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Impact of pesticide outsourcing services on farmers' low-carbon production behavior

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Introduction: Promoting low-carbon development in agriculture is crucial for achieving agricultural modernization. One practical issue worth studying is whether outsourcing services can encourage farmers to adopt low-carbon production practices. This study analyzes the impact of pesticide outsourcing services on the low-carbon production behavior of farmers to provide China with practical recommendations.

Methods: This empirical study investigates the impact of pesticide outsourcing services on farmers' low-carbon production behavior using survey data from 450 rice growers in the Ningxia and Shaanxi provinces by endogenous switching regressions (ESR) model.

Results and Discussion: Results showed that 1) outsourcing services have a significant negative impact on farmers' manual weeding behavior, leading to a reduction in the frequency of manual weeding; 2) outsourcing services have a significant positive impact on farmers' herbicide application behavior. In other words, participation in outsourcing leads to excessive pesticide application; 3) outsourcing services do not support a green and low-carbon production model where manual weeding replaces herbicide application. Due to the imperfect development of the outsourcing market in China, especially in the northwest region, the construction of outsourcing service system is lagging, and it is difficult for non-professional outsourcing services to play a driving role in green and low-carbon production for farmers, who will often choose the lower-cost mechanical application for maximum profit. The policy implication of this study is the need for a comprehensive and objective understanding of the impact and role of pesticide outsourcing services on farmers' low-carbon production behavior. This understanding can help improve the market, policy, and other external environments for farmers to participate in outsourcing, ultimately promoting the sustainable development of green and low-carbon agriculture. This paper adds to the discussion of pesticide outsourcing services and farmers' low-carbon production by drawing different conclusions from previous studies, providing a fresh foundation for policy-making.

KEYWORDS

outsourcing services, farmers' low-carbon production behavior, pesticide reduction, endogenous switching regressions (ESR) model, low-carbon agriculture

1 Introduction

The disadvantages of the traditional high-carbon agricultural development model are increasingly obvious, which has a negative impact on food security, farmers' income, ecological stability and sustainable development (Luo et al., 2022). Farmers' low-carbon production behavior is of great significance in achieving the development concept of harmonious coexistence between humans and nature. However, currently, the low-carbon production level of farmers is low, and there is excessive use of chemical inputs (Zhang et al., 2015). From 1991 to 2019, pesticide use in China increased from 765,300 tons to 1,391,700 tons, leading to various environmental and human health problems (Tariq et al., 2007). It is evident that reducing the use of harmful inputs in the application process and transitioning to green and low-carbon alternatives such as manual weeding is crucial for promoting low-carbon agricultural production behavior. In the "Central Document No. 1" of 2023, it is proposed to accelerate the promotion and adoption of agricultural input reduction and efficiency technologies, as well as the development of green and low-carbon agriculture. Meanwhile, the report of the Party's 20th National Congress has called for "actively and steadily promoting carbon peak and carbon neutrality." In light of these objectives, it is urgent matter to study and address how to transform and upgrade from high-carbon agriculture to low-carbon agriculture, promote farmers' low-carbon production behavior, and reduce pesticide usage.

However, several obstacles hinder the promotion of pesticide reduction, including farmers' lack of risk awareness, resistance to change, inadequate perception, and the presence of unregulated retailers (Chen et al., 2013; Mohanty et al., 2013; Yang et al., 2014; Li et al., 2021; Young et al., 2022). China urgently needs the intervention of third-party organizations to build a robust service mechanism (Li et al., 2021). Existing researches on pesticide reduction primarily foucus on third-party entities such as cooperatives, social services, and financing services (Sun et al., 2019; Levesque et al., 2021; Yu et al., 2021; Zhang et al., 2023; Tambo et al., 2023). The 14th Five-Year Plan for the Green Development of Agriculture in China emphasizes the cultivation of social service organizations and professional cooperatives to promote pesticide reduction and increase efficiency. In recent years, with the development and expansion of outsourcing services in the field of agriculture, researches have also emerged on the study of outsourcing services and pesticide reduction, with varying perspectives. Some scholars argue that outsourcing services have a positive impact on pesticide reduction. They suggest that the introduction of outsourcing services effectively disperses the transaction risks associated with factor markets (Liang et al., 2020), enhances farmers' knowledge and technical capabilities through knowledge training initiatives (Pan et al., 2017), and reduces the reliance on chemical inputs. On the other hand, some scholars argue that outsourcing service has a negative effect on pesticide reduction. They highlight the imperfect state of the outsourcing service market in China, where participation in outsourcing services has not curbed the excessive pesticide use by farmers (Wang and Gu., 2013; Cai and Liu., 2019).

While many studies have examined the impact of outsourcing services on pesticide reduction, discrepancies persist. Moreover, few studies have specifically focused on the influence of outsourcing services on the adoption of green and low-carbon alternatives. Therefore, this study aims to address this gap by examining the influence of pesticide outsourcing services on farmers' low-carbon production behavior, with a particular focus on manual weeding and herbicide application practices. Subsequently, targeted policy recommendations will be proposed to promote the development of low-carbon agriculture. This study contributes to the research field mainly in three ways. Firstly, it continues the investigation of the impact of outsourcing services on pesticide reduction, aiming to resolve the disparities found in previous studies. Secondly, unlike most existing research that adopts a macro perspective on pesticide reduction, this study focuses on the micro perspective, specifically examining weeding practices. By selecting manual weeding behavior and herbicide application behavior as research objects, this study fills a crucial gap in the literature. Lastly, the endogenous transformation model (ESR) is utilized to explore the interrelationships between variables, providing a deeper understanding of the mechanisms at play.

2 Literature review and hypothesis development

Climate change will affect cereal production, and farmer behavior can mitigate climate change (Guan et al., 2021; Chandio et al., 2022a; Chandio et al., 2022b; Chandio et al., 2023). The low-carbon production behavior of farmers refers to the production behavior of reducing greenhouse gas emissions and achieving the goal of "low energy consumption, low pollution and low emission" through strategies such as reducing fertilizer application intensity, reducing pesticide usage and improving straw utilization efficiency (Jiang et al., 2018). In the application process, manual weeding instead of pesticide application can effectively reduce pesticide usage.

Specialized production has been found to facilitate pesticide reduction (Yue et al., 2023), and outsourcing organizations are typically more professional than smallholder farmers. Outsourcing service providers possess greater capital strength and technical ability to invest in agricultural production, helping overcome limitations in capital endowments (Zhang et al., 2022). By purchasing outsourcing services, farmers can save labor, promote non-agricultural employment, allocate household labor force elements more efficiently, reduce the cost of agricultural production, and alleviate the problem of insufficient green production capacity, thus promoting low-carbon production behavior (Chen et al., 2023; Li et al., 2023). For outsourcing service organizations, pesticide reduction can enhance their social reputation capital due to the influence of the reputation effect. (Vatn et al., 2020). Additionally, the familiarity and high level of trust established through multiple transactions between farmers and outsourcing service providers in the application process contribute to green and low-carbon production (Zhang et al., 2023). However, due to the imperfect development of China's outsourcing market, especially in the construction of the outsourcing service system in northwest China, non-professional outsourcing services struggle to facilitate farmers' green and low-carbon production.

Regarding weeding, as farmers pursue green production, which requires a significant labor force (Wang et al., 2023), manual weeding becomes more labor-intensive compared to herbicide application. However, manual weeding is limited by labor availability and cost. Field investigations have revealed that most local outsourcing service organizations are private providers with

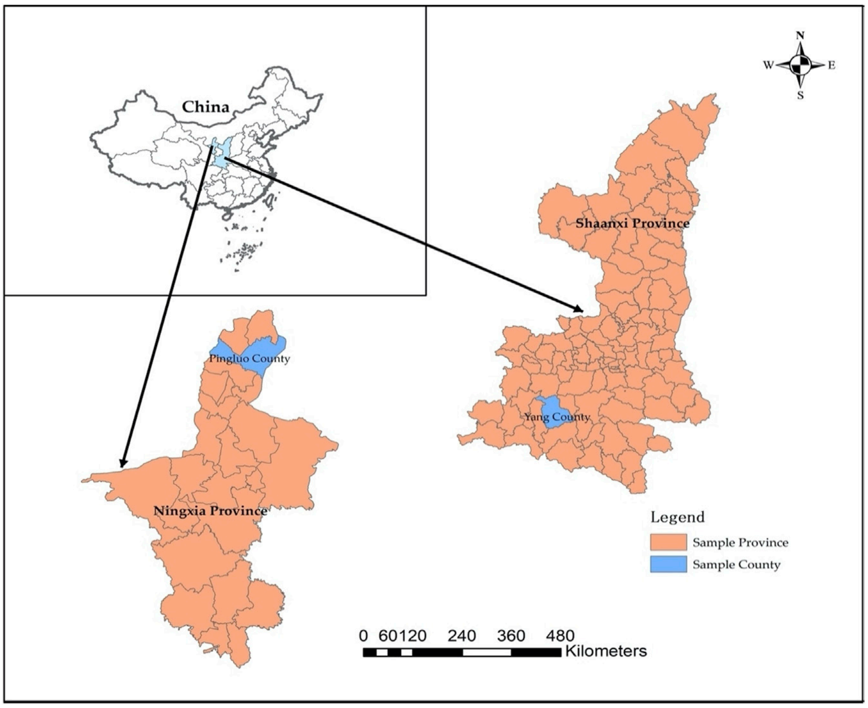

FIGURE 1
The location of the investigated area in this study.

limited numbers and high labor costs. Principal-agent behavior in outsourcing can lead to opportunism, causing harm to farmers, especially given the natural nature of agriculture, which makes comprehensive supervision challenging (Zhang and Qian., 2017; Cai and Liu, 2019; Nwajei et al., 2022). In the application process, outsourcing service organizations may prioritize using low-cost drones for herbicide spraying to maximize profits. Field investigations have shown that individual farmers retain decision-making power over herbicide application in outsourcing services. Some farmers, when given decision-making authority, may choose excessive herbicide application to avoid reduced production (Liu and Huang., 2013; Chèze et al., 2020). Based on these observations, the following hypotheses are proposed:

H1: Pesticide outsourcing services contain manual weeding.

H2: Pesticide outsourcing services contribute to excessive herbicide application.

3 Materials and methods

3.1 Data source and study area

In this study, the Yellow River Basin, specifically Ningxia and Shaanxi provinces, is selected as the investigation area due to its significant role in China's ecological construction and the national strategy of ecological protection and high-quality development of the Yellow River basin. The choice of these provinces is motivated by the low level of low-carbon agriculture development in Northwest China, which necessitates stronger ecological construction efforts. Additionally, the outsourcing service system in the region is relatively underdeveloped, and the outsourcing market is imperfect. Therefore, studying the impact of outsourcing services on farmers' low-carbon production in this context becomes crucial.

The analysis in this study utilizes sample survey data collected by the research group in October 2021 from the main rice-producing areas of Ningxia and Shaanxi provinces. The sample consists of 455 randomly selected farmers from seven townships in the two provinces and two counties. The sampling process involves stratification, where the population is divided into sub-groups (first-order units) and further divided into smaller units (second-order units). These units are then selected as investigation units following the principle of randomness. The survey methodology employed face-to-face question-and-answer surveys. After eliminating questionnaires with missing key variables, the study obtained 450 valid samples that meet the requirements of the research. Figure 1.

3.2 Econometric model

The application process, whether outsourced or not, is influenced by farmers' "self-choice," which can be influenced by unobservable factors such as management abilities. Consequently, the outsourcing decision of farmers cannot be considered an exogenous variable. To address these issues, the endogenous transformation model, proposed by Maddala. (1983), offers distinct advantages. This model is a modification of the

Heckman selection model, which can only analyze the relationship between two variables and is prone to sample selection bias. The endogenous transformation model is primarily employed to account for observable and unobservable factors, addressing selectivity bias and endogeneity concerns. By utilizing an endogenous transformation model, it is possible to estimate the equation that illustrates the impact of pesticide outsourcing services on farmers' manual weeding behavior. Similarly, the equation capturing the effect of pesticide outsourcing services on farmers' herbicide application behavior can be estimated as well, although it is unnecessary to delve into its specific details in this context.

The equation is divided into two stages: the first stage is a decision equation estimating the adoption behavior of the outsourcing services, see Eq. 1; the second stage is an outcome equation estimating the manual weeding behavior of the outsourced and non-outsourced farmers, see Eqs 2, 3 respectively.

$$\boldsymbol{O_i = \gamma Z_i + \mu_i} \tag{1}$$

$$\boldsymbol{Y_{i1} = \beta_{i1} X_i + \varepsilon_{i1}, if\ O_i = 1} \tag{2}$$

$$\boldsymbol{Y_{i0} = \beta_{i0} X_i + \varepsilon_{i0}, if\ O_i = 0} \tag{3}$$

In the above, $O_i = 1$ indicates that the farmer used the outsourcing service; otherwise, $O_i = 0$; Z_i denotes the explanatory variable influencing the farmer's choice of outsourcing; Y_{i1} and Y_{i0} are the average number of days of manual weeding per unit area (mu) for outsourced and non-outsourced farmers, respectively; X_i is the explanatory variable; and ε_{i1} and ε_{i10} are the random disturbance terms. After estimating Eq. 1, the inverse Mills ratio λ_{i1}, λ_{i0} and the covariance of the error term $\sigma_{\mu 1} = cov(\mu_i, \mathcal{E}_{i1})$, $\sigma_{\mu 0} = cov(\mu_i, \mathcal{E}_{i0})$ were calculated, and brought into Eqs 2, 3 to obtain:

$$\boldsymbol{Y_{i1} = \beta_{i1} X_i + \sigma_{\mu 1}\lambda_{i1} + \zeta_{i1}, if\ O_i = 1} \tag{4}$$

$$\boldsymbol{Y_{i0} = \beta_{i0} X_i + \sigma_{\mu 0}\lambda_{i0} + \zeta_{i0}, if\ O_i = 0} \tag{5}$$

The ESR model treats the unobservable variable as a missing value; after controlling for selectivity bias arising from the unobservable variable via λ_{i1} and λ_{i0}, the error terms ζ_{i1} and ζ_{i0} satisfy the conditional zero-mean hypothesis, and the correlation coefficients of the selection and outcome equation covariances are expressed using $\rho_{\mu 1} = \sigma_{\mu 1}/\sigma_\mu \sigma_{i1}$ and $\rho_{\mu 0} = \sigma_{\mu 0}/\sigma_\mu \sigma_{i0}$. If the correlation coefficient is significant, this indicates the presence of selection bias caused by the generation of unobservable variables. Once the estimated parameters were obtained, the net effect of the pesticide outsourcing services on farmers' manual weeding behavior was assessed in a counterfactual framework, i.e., the average treatment effect of the pesticide outsourcing services on farmers' manual weeding behavior.

The expectation of the average number of days of manual weeding per unit area (mu) in the real situation of farmers in the treatment group (when the outsourced group is involved in the pesticide outsourcing services).

$$\boldsymbol{E[Y_{i1} \mid O_i = 1] = \beta_{i1} X_{i1} + \sigma_{\mu 1}\lambda_{i1}} \tag{6}$$

The average number of days of manual weeding per unit area (mu) expected by farmers in the control group in the real situation (when the non-outsourced group is not involved in pesticide outsourcing services).

$$\boldsymbol{E[Y_{i0} \mid O_i = 0] = \beta_{i0} X_{i0} + \sigma_{\mu 0}\lambda_{i0}} \tag{7}$$

The average number of days of manual weeding per unit area (mu) in the counterfactual situation (when the outsourced group is not involved in pesticide outsourcing services) in the treatment group is expected.

$$\boldsymbol{E[Y_{i0} \mid O_i = 1] = \beta_{i0} X_{i1} + \sigma_{\mu 0}\lambda_{i1}} \tag{8}$$

The average number of days of manual weeding per unit area (mu) in the counterfactual situation (when the non-outsourced group is involved in pesticide outsourcing services) in the control group is expected.

$$\boldsymbol{E[Y_{i1} \mid O_i = 0] = \beta_{i1} X_{i0} + \sigma_{\mu 1}\lambda_{i0}} \tag{9}$$

Then, the difference between Eqs 6, 8 is the average treatment effect on the treated (ATT), which can be expressed as.

$$\begin{aligned} \boldsymbol{ATT} &= \boldsymbol{E[Y_{i1} \mid O_i = 1] - E[Y_{i0} \mid O_i = 1]} \\ &= \boldsymbol{(\beta_{i1} - \beta_{i0}) X_{i1} + \lambda_{i1}(\sigma_{\mu 1} - \sigma_{\mu 0})} \end{aligned} \tag{10}$$

Correspondingly, the difference between Eqs 7, 9 is the average treatment effect on the untreated (ATU), which can be expressed as.

$$\begin{aligned} \boldsymbol{ATU} &= \boldsymbol{E[Y_{i0} \mid O_i = 0] - E[Y_{i1} \mid O_i = 0]} \\ &= \boldsymbol{(\beta_{i0} - \beta_{i1}) X_{i0} + \lambda_{i0}(\sigma_{\mu 0} - \sigma_{\mu 1})} \end{aligned} \tag{11}$$

3.3 Variable selection

In this study, the low-carbon production behavior of farmers is measured by two variables: the number of days of manual weeding per unit area (mu) and the amount of herbicide input per unit area. These variables serve as indicators of the farmers' adoption of low-carbon practices, specifically the switch from herbicide application to manual weeding. The core explanatory variable in this study is the pesticide outsourcing services, which measures the degree to which farmers outsource their application activities. This variable captures the extent to which farmers rely on outsourcing services for the application of herbicides or other related tasks. The level of outsourcing is used as a proxy for the farmers' engagement with outsourcing services and serves as the main independent variable in the analysis. By examining the relationship between the pesticide outsourcing services and the low-carbon production behavior of farmers, the study aims to assess the impact of outsourcing services on farmers' adoption of low-carbon practices.

Based on existing studies and investigations, this paper selects the following control variables: external characteristics, cognitive characteristics, personal characteristics, and family and production characteristics (Li et al., 2023). The external features mainly include variables such as quality testing of pesticide residues, compliance with the rules by surrounding farmers, community training and promotion of green knowledge. Cognitive characteristics include whether farmers know the safety interval. Personal characteristics include variables such as age, gender and political identity of the head of household. The household and production characteristics include variables such as the number of land plots, the proportion of yield reduction without pesticide application, and the total household income.

To ensure the model's validity, it is important to incorporate instrumental variables into the selection equation. When individuals lack sufficient information, they often observe the behavior of others

TABLE 1 Variable definition table[a].

Dimension	Variables	Definition and assignment
Explained variables	Farmers' manual weeding behavior	Th average number of days of manual weeding per unit area (mu) of rice (days)
	Farmers' herbicide application behavior	Th average amount of herbicide input per unit area (mu) of rice (RMB)
Core Explanatory variables	Pesticide outsourcing services	Does your family outsource the pesticide application to the service organizations? (1 = Yes, 0 = No)
Other Explanatory variables		
External characteristics	Quality testing of pesticide residues	Product quality of testing pesticide residues are very strict (1 = completely disagree, 2 = disagree, 3 = fair, 4 = agree, and 5 = completely agree)
	Community green knowledge training and promotion	Does the community provide training on knowledge related to green products as well as advocacy services? (1 = Yes, 0 = No)
	Compliance with rules by surrounding farmers	Surrounding farmers consciously comply with the production rules agreed upon in the market buying and selling process (1 = completely disagree, 2 = disagree, 3 = fair, 4 = agree, and 5 = completely agree)
	Pesticide bag recycling supervision	Is pesticide bag recycling supervised? (1 = Yes, 0 = No)
Cognitive characteristics	Safety interval	Do you know the safety interval for pesticide application? (1 = Yes, 0 = No)
Individual characteristics	Gender	Gender of household head (1 = Male, 0 = Female)
	Age	The actual age of head of household (years)
	Years of education	Years of education of the head of household (years)
	Political identity	Is he/she a party member? (1 = Yes, 0 = No)
	Health statusa	Health status of the head of household (1 = unable to take care of themselves, 2 = have disease affecting agricultural production, 3 = have disease but not affecting agricultural production, and 4 = healthy)
	Technology demonstration households	Is he/she a technology demonstration household? (1 = Yes, 0 = No)
Family and production characteristics	Processing plant or sales store	Is there a processing plant or sales store? (1 = Yes, 0 = No)
	Number of land plots	Number of land plots (blocks)
	The proportion of yield reduction without pesticide application	No pesticide application yield reduction/original yield
	Total household income	Total household income (RMB)
Instrumental variable	Degree in village outsourcing	The average of the number of other farmers in the village involved in the pesticide outsourcing services

[a]Farmers' manual weeding behavior, farmers' herbicide application behavior, and total household income were logarithm values.

to align their own behavior with the group and maximize their utility in situations of incomplete information. Social norms within a farmers' group or community can have a significant influence on their behavior, sometimes even more so than external factors (Tang and Chen., 2022). In this study, the degree of village outsourcing is selected as the instrumental variable of outsourcing decision, and the average number of other rural households in the village is used for measurement (Chen et al., 2022). In the village setting, the social interactions and observational learning among farmers can create a demonstration effect and peer effect within their own families. When other farmers participate in link outsourcing, it can motivate farmers who are not participating to consider using outsourcing as well. However, it is important to note that farmers' decision-making regarding outsourcing is influenced by their individual economic independence and cognitive limitations. Additionally, farmers' own outsourcing behaviors do not have a direct impact on the low-carbon production behaviors of other farmers. Therefore, the instrumental variables used in the model should be related to the decision-making process of outsourcing but not to the disturbance term. Table 1.

4 Results

4.1 Descriptive statistics

Table 2 presents the descriptive statistics of the variables. We found that there were differences in low-carbon production

TABLE 2 Descriptive statistics results.

Dimension	Variables	Average value	Standard deviation	Minimum value	Maximum value
Explained variables	Farmers' manual weeding behavior	0.272	0.394	0	1.705
	Farmers' herbicide application behavior	3.349	1.456	0	6.201
Core Explanatory variables	Pesticide outsourcing services	0.316	0.465	0	1
Other Explanatory variables					
External characteristics	Quality testing of pesticide residues	2.384	1.176	1	5
	Community green knowledge training and promotion	0.400	0.490	0	1
	Compliance with rules by surrounding farmers	2.967	1.242	1	5
	Pesticide bag recycling supervision	0.136	0.343	0	1
Cognitive characteristics	Safety interval	0.718	0.451	0	1
Individual characteristics	Gender	0.833	0.373	0	1
	Age	57.491	10.488	23	85
	Years of education	6.713	3.511	0	16
	Political identity	0.091	0.288	0	1
	Health status	3.669	0.558	2	4
	Technology demonstration households	0.031	0.174	0	1
Family and production characteristics	Processing plant or sales store	0.027	0.161	0	1
	Number of land plots	9.807	14.119	1	200
	The proportion of yield reduction without pesticide application	4.011	1.881	0	6
	Total household income	10.642	0.959	6.628	13.468
Instrumental variable	Degree in village outsourcing	0.316	0.322	0	0.909

TABLE 3 Comparison of the variability of whether farmers participated in pesticide outsourcing services.

Indicators	The average manual weeding days per unit area (mu) (days)		The average amount of herbicide input per unit area (mu) (RMB)	
	Non-participants	Participants	Non-participants	Participants
Average value	0.508	0.300	44.491	90.387
Standard deviation	0.867	0.448	65.756	67.850
Sample size	308	142	308	142

behaviors among the different farmers. To explore the relationship between pesticide outsourcing services and farmers' low-carbon production behavior, we first compared the differences in the average number of days of manual weeding per unit area (mu) and the average amount of herbicide input per unit area (mu) between farmers. The results indicated that out of the total sample of households, 308 households did not participate in pesticide outsourcing services, while 142 households chose to participate in pesticide outsourcing services. This means that only 31.6% of the total households in the sample opted for pesticide outsourcing services. Table 3 presents the manual weeding and herbicide input of the two groups of farmers, namely, the participants and non-participants of pesticide outsourcing services. The average number of days of manual weeding per unit area (mu) for farmers who did not participate in pesticide outsourcing services was 0.51—higher than the average number of days of manual weeding per unit area (mu) for farmers who participated in pesticide outsourcing services (0.30 days). The average herbicide input per unit area (mu) for farmers who did not participate in pesticide outsourcing services was 44.5 RMB—lower than the average herbicide input per unit area (mu) for farmers who participated in pesticide outsourcing services (90.39 RMB).

Additionally, an inter-variable correlation analysis was conducted prior to the empirical analysis. The average number of manual-weeding days per unit area (mu) showed a negative correlation with pesticide outsourcing services, while the average amount of herbicide input per unit area (mu) exhibited a positive correlation with pesticide outsourcing services. These findings initially support the research hypothesis as expected. Furthermore, the statistical analysis revealed that most of the variables had small correlation coefficients. Additionally, after conducting the inflation factor analysis, it was determined that the largest inflation factor was only 1.51, which is well below the critical value of the inflation factor VIF = 10. This indicates that there is no significant issue of multicollinearity among the variables in the model designed for this study.

4.2 Test results

The empirical analysis was conducted using Stata 16 software, employing an endogenous transformation model to assess the impact of pesticide outsourcing services on farmers' low-carbon production behavior. The "outsourcing decision" column represents estimates of the factors influencing the decision to outsource in the first stage of the model. The "non-outsourced group" and "outsourced group" indicate estimates of the outcome equations in the second stage of the model for each respective group. The symbols of ρ_T and ρ_U denote the correlation coefficients of the error terms of the outsourcing decision model and the low-carbon production behavior model of farmers, respectively. The significance of ρ_T, ρ_U , and the joint independent likelihood ratio (LR) at the 10%, 5%, and 1% levels indicates that there is a significant presence of self-selection problems within the sample. This suggests the need to correct for sample selection bias caused by unobservable factors. The positive correlation coefficient estimates for the error term in Model 1 indicate a negative selectivity bias. This means that farmers who did not participate in pesticide outsourcing services spent more days on manual weeding compared to the average number of days spent by random farmers in the sample. On the other hand, the negative correlation coefficient estimates for the error term in Model 2 indicate a positive selectivity bias. This implies that farmers who participated in pesticide outsourcing services had a higher amount of herbicide input compared to the average amount of herbicide input by random farmers in the sample. Specifically, the amount of herbicide input exceeded the average amount observed among random farmers in the sample.

Regarding the factors influencing the decision to outsource the application process, it was found that community training and promotion of green knowledge, as well as compliance with the rules by surrounding farmers, had a significant positive impact on the choice to outsource. This may be attributed to the influence of the external environment on farmers' production behavior, as indicated by Ma et al. (2023). Additionally, the traditional perception of outsourcing services was found to be favorable for green and low-carbon production. Farmers who were aware of green and low-carbon production practices were more likely to choose to outsource. Pesticide bag collection monitoring was found to have a significant positive effect on the choice to outsource, likely due to the convenience associated with outsourcing, as mentioned by Zheng et al. (2022). Gender was also found to have a significant positive effect on the outsourcing decision, indicating that male heads of households were more inclined to choose outsourcing services. This suggests that male heads of households tend to be risk-averse and more proactive in adjusting their production decision-making behavior, as highlighted by Cheng et al. (2022). Age, on the other hand, had a significant negative effect on the choice to outsource, indicating that younger household heads, who tend to be more receptive to new ideas, were more likely to choose outsourcing, as discussed by Su et al. (2017). The presence or absence of technology demonstration households also played a significant role, with technology demonstration households being more aware of green and low-carbon production practices and choosing to outsource due to the reputation associated with being a technology demonstration household, as noted by Han et al. (2022). The number of land plots had a significant positive effect on the choice to outsource. As farmers with more land plots have more work to handle, they were more inclined to choose outsourcing. The proportion of yield reduction without pesticide application also had a significant positive effect on the outsourcing decision. Farmers, based on their awareness of safety risks, chose to outsource the application process to professional organizations to ensure higher yield, as highlighted by Chèze et al. (2020). Total household income was found to have a significant positive effect on the decision to outsource. This suggests that income plays a role in promoting the development of the outsourcing market, as indicated by Zheng et al. (2023). Regarding instrumental variables, the extent of outsourcing in villages showed a significant positive effect on both groups of farm households, indicating its influence on the outsourcing decision Table 4.

In terms of factors influencing farmers' low-carbon behavior, several significant findings were observed. Quality testing for pesticide residues and community training and promotion of green knowledge had a significant positive effect on the manual weeding behavior of farmers in the non-outsourced group, while having a significant negative effect on herbicide application behavior. This suggests that farmers, influenced by external constraints on pesticide residues and the promotion of green production, are more likely to choose manual weeding to reduce pesticide residues. Additionally, norms within the group or community to which farmers belong were found to influence their behavior, aligning with previous studies showing that group norms influence farmers' intentions to engage in sustainable agricultural practices (Borges et al., 2016; Bjørnåvold et al., 2022). The compliance by surrounding farmers also had a significant positive effect on the manual weeding behavior of farmers in the outsourced group, indicating that the choice of surrounding farmers influences low-carbon production under the influence of peer effects (He et al., 2023). Pesticide bag collection monitoring was found to have a significant positive effect on farmers' manual weeding behavior and a significant negative effect on herbicide application behavior. This suggests that farmers choose manual weeding for added convenience, thereby avoiding the process of collecting pesticide bags. Perceptions of safety intervals had a significant positive effect on manual weeding behavior and a significant negative effect on herbicide application behavior in the non-outsourced group. Scientific perceptions were found to be conducive to regulating pesticide application (Udimal et al., 2022). Gender also played a significant role, with a negative effect on manual weeding and a positive effect on herbicide application in the non-outsourced group. This suggests that female heads of households prefer manual weeding, while male heads of households prefer herbicide application (Chen et al., 2023a). It indicates that women may be more inclined to participate in low-carbon production compared to men. Years of

TABLE 4 Regression results of the effect of pesticide outsourcing services on low-carbon production behavior.

Dimension	Variables	Model 1			Model 2		
		Select equation	Impact effect equation		Select equation	Impact effect equation	
		Outsourcing decision	Outsourced group	Non-outsourced group	Outsourcing decision	Outsourced group	Non-outsourced group
External Characteristics	Quality testing of pesticide residues	−0.045 (0.073)	0.024 (0.020)	0.057** (0.023)	−0.044 (0.075)	−0.104 (0.068)	−0.155** (0.074)
	Community green knowledge training and promotion	0.510** (0.186)	0.072 (0.051)	0.120** (0.058)	0.475** (0.189)	0.114 (0.168)	−0.502** (0.183)
	Compliance with rules by surrounding farmers	0.120* (0.072)	0.040* (0.022)	0.013 (0.021)	0.165** (0.070)	−0.108 (0.070)	0.021 (0.069)
	Pesticide bag recycling supervision	0.909*** (0.237)	0.271*** (0.059)	0.229** (0.084)	0.729** (0.235)	−0.905*** (0.205)	−0.299 (0.261)
Cognitive characteristics	Safety interval	−0.060 (0.220)	−0.006 (0.063)	0.106* (0.057)	−0.150 (0.217)	−0.229 (0.200)	−0.375** (0.186)
Individual Characteristics	Gender	1.330** (0.444)	0.194 (0.137)	−0.153** (0.066)	1.371** (0.445)	−0.245 (0.463)	0.383* (0.207)
	Age	−0.021** (0.010)	−0.001 (0.003)	−0.001 (0.003)	−0.019* (0.010)	−0.006 (0.009)	−0.005 (0.009)
	Years of education	−0.004 (0.027)	−0.001 (0.007)	0.002 (0.008)	0.009 (0.028)	−0.034 (0.023)	−0.049* (0.025)
	Political identity	−0.231 (0.294)	−0.041 (0.072)	−0.064 (0.090)	−0.159 (0.291)	−0.208 (0.236)	0.013 (0.290)
	Health status	0.104 (0.173)	−0.053 (0.046)	−0.018 (0.046)	0.039 (0.177)	−0.179 (0.154)	−0.250* (0.149)
	Technology demonstration households	0.763* (0.451)	0.168 (0.120)	−0.038 (0.165)	0.644 (0.465)	−0.803** (0.405)	0.385 (0.530)
Family and production characteristics	Processing plant or sales store	0.464 (0.469)	0.173 (0.125)	0.001 (0.173)	0.718 (0.453)	−1.306** (0.401)	−0.567 (0.552)
	Number of land plots	0.024** (0.012)	0.000 (0.001)	−0.001 (0.005)	0.019* (0.011)	−0.006 (0.005)	0.007 (0.014)
	The proportion of yield reduction without pesticide application	0.157** (0.069)	0.038** (0.018)	0.026 (0.016)	0.094 (0.062)	0.081 (0.064)	0.136** (0.049)
	Total household income	0.267** (0.114)	−0.065** (0.031)	−0.022 (0.026)	0.248** (0.111)	−0.108 (0.102)	0.068 (0.084)
Instrumental Variable	Degree in village outsourcing	2.320*** (0.455)	-	-	2.821*** (0.381)	-	-
	Constant term	−6.177*** (1.768)	0.365 (0.474)	0.446 (0.439)	−5.883** (1.768)	7.897*** (1.599)	3.483** (1.432)
	ρ_T	-	1.271**	-	-	−0.963**	
	ρ_U	-		0.433*	-	-	−0.790***
	LR	11.27***	-	-	24.70***	-	-
	Loglikelihood	−295.073	-	-	−821.935	-	-
	Sample size		450			450	

Note: *, ** and *** represent significant levels of 10%, 5% and 1%, respectively.

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TABLE 5 Average treatment effects of pesticide outsourcing services on the impact of low-carbon production behavior.

Variables	Manual weeding behavior		Herbicide application behavior	
	ATT	ATU	ATT	ATU
Outsourced pesticide services	−0.294*** (0.017)		1.807*** (0.076)	
		−0.405*** (0.013)		1.946*** (0.053)

Note: *, ** and *** represent significant levels of 10%, 5% and 1%, respectively.

education significantly negatively affected the herbicide application behavior of farmers in the non-outsourced group, with higher levels of education and greater awareness of green and low-carbon production leading to a reduction in herbicide application (Sharma et al., 2015). Health status also had a significant negative effect on the herbicide application behavior of farmers in the non-outsourced group, possibly because healthy farmers are capable of manual weeding, resulting in reduced herbicide application. The presence or absence of a technology demonstration household and the presence of a sales shop or processing plant had a significant negative effect on the herbicide application behavior of farmers in the outsourced group. This may be attributed to the possession of green production techniques by technology demonstration households and the need for farmers with sales shops and processing plants to ensure the quality of their produce, respectively. The proportion of yield reduction without pesticide application had a significant positive effect on the herbicide application behavior of farmers in the non-outsourced group, indicating that farmers choose to apply more herbicides due to safety risks (Liu and Huang, 2013). It also had a significant positive effect on the manual weeding behavior of farmers in the outsourced group, suggesting that the outsourcing organization does not take into account the yield issues faced by farmers. Total household income significantly negatively affected the manual weeding behavior of farmers in the outsourced group, indicating that farmers with higher household incomes prefer to use pesticides (Li et al., 2023).

4.3 Results of treatment effects

Table 5 presents the results of estimating the treatment effect of pesticide outsourcing services on farmers' low-carbon production behavior. In the equation for manual weeding behavior, pesticide outsourcing services had a suppressive effect, resulting in a decrease in farmers' manual weeding behavior. The average treatment effect (ATT) in the treatment group was −0.294, and for the control group, it was −0.405, indicating a significant reduction in manual weeding behavior after participating in pesticide outsourcing services. Comparing the magnitude of ATT and ATU, it can be observed that ATT>ATU, suggesting that farmers who participated in pesticide outsourcing services had lower manual weeding inputs compared to those who did not participate. This supports the verification of hypothesis H1, indicating that participation in pesticide outsourcing services lead to a decrease in the number of manual weeding activities. In the equation for herbicide application behavior, pesticide outsourcing services promoted farmers' herbicide application behavior. The average treatment effect (ATT) in the treatment group was 1.807, and the average treatment effect (ATU) for the control group was 1.946, indicating a significant increase in herbicide application behavior after participating in pesticide outsourcing services. Comparing the magnitude of ATT and ATU, it can be observed that ATT < ATU, suggesting that farmers who participated in pesticide outsourcing services had higher herbicide application inputs compared to those who did not participate. This supports the verification of hypothesis H2, indicating that participation in pesticide outsourcing services lead to excessive herbicide application. These findings indicate that pesticide outsourcing services are not conducive to low-carbon production by farmers.

5 Discussion

Based on data collected from 450 surveys conducted in Ningxia and Shaanxi provinces, this study examined the effect of outsourcing services on farmers' manual weeding and herbicide application behavior using an endogenous transformation model. Previous studies have mostly analyzed the impact of outsourcing behavior on green agriculture as a whole, with limited focus on specific alternative models. The study findings revealed that, in the surveyed area, pesticide outsourcing services had a negative and significant impact on farmers' low-carbon production behavior. Farmers participating in the application process through outsourcing exhibited lower input in manual weeding compared to those not participating, while their input in herbicide application was higher. This differs from the findings of Chen et al. (2023), who suggested that outsourcing agricultural production in China could reduce agricultural non-point source pollution. The results of this study may be attributed to the imperfect development of the outsourcing service market. Most of outsourcing services acquired by farmers are primarily from individuals or private entities, lacking professionalism, which hinders the effective role of outsourcing services in driving the low-carbon development of agriculture. Therefore, participation in outsourcing services does not promote farmers' low-carbon production.

In his work "The Wealth of Nations," Adam Smith was the first to systematically discuss the theory of economies of scale and division of labor in the economic context. He argued that a rational division of labor could enhance production efficiency and specialization. Based on the ideal theoretical mechanism and the principles of economies of scale and division of labor, outsourcing services have the potential to achieve large-scale and specialized management, leading to improved utilization of resources and the adoption of green production technologies (Picazo-Tadeo and Reig, 2006), thus facilitating green and low-carbon production. However, this study posits that in an imperfect market, outsourcing services tend to facilitate the flow of factors and shift from labor-intensive to capital-intensive processes. With increasing labor costs, outsourcing organizations often opt for mechanical spraying rather than manual weeding during the application process. Consequently, pesticide outsourcing services do not effectively promote the realization of farmers' low-carbon production.

The findings of this study have implications for farmers in developing countries who aim to adopt low-carbon production practices. For instance, regions cultivating Iranian potatoes, Southeast Asian vegetables, and Pakistani cotton (Khan et al., 2015; Schreinemachers et al., 2020; Sookhtanlou et al., 2022) have experienced issues related to excessive pesticide application. These economically underdeveloped areas may also face challenges with an imperfect outsourcing market, similar to the research region. Reducing reliance on outsourcing or regulating the outsourcing market could help mitigate the problem of high carbon emissions in agriculture.

However, this study has several limitations. Firstly, it solely focuses on the impact of weeding during the application stage on farmers' low-carbon production. Future research could incorporate other variables such as physical and biological pest control, pesticide usage, organic fertilizer application, and fertilizer usage. Secondly, this study only examines the behavior of farmers in Northwest China using cross-sectional data. Future studies could delve into the dynamic changes in farmers' practices and expand the scope of research to include a broader range of agricultural regions. Thirdly, the survey data in this study primarily concentrates on rice, and no extensive investigation or discussion was conducted on different crops such as corn and wheat, necessitating further research in this area to provide more comprehensive insights.

6 Conclusion and policy recommendations

This study examined the influence of pesticide outsourcing services on farmers' behavior regarding manual weeding and herbicide application. It utilizes an endogenous transformation model and analyzes 450 research data from Ningxia and Shaanxi provinces. The study finds that pesticide outsourcing services have a significant negative impact on farmers' low-carbon production behavior. It is concluded that pesticide outsourcing services adversely affect farmers' adoption of low-carbon production practices. It leads to a reduction in manual weeding behavior and promotes excessive herbicide application. This is attributed to the imperfect nature of the outsourcing market, where outsourcing organizations tend to prioritize cost-effectiveness by employing more low-cost machinery for herbicide application, aiming to maximize their profits. Consequently, this practice results in increased surface pollution, which is detrimental to the development of low-carbon agriculture. Overall, the findings suggest that pesticide outsourcing services hinder the achievement of low-carbon production goals among farmers.

In light of these findings, we propose the following policy recommendations to enhance farmers' low-carbon production behavior:

(1) Increase awareness: Currently, farmers do not widely adopt low-carbon practices in pesticide application. It is crucial to develop a comprehensive and objective understanding of the impact of pesticide outsourcing services on farmers' low-carbon production behavior. Participating in pesticide outsourcing services alone is insufficient to achieve low-carbon production goals.
(2) Improve the outsourcing market: A significant portion of the negative impact on farmers' low-carbon production behavior can be attributed to the shortcomings of the outsourcing market and system. Therefore, it is recommended to continually enhance the outsourcing market and establish measures to control excessive outsourcing by implementing effective outsourcing contracts.
(3) Strengthen policy support: The policy support system for outsourcing services in low-carbon agricultural production should be enhanced. The government should introduce more policies focused on promoting low-carbon production. This includes strengthening supervision, providing subsidies to farmers and outsourcing organizations, and striking a balance between asserting its leading role and facilitating market-based service functions.

By implementing these policy recommendations, we aim to encourage farmers to adopt sustainable and low-carbon agricultural practices while addressing the challenges posed by pesticide outsourcing services. This will contribute to the development of a more environmentally friendly and sustainable agriculture sector.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

Author contributions

YiY: methodology, software, validation, formal analysis, investigation, data curation, drafting-Original draft, review and editing, visualization. YaY: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, review and editing, visualization, supervision. RL: data curation, review and editing. DJ: review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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