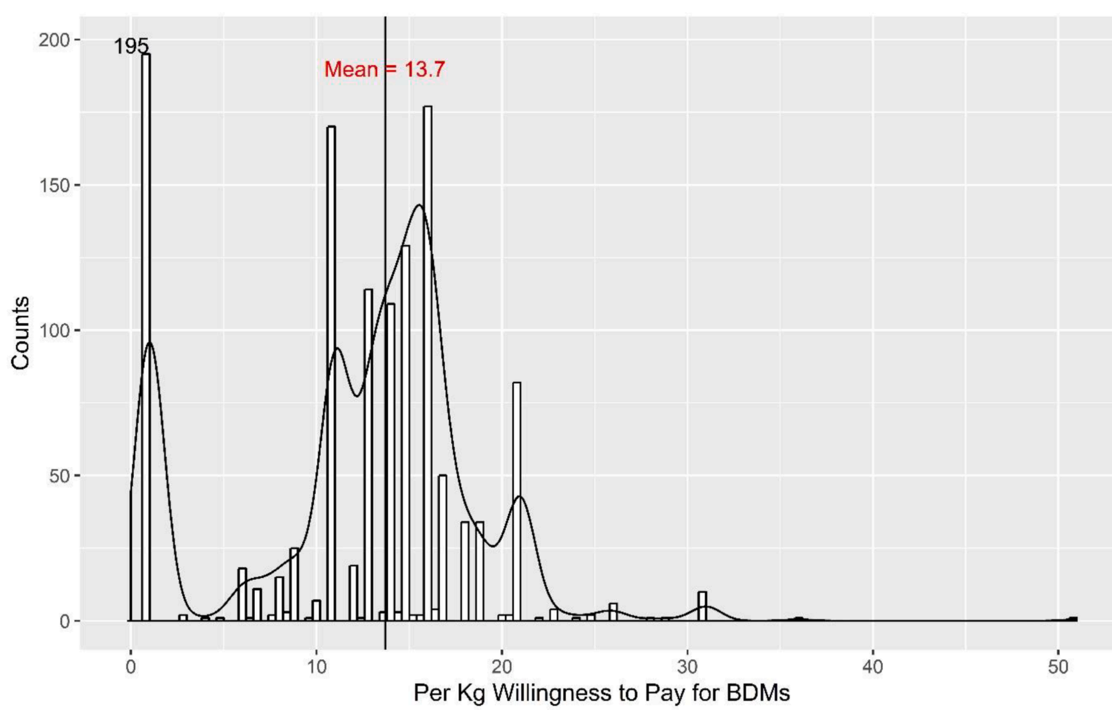

Fig. 2. The distribution of farmers' willingness to pay for BDMs.

Table 2
Double-hurdle and Tobit model estimation results of factors influencing WTP for BMDs.

Factors[b]	Double-hundle model[a] WTA (Probit estimator $n = 1247$)	WTP (Truncated Normal estimator $n = 1052$)	Tobit model WTP ($n = 1247$)
Intercept	3.07***(0.73)	0.94***(0.10)	2.61*** (0.47)
Age	0.0002(0.005)	0.0001(0.001)	0.001 (0.004)
Gender	0.04(0.11)	−0.01(0.03)	−0.07 (0.08)
Ethnicity	−0.14(0.11)	−0.06(0.07)	−0.12 (0.11)
education	0.03**(0.014)	0.01***(0.003)	0.03*** (0.01)
labor	0.04(0.04)	0.01(0.01)	0.03(0.03)
Farm type	−0.158(0.25)	−0.10(0.06)	−0.14 (0.18)
Farm size	0.003(0.002)	0.001(0.0004)	0.01(0.001)
Log (Household income)	0.13***(0.05)	0.0001(0.0005)	0.04(0.04)
% Agricultural Income	0.23*(0.09)	0.01(0.03)	0.12(0.08)
Main crop - Tobacco	−0.47***(0.12)	−0.04(0.03)	−0.41*** (0.09)
Main crop - Fruit & vegetable	0.21**(0.08)	0.02(0.13)	0.25** (0.09)
Main crop - others	−0.26*(0.11)	0.01(0.24)	−0.34* (0.15)
Mulch usage – same	0.25(0.16)	0.03(0.04)	−0.16 (0.12)
Mulch usage – increase	0.49**(0.18)	0.09**(0.04)	−0.25* (0.13)
Recycle subsidy	−0.05(0.12)	−0.04(0.03)	0.03(0.09)
Training	0.55***(0.11)	0.05***(0.01)	0.37*** (0.08)
Damage to environment	0.27*(0.12)	−0.02(0.03)	0.15(0.09)
Usefulness – important	1.25***(0.47)	0.16***(0.06)	0.32*(0.19)
Usefulness – very important	1.34***(0.47)	0.13**(0.06)	0.37*(0.19)
BDMs Promotion	−0.02(0.11)	−0.02(0.03)	−0.08 (0.08)
BMDs attributes - Efficiency	–	−0.08***(0.02)	−0.05*** (0.01)
BMDs attributes - Brand	–	−0.001(0.02)	−0.02 (0.08)
BMDs attributes - others	–	−0.13***(0.03)	−0.03 (0.09)
ρ	0.84***(0.03)		–
Loglike	−734.43		−1860.9
AIC	−754.91		7644.48
BIC	−395.91		7767.56

Note:
[a]This is the double-hurdle model assuming the errors of two equations are correlated, i.e., $\rho \neq 0$.
[b]Standard error in parathethese and $*p<0.1$; $**p<0.05$; $***p<0.01$.
[c]The variables of BDMs attributes are only included in the second hurdle of the double hurdle model.

(Barham et al., 2015; Marí et al., 2019). However, farmers who mainly rely on agricultural income may be concerned about the high cost of BDMs and find it risky to invest in BDMs, compared to those who have more off-farm income (Gedikoglu et al., 2011).

Farmers' adoption of BDMs differs across types of crops planted. Compared to food crop growers, tobacco and other crop growers are less likely to adopt BDMs, and fruit & vegetable growers are more likely to adopt BDMs. Sastre *et al.* (2017) (Sastre et al., 2017) state that farmers often relate themselves to the crops they grow, and some are proud of growing the crops for generations – their decision-making of adopting technology and practice is dependent on the types of crops they grow. In our case, the difference across types of crops indicates a direct technology rejection of tobacco and flower growers. As the pillar industry of Yunnan's economy, the tobacco industry has its own supply chain and operation system to manage suppliers (tobacco growers). For instance, to ensure the quality and quantity of tobacco production, the industry provides a variety of support for tobacco growers, including providing low-price PE mulch films, training, and subsidy (Huang et al., 2020). Similarly, flower cooperatives provide flower growers with strong support, including technology training and networking. Given the support they obtain from the industry, the two groups of farmers are less likely to change from using PE mulch films to BDMs. Table 3 shows the predicted adoption (the probability) and WTP (per kg BDMs in China Yuan) across the groups of growers at the sample means of independent variables. Based on the results, the estimated probability of adopting BDMs for tobacco growers and other crop growers is relatively low compared to food crop growers and fruit & vegetable growers. Regarding the predicted values of WTP, fruit & vegetable growers have the highest WTP whilst tobacco growers have the lowest. However, regardless of the types of growers, the estimated WTP is similar to the per kg price of PE films (around 10–14 China Yuan), meaning it is far less than the market price of BMDs (22–28 China Yuan).

Compared to farm and farmer characteristics, more technology-specific variables are found to affect farmers' adoption of and WTP for BDMs. Higher usage of PE mulch films increases the propensity for farmers to adopt BDMs, and farmers' WTP for BDMs is higher if they have had an increase in mulch usage in the past five years. Training is found to be an important determinant of farmers' adoption and WTP; those who obtain training for mulching technology (offered by the government or industry) are more likely to adopt and pay more for BDMs. This finding is consistent with Goldberger et al. (Goldberger et al., 2019), the majority of strawberry growers in the USA express their interest in learning more about BDMs, regardless of region. Training in the form of workshops, field days on demonstration farms, or "farmer school" are generally regarded as an important pathway of knowledge transformation: experts can directly provide farmers with information and knowledge about new technologies; farmers can network and share knowledge with other farmers, increasing their confidence in adopting new technologies or practices (Baird et al., 2016). Receiving a subsidy for recycling residual plastic films does not affect either farmers' adoption or WTP.

The attributes that are directly related to BDMs may influence farmers' choices of whether or not to adopt BDMs and how much to pay for BDMs, which is in line with the results of the existing studies in developed countries, such as the USA (Chen et al., 2020; Velandia et al., 2020). For example, based on empirical analysis in the USA, (Chen et al., 2020) find that farmers in the USA may associate the greatest value with BDM attributes that offer better production and environmental performance, such as higher productivity and better soil health. Similarly, (Velandia et al., 2020) find price of BDMs and cost of using BDMs are the key factors that influence fruit and vegetable farmers' adoption of BDMs in Tennessee, USA. Interestingly, our results show that farmers who see price as the most important attribute are more likely to adopt and pay more for BDMs than those who value the other attributes of BDMs, such as efficiency and quality. This finding indicates that, when price is the focus of BDMs, farmers may have already overcome the adoption barrier

Table 3
Predicted WTA and WTP by types of main crops.

	WTA (probability)	WTP (per kg BDMs)
Food crop	0.87	11.83
Tobacco	0.78	10.26
Fruit & vegetable	0.89	14.42
Other crops	0.76	11.33

(e.g., technology barrier), whilst farmers who value efficiency and quality the most are still skeptical about the technology. Brand and farmers' awareness of the promotion of BDMs has no influence on their adoption and WTP.

All the perception variables are found to influence farmers' adoption but not WTP. Note that, if farmers are aware of the negative impact of PE mulch films on the environment, they tend to adopt an environmentally friendly technology, i.e., BDMs. Their perceptions of the usefulness of the mulching technology increase the likelihood of BDMs adoption – the more important they feel about plastic film mulching in agricultural production the more likely they adopt BDMs. This reflects the natural embedded connection between perception/ awareness and behavior change (Ajzen, 1991; Y. Wang et al., 2018). However, high perception and/ or awareness may not necessarily lead to high WTP.

4. Discussion and conclusion

This paper uses a double hurdle model to empirically analyze the determinants of farmers' adoption of BDMs in China, using the survey data from Yunnan province. It is the first attempt that explores both farmers' adoption of and WTP for BDMs. Considering using BDMs is relatively new in China and many other countries, understanding the different factors that affect farmers' decision-making is important for promoting the use of BDMs in agriculture. The double hurdle model has the advantage of modeling farmers' decision-making in two stages. We address the impact of three groups of factors, i.e., farm and farmer characteristics, technology-related and perception - and awareness-related variables, on farmers' adoption and WTP. Our results show that farmers have to overcome the first hurdle, i.e., choose to adopt or not adopt, and then decide how much they are willing to pay for BDMs. Notably, we find that education, training, and preference over the attributes of BDMs significantly affect farmers' adoption and WTP. However, once farmers decide to adopt BDMs, many other factors that affect their adoption, such as income and crop type, may not affect their WTP for BDMs.

The results and findings may lead to several policy implications. To begin with, it is important that policymakers understand the key barriers of farmers' adoption prior to investigating their WTP for BDMs. The double hurdle modeling process provides some insights into better targeting farmers' needs at different decision-making processes. Second, the role of technology-specific characteristics is more important than adopter-specific characteristics in the adoption of BDMs in China, and possibly in other developing countries. It is not until recent years that BDMs have been introduced to farmers as a substitute for PE mulching technology. Hence, to promote the adoption of BDMs, more emphasis should be placed on providing information and knowledge about technology characteristics (de Oca Munguia and Llewellyn, 2020). No matter where they are based, farmers need to have a good understanding of the technology before making decisions (Goldberger et al., 2019). Notably, training is an ideal investment for both policymakers and farmers. Besides offering information, it provides opportunities for farmers, experts, and policymakers to exchange and share knowledge, and experience, and most importantly, to build trust that contributes to farmers' adoption of BDMs (Yang et al., 2021; Baird et al., 2016). Additionally, given the price of BDMs is generally higher than PE mulch films, participating in training may motivate farmers to invest more (i.e., higher WTP) in the new mulch films that are environmentally friendly and not requiring recycling efforts. Lastly, policymakers need to consider the difference in WTP amongst different crop growers, and the overall WTP (11 – 14 RMB) for BDMs is much lower than the market price (22 – 28 RMB). The government may promote the adoption of BDMs for tobacco and flower growers through tobacco firms and flower cooperatives that provide technical training and support to farmers. Similarly, when targeting other areas or countries with high usage of plastic mulch films, the local government has to relate the promotional policy to the specific crops grown by farmers.

Note that the study is limited by the cross-sectional nature of the sample data and the dynamics of farmers' adoption behaviors across years cannot be captured. Future studies may conduct multi-year surveys to replicate the empirical analysis proposed by the study to examine behavior changes in farmers' adoption of and WTP for BDMs. Besides, the results and findings are based on the data of one province that may represent the southwestern provinces but not all regions in China. However, the design of the study is robust as we included the variable "recycle subsidy" in the empirical analysis – for farmers in the northern regions, it would be much easier to adopt recycling machines for collecting PE residues due to larger and flatter farmlands. Hence, the effect of subsidy for recycling can be significant on their adoption and WTP for BDMs. When more data are available (e.g., data about the northern part of China), future studies may consider comparing the effect of subsidies for recycling on farmers' adoption behaviors between the southern and northern parts of China, where farmers from the north may be more likely to have a positive response to the subsidy for recycling PE residues due to the ease of using recycling machines on larger and flatter farmlands. Lastly, we find no relationships between the age of the farmer and the adoption and WTP for BDMs. Future studies may consider using farming experience (in years) as a potential substitute in the empirical analysis.

Declaration of Competing Interest

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

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