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Will land transfer improve grain farmers' adoption of agricultural green production technology? Evidence from Jiangxi Province, China

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The application of agricultural green production technologies (AGPTs) promotes green agricultural development and enhances the rural environment. Scale operations can allocate land resources rationally and modernise agricultural technology and management practices. Although previous studies have shown that expanding land transfer facilitates the adoption of AGPTs by farmers, research on how to further promote farmers' adoption behaviour is still lacking. To understand the mechanism of land transfer on farmers' adoption behaviour of AGPTs, this study uses survey data from farmers in Jiangxi Province, China, and employs an endogenous switching regression (ESR) model for counterfactual estimation. The results show that farmers who have acquired land through transfer adopt AGPTs at a significantly higher rate than those who have not. Land transfer promotes farmers' adoption behaviour by increasing household income, financial support, and agricultural socialised services. Land transfer contracts, long-term transfers, and moderate land rent are also conducive to farmers' adoption behaviour of AGPTs. The impact of the land transfer on farmers' adoption behaviour of AGPTs is more significant among large-scale farmers, those with higher field fertility, and those with lower land fragmentation.

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Introduction

Ensuring sustainable consumption and production patterns is one of the 17 United Nations Sustainable Development Goals. In agriculture, this specifically means transforming the grain sector towards sustainable consumption and production. In agriculture, this involves transitioning the grain sector towards sustainable consumption and production. However, unsustainable farming practices, such as the excessive use of fertilisers and pesticides, have led to significant environmental challenges. Over-fertilisation and improper chemical application degrade soil quality and water resources, exacerbating agricultural pollution and threatening the long-term sustainability of arable land (Craswell, 2021; Pan et al., 2022). Addressing these challenges requires the adoption of agricultural green production technologies (AGPTs), which integrate resource conservation and environmental protection to achieve sustainable agricultural development (Gao et al., 2022).

AGPTs encompass a range of sustainable methodologies designed to enhance agricultural productivity and balance economic viability with ecological stewardship. These approaches prioritise not only the yield of crop products but also the efficient utilisation of resources and the safeguarding of environmental integrity. AGPTs mainly include soil improvement and fertilisation, rainfed and water-saving irrigation, precision fertilisation, green pest control, healthy livestock and aquaculture farming, waste recycling, and non-point source pollution management (Mpanga et al., 2023).

Compared to existing agricultural technologies that focus mainly on yield but are limited in resource utilisation and environmental protection, AGPTs offer significant advantages in both environmental protection and economic benefits (Reganold and Wachter, 2016). APGTs reduce agricultural pollution and improve the environment by substituting organic fertilisers, employing precision fertilisation, and using biological control methods, protecting water resources and soil ecosystems (Asiedu-Ayeh et al., 2022). These technologies also enhance the efficiency of water and fertiliser, reducing waste and harmful emissions through practices like water-saving irrigation and recycling pesticide packaging waste (Sui and Gao, 2023). Moreover, AGPTs prioritise long-term ecological and economic benefits, boosting farmers' incomes by enhancing agricultural product quality, motivating them to sustain green agricultural practices, and promoting sustainable agricultural development. Therefore, adopting AGPTs is an effective way to tackle agricultural pollution and promote green development.

China, as one of the world's largest agricultural producers, faces significant challenges from agricultural pollution, including improper wastewater treatment and the overuse of agricultural chemicals (Yang et al., 2022). Despite these pressing issues, the adoption rate of AGPTs among Chinese farmers remains low. Between 2011 and 2017, adoption rates in both major and non-major grain-producing areas were below 20% (He et al., 2021). Meanwhile, land transfer policies in China have been reshaping land resource allocation, legally redistributing land use rights for compensation (Fei et al., 2021). These policies present opportunities to address agricultural pollution by influencing farmers' adoption of AGPTs. Land transfer reallocates land resources, enhances economies of scale, and creates favourable conditions for mechanisation, all of which can encourage the adoption of green agricultural practices (Qiao et al., 2022; Pei et al., 2024).

Land transfer plays a multifaceted role in improving agricultural sustainability. First, it facilitates economies of scale, reducing the costs associated with adopting green technologies (Hebsale Mallappa & Pathak, 2023). Second, it improves land contiguity, enabling mechanisation and enhancing farmers' capacity to implement AGPTs (Zhang et al., 2024b). Third, by optimising land resource distribution, land transfer increases farmers' willingness to adopt green practices, promoting a shift towards sustainable agricultural methods (Hui and Kai, 2019). These mechanisms suggest a strong correlation between land transfer and the adoption of AGPTs. Understanding this relationship and its contextual variations will provide targeted policy recommendations to promote green farming practices.

Literature review

Research on farmers' AGPTs adoption behaviour. Farmers' endowment characteristics, such as gender, age, and education level, influence their adoption of AGPTs (Sui and Gao, 2023). Training in agricultural technology has shifted farmers' perceptions of green agriculture, with technical knowledge and green awareness being key factors in the adoption of AGPTs (Huang et al., 2015; Adnan et al., 2017). Internet use now also supports farmers with information and technical knowledge (Kwon et al., 2015). Financially, improved credit access plays a crucial role in boosting adoption of AGPTs (Yu et al., 2020). Government subsidies and market incentives further encourage adoption (Dai and Cheng, 2022). By joining cooperatives, which lower the threshold for subsidies, farmers can enhance their uptake of AGPTs (Velten et al., 2021). Moreover, interactions with neighbours also promote the adoption of AGPTs (Niu et al., 2022).

Research on land transfer to farmers. In rural China, land transfer refers to the exchange of land management rights among farmers, enterprises, and cooperatives (Mao and Xu, 2015). It has optimised land use, increased farmers' income, and improved agricultural efficiency. On one hand, land transfer promotes non-agricultural employment, raising incomes and reducing relative poverty (Ding et al., 2024). On the other hand, it concentrates land, expanding management scale and encouraging the adoption of modern technologies, indirectly boosting production efficiency (Li and Nanseki, 2023). However, land transfer may be detrimental to grain production, significantly reducing grain output and serving as a major reason for the decline in the growth rate of China's grain production (Jin et al., 2023; Tan et al., 2023).

Research on the relationship between land transfer and farmers' AGPTs adoption behaviour. Land transfer can significantly enhance farmers' green production practices (Cao et al., 2022). Zhang and Liu (2021) used data from fruit farmers in Xinjiang to demonstrate that land transfer increases the adoption rate of green pest control technologies among farmers. Similarly, Cao et al. (2020) found that land transfer positively affects wheat farmers' use of straw return techniques. Furthermore, Lu et al. (2022) showed land transfer facilitates farmland conservation technologies, though this is moderated by the context and contract terms. In contrast, Liu et al. (2017) identified a robust inverted U-shaped relationship between operational scale and the adoption of green technologies, challenging the assumption of a purely positive correlation.

Gaps in the existing literature

In summary, while existing research has explored the relationship between land transfer and farmers' adoption of green production technologies, it has primarily focused on the adoption of individual green technologies. There is a lack of empirical investigation into the relationship between land acquisition and the breadth of green production technology implementation by farmers, as well as how land transfer affects the overall adoption of green practices. This represents a notable gap in the current body of knowledge. While there have been in-depth studies on the effects

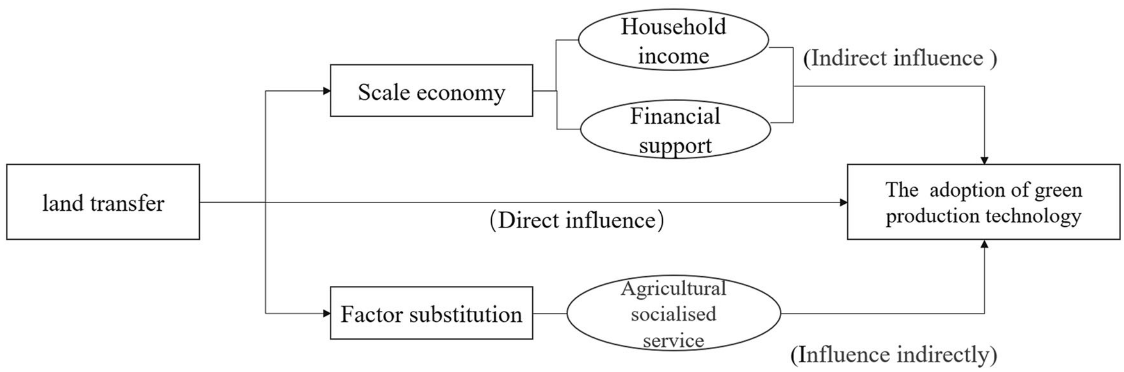


Fig. 1 Theoretical framework.

of land transfer on fruit farmers, research on its impact on grain farmers is still limited. Grain production involves more advanced and widely adopted green technologies compared to fruit and other cash crops, making it a more representative area for study. Moreover, some research focuses on the adoption of a single green technology, lacking an in-depth analysis of the mechanisms driving this process. A better understanding of these mechanisms could enrich the theoretical framework and provide policymakers with evidence to develop targeted policies for promoting green technologies.

Contributions of this study

This study addresses these gaps by focusing on rice farmers as a representative group of grain producers. It examines the changes in AGPTs adoption behaviour before and after land transfer using an endogenous switching model. Specifically, the study contributes to the literature in two ways: (1) By focusing on grain farmers and multiple green technologies, including water-fertiliser integration, water-saving irrigation, and integrated pest management, and assess whether land transfer influences technology adoption. (2) Exploring how economies of scale and factor substitution affect farmers' adoption of AGPTs, enriching the theoretical understanding of land transfer and green production.

To achieve these research objectives, the paper is structured as follows: Introduction, Literature review, Theoretical analysis and research hypotheses, Research design (which provides an overview of the data and methods), Empirical results, Discussion, Implications and Conclusion.

Theoretical analysis and hypothesis development

The direct impact of the land transfer on farmers' AGPTs adoption behaviour. Schultz's "rational smallholder" theory asserts that farmers in traditional agriculture operate efficiently and remain rational economic agents (Schultz, 1966). In their production decisions, farmers pursue profit maximisation, adopting new technologies based on cost-benefit considerations (Li et al., 2019; Chen and Wang, 2023). Farmers' decisions regarding land transfer directly impact the expansion of their operational scale, as those who acquire land through transfer can increase their cultivated area. The theory of economies of scale suggests that as production scales increase, unit costs decrease, enhancing efficiency and profitability. Farmers who have acquired land through transfer have expanded farmers' operational scales, reducing the costs associated with adopting new technologies and facilitating the use of AGPTs through large-scale operations. (Li and Shen, 2021; Chen et al., 2022). Therefore, the following research hypothesis is proposed:

H 1: Land transfer has a significant promoting effect on the adoption of AGPTs by farmers

The indirect impact of the land transfer on farmers' AGPTs adoption behaviour

The high initial investment and maintenance costs of AGPTs are major barriers to farmers adopting new technologies (Pannell, 2001). From the economic effects of land transfer, income effect theory suggests that crops scaled up through land transfer are more likely to achieve higher returns and boost household income (Peng et al., 2020; Ding et al., 2024). Land transfer enhances farmers' financial capacity and risk tolerance, making them more willing to adopt AGPTs (Kuang et al., 2023). According to financing constraint theory, farmers' access to credit can be improved through land as an asset (Stiglitz and Weiss, 1981). Expanding the land management scale raises farmers' credit ratings and enables them to access mortgage financing, providing financial support for the adoption of AGPTs (Chen et al., 2023). Based on this, the following research hypothesis is proposed:

H2: Land transfer promotes the adoption of AGPTs by farmers by increasing household income and financing support.

From a factor allocation perspective, expanding land operations increases the likelihood of small farmers growing into medium-sized and large-scale farms, which in turn require new forms of agricultural services (Zhang et al., 2020). According to technology diffusion theory, large-scale farming demands specialised technical and service support, driving the need for agricultural services (Ryan & Gross, 1943). Agricultural socialised services help farmers adopt AGPTs by reducing information barriers and sharing technological investment risks. On the one hand, Agricultural socialised services increase farmers' access to green technologies and resources, reducing information search costs and improving accessibility, which in turn facilitates the adoption of AGPTs by farmers (Cheng et al., 2022). On the other hand, Agricultural socialised services build farmers' trust in green technologies and their applicability, reducing perceived risks, and lowering barriers to adopting AGPTs (Shi et al., 2023). Based on this, the following research hypotheses are proposed:

H3: Land transfer promotes the adoption of AGPTs by farmers by increasing agricultural socialised services. Figure 1 presents the theoretical framework used in this study.

Research design

Research area. The data for this study were collected through a questionnaire survey in July 2023 by the Institute of Rural Revitalisation Strategy at Jiangxi Agricultural University, targeting household farmers in Jiangxi Province. Stratified random sampling was used to select 24 counties from 11 prefecture-level cities, based on economic development, topography, and lighting data. This included 72 towns, 216 villages, and 10 randomly surveyed households from each village, totalling 216 administrative villages and 2160 households.

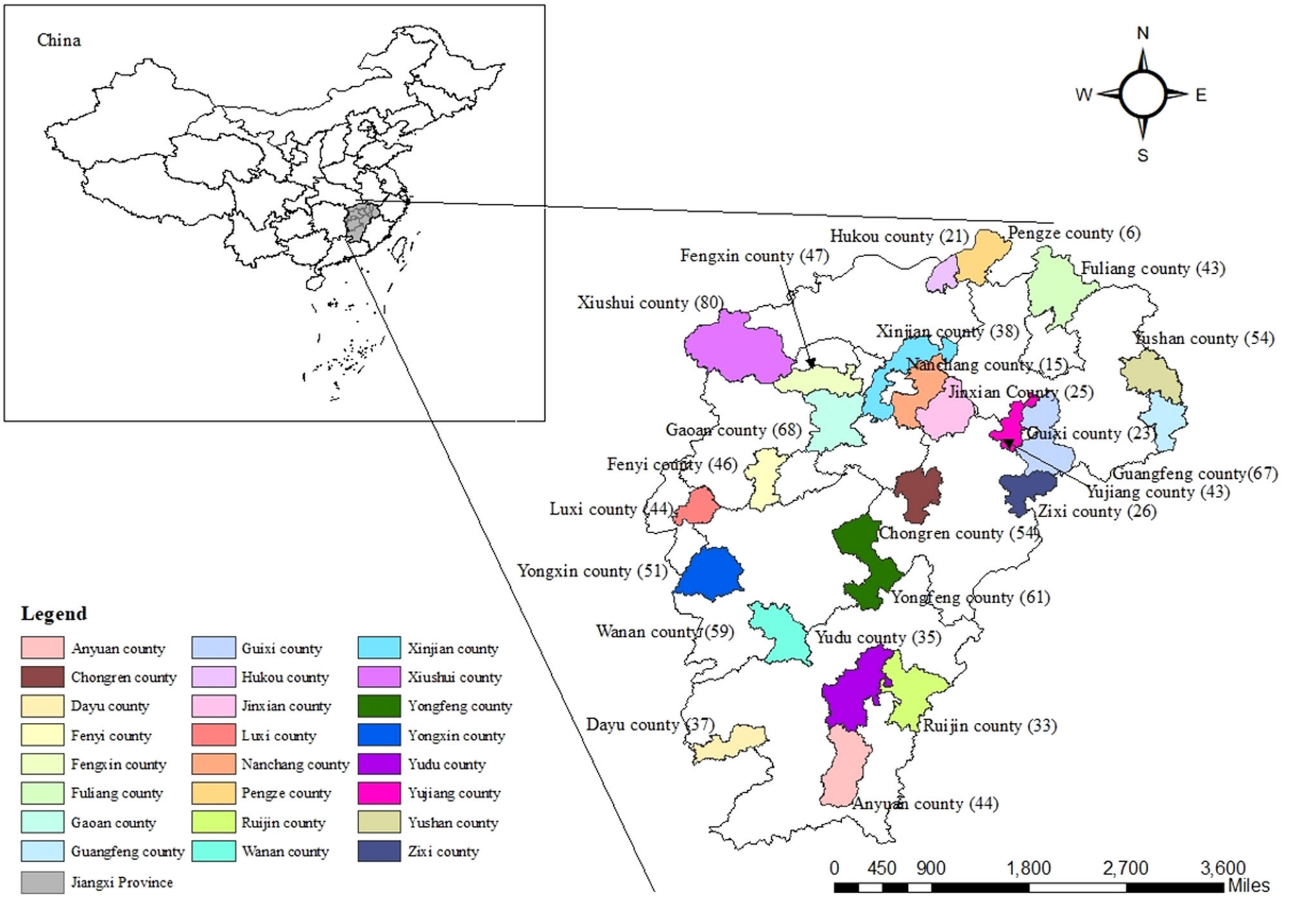


Fig. 2 Study area.

The questionnaire gathered data on household characteristics (age, gender, education, health, labour force, employment), farmland details (size, number of plots, soil fertility, land transfer), and rice production (enthusiasm for and adoption of AGPTs, use of agricultural services). The sample selection process minimised selection bias, ensuring representativeness and reliability. The study focused on grain farmers, yielding a final sample of 1020 (Fig. 2). The data screening criteria were: (1) exclusion of farmers who did not grow rice in 2022, and (2) removal of missing data related to land transfer and AGPTs adoption.

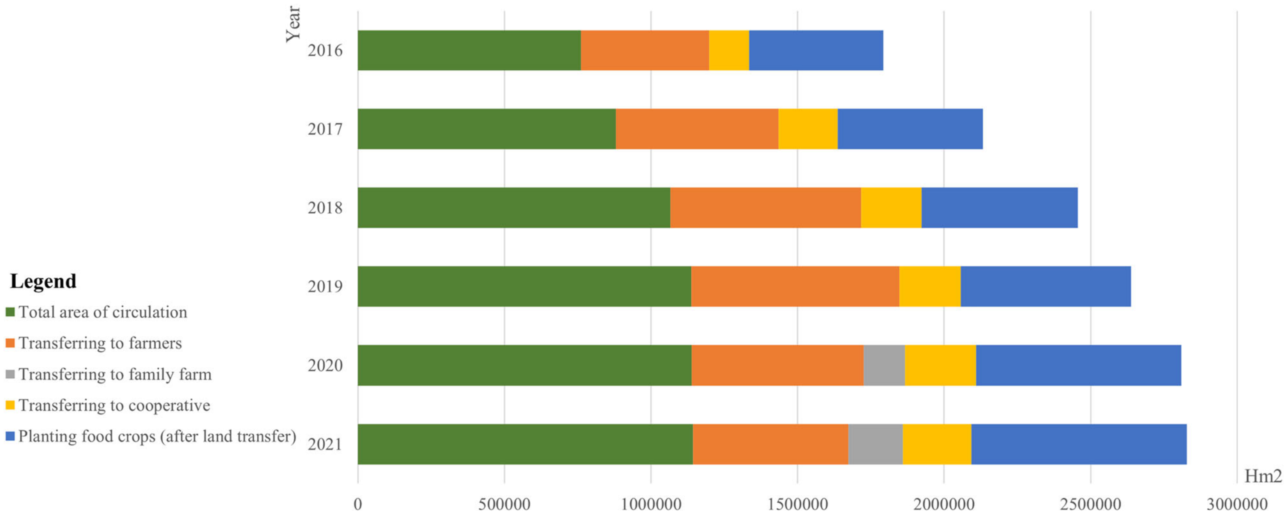
Jiangxi Province is among China's 13 major grain-producing regions. In 2022, official data indicates that out of the 56.645 million mu of grain sown area, 51.045 million mu was allocated to rice, making it the province's dominant grain crop. A rice-centred sample, therefore, conforms to Jiangxi's agricultural framework and effectively represents its grain production tendencies. Derived from the China Rural Management Statistical Yearbook, land transfers in Jiangxi steadily rose (Fig. 3). land transfers to small farmers initially increased and then decreased, transfers to family farms and cooperatives escalated, with the latter remaining relatively smaller. Meanwhile, land transferred for grain cultivation also expanded. Consequently, the sample selection within the framework of land transfer encompasses key agricultural regions, accurately reflecting the experiences of farmers under these policies and ensuring high reliability and validity.

Sample characteristics

Table 1 summarises the basic characteristics of the sample households. Of these, 79.61% are household heads, 83.73% are male, with most aged between 51 and 60. Primary and junior secondary education are the most common. Over 66.38% of farmers are in good health or better. Additionally, 75.78% are not village cadres. Around 73.33% of households own less than 1.64 acres of rice fields, and 36.76% manage three to five plots. Most households are medium-sized, with three to five members, and 40.24% of farmers engage in both agricultural and non-agricultural work. Among the farmers who have acquired land through transfer, only 22.93% have written contracts, and 20.57% have lease durations exceeding five years. Most land rents range from 100 to 500 yuan per 0.164 acres annually.

According to the China Population and Employment Statistical Yearbook, in 2022, 37.38% of rural residents in Jiangxi had primary education, 40.80% had a junior secondary education, the average cultivated land per household was 1.66 acres, and 53.75% of households had three to five members. These comparisons show that the sample closely matches key statistical data, validating its representativeness and ensuring the reliability of the study's conclusions.

This study examines farmers' use of green production technologies, focusing on two main areas: energy-saving cultivation techniques and agricultural waste recycling technologies. These include integrated water and fertiliser management, green-integrated pest management (IPM), eco-efficient crop-livestock integration, straw utilisation, pesticide packaging recycling, water-saving irrigation, and straw chopping and returning. As shown in Table 2, 69.69% of farmers without land transfers have not adopted any AGPTs. The adoption rate of integrated water and fertiliser management shows a minimal difference (0.97%) between those with and without land transfers. However, the adoption rate of other AGPTs by farmers with land transfer is significantly higher, which indicates that there may be a positive correlation between land transfer and farmers' adoption behaviour of AGPTs.



	2021	2020	2019	2018	2017	2016
Total area of circulation	1142541	1139125	1136915	1066389	880840	761298
Transferring to farmers	531410	586232	710576	650119	554568	437576
Transferring to family farm	185367	140534				
Transferring to cooperative	233419	242857	209083	206137	201276	136002
Planting food crops (after land transfer)	734627	700247	581616	533451	496268	457320

Fig. 3 Changes in land transfer in Jiangxi Province from 2016 to 2021.

Table 1 Basic characteristics of sample farmers.

Feature	Type	Number	Proportion	Feature	Type	Number	Proportion
Household head	Yes	812	79.61%	Cultivated area of paddy fields(acres)	Below 1.64	748	73.33%
	No	208	20.39%		1.64–3.29	93	9.12%
Gender	Male	854	83.73%		3.29–4.92	23	2.15%
	Female	166	16.27%		Over 4.92	156	15.29%
Age	30 and under	15	1.47%	Number of paddy fields(pieces)	2 and under	264	25.88%
	31–40	64	6.27%		3–5	375	36.76%
	41–50	169	16.57%		6–8	164	16.08%
	51–60	356	34.90%		9 and above	217	21.27%
	61–70	293	28.73%	Household population	2 and under	141	13.82%
	71 and above	123	12.06%		3–5	418	40.98%
Education level	Not attending school	48	4.71%		6–8	353	34.61%
	Primary school	344	33.73%		9 and above	108	10.59%
				Number of part-time employees in the family	0	609	59.71%
	Junior high school	417	40.88%		1	207	20.29%
					2	164	16.08%
	High School (Technical Secondary School)	151	14.80%		3 and above	40	3.92%
				Land Transfer Contract	No contract	162	38.30%
	College degree or above	60	5.88%		Oral contract	164	38.77%
Health level	Very unhealthy	17	1.67%		written contract	97	22.93%
	Relatively unhealthy	92	9.02%	Land transfer period(year)	Below 1	232	54.85%
	Commonly	234	22.94%		1–4	104	24.59%
	Relatively healthy	379	37.16%		Over 5	87	20.57%
	Very healthy	298	29.22%	Land transfer rent(yuan)	Zero rent	161	38.06%
Village cadres	Yes	247	24.22%		100 and under	74	17.49%
					100–500	182	43.03%
	No	733	75.78%		Over 500	6	1.42%

Table 3 provides a cross-analysis of land transfer and AGPTs adoption behaviour. As adoption levels increase, the number of farmers in both groups decreases, indicating that high adoption levels are rare and not yet widespread. Farmers without land transfers are more likely to adopt 1–2 types of technologies compared to those with land transfers (198 > 164; 77 > 72). However, farmers involved in land transfers are more likely to adopt 3–6 types of technologies (18 < 38; 5 < 9; 3 < 4; 1 < 7). This suggests that land transfer is linked to a higher likelihood of adopting multiple AGPTs.

Variable declaration

As shown in Table 4, 597 of the 1020 farmers surveyed in this study had no land transfer, and 423 farmers had land transferred.

Table 2 Land transfer and adoption behaviour of AGPTs by farmers.

Type of Adoption	No land transfer	Proportion	Land transfer	Proportion
Not adopted any AGPTs	292	69.69%	127	30.31%
Integrated water and fertiliser management	52	50.49%	51	49.51%
Green-integrated pest management	45	45.92%	53	54.08%
Eco-efficient crop-livestock integration	11	35.48%	20	64.52%
Straw utilisation	45	46.88%	51	53.13%
Pesticide packaging recycling	69	42.86%	92	57.14%
Water-saving irrigation	20	38.46%	32	61.54%
Straw chopping and returning	226	49.02%	235	50.98%

Table 3 Land transfer and the degree of adoption of AGPTs by farmers.

Number of adoptions	No land transfer	Land transfer
1	198	164
2	77	72
3	18	38
4	5	9
5	3	4
6	1	7
7	3	2

The low land transfer rate is consistent with other research findings. Moreover, this table displays the descriptive statistics for dependent variables, independent variables, and control variables.

Dependent variable. The adoption behaviour of AGPTs. The number of AGPTs adopted by farmers is used as an indicator to assess their adoption behaviour (Yu et al., 2020; Velten et al., 2021). Due to varying agricultural production contexts, there are differences in the types of AGPTs promoted across different provinces. A value of 0 is assigned to no adoption, 1 for the adoption of one, 2 for the adoption of two, and so on, up to 7 for the adoption of all seven AGPTs.

Independent variable

Land transfer. The fundamental role of land transfer in the development of modern agriculture (Fei et al., 2021). In this research, land transfer is mainly measured by whether farmers acquire operational land through lease-in forms, a value of 0 is assigned to no land transfer, and a value of 1 is assigned to land transfer.

Control variables. This study selects farmers' basic characteristics and farmland information as control variables, as these have been widely used in various studies and have shown significant impacts across different contexts (Sui and Gao, 2023). Key variables include gender, age, education, health and paddy field area. Additionally, based on theoretical analysis and informed by information asymmetry, technology adoption, and social capital theories, specific variables such as production technology information needs, digital technology use, and cooperative participation are included (Kwon et al., 2015; Velten et al., 2021).

Mediating variables. Household income refers to farmers' disposable income in 2022 (Peng et al., 2020), measured based on the questionnaire item "What was your household's disposable income in 2022?". Financing support refers to whether they could obtain financing from banks (Chen et al., 2023), measured based on the item "Did your household obtain financing from a bank?" with a response of yes coded as 1 and no coded as 0. Agricultural socialised services refer to whether farmers used socialised services during rice production (Yang et al., 2022), measured by the item "In which stages of rice cultivation did you use socialised services (including seedling raising, land preparation, transplanting, fertilising, pesticide application, and harvesting)?" If any service was used at any stage, it was coded as 1; otherwise, it was coded as 0.

Model specification

Endogenous switching regression model. Land transfer among farmers can cause sample selection bias and endogeneity due to economic, and social capital, and unobservable factors like learning abilities. While farmers' decisions regarding land transfer can be observed, a linear regression model alone cannot estimate the outcomes for farmers before they make their decisions. The endogenous switching regression (ESR) model addresses this by accounting for both observable and unobservable factors, separately estimating AGPTs adoption behaviour for farmers with and without land transfer. This provides a more accurate assessment of the impact of farmers' land acquisition decisions through transfer. Using the full information maximum likelihood method, this study avoids omission bias. The ESR model constructs a "counterfactual" framework to evaluate technology adoption in both scenarios, allowing analysis of the average treatment effect of land transfer. It includes a selection equation for land transfer and two outcome equations for technology adoption. The first step is constructing the selection equation as follows:

$$S_i^* = \delta_i Z_i + \varepsilon_i I_i + \mu_i \tag{1}$$

Among them, S_i^* represents the latent variable that determines whether farmer i will transfer land, δ_i, ε_i is the parameter to be estimated, Z_i is an explanatory variable affecting land transfer (including 14 control variables). I_i is the identification variable, and μ_i is the random error term. T To address selectivity bias, the decision equation needs an identification variable not in the income equation. This variable must correlate with the land transfer but not directly affect farmers' adoption behaviour of AGPTs. Farmers' assessment of grain prices is used as the identification variable. Assuming S_i is the corresponding observable result of the latent variable S_i^*, if S_i^* å 0, then $S_i = 1$ (farmer i s transfers land, treatment group); Otherwise, $S_i = 0$(farmer i has not transferred land, control group).

The second step is to construct a determining equation for the degree of adoption of AGPTs by farmers, as follows:

$$\text{If} S_i = 1, Y_{1i} = \sum_{j=1}^{n} \alpha_{1j} X_{1ij} + \mu_{1j} \tag{2}$$

$$\text{If} S_i = 0, Y_{0i} = \sum_{j=1}^{n} \alpha_{0j} X_{0ij} + \mu_{0j} \tag{3}$$

Equation (2) estimates the adoption of AGPTs by farmers who have transferred land, while equation (3) does so for those who have not. In the formula: Y_{1i} and Y_{0i} represent the adoption of AGPTs for these groups, X_{1ij} and X_{0ij} are the factor vectors

Table 4 Variable description and mean difference.

Variable	Assignment	No land transfer($N = 597$)	Land transfer ($N = 423$)	Mean difference
Land transfer	Land transfer = 1, No Land transfer = 0	0	1	—
The adoption of AGPTs	Not adopted = 0, adopted one = 1, Adopting two = 2, adopting three = 3, Adopting four options = 4, adopting five options = 5, Adopting six = 6, adopting seven = 7	0.784 (1.036)	1.262 (1.301)	−0.478*** (6.010)
Gender	Male = 1, female = 0	0.816 (0.388)	0.868 (0.339)	−0.052** (2.251)
Age	30 and below = 1, 31–40 old = 2, 41–50 = 3, 51–60 old = 4, 61–70 = 5, 71 and above = 6	4.248 (0.049)	4.118 (0.050)	0.130* (−01.845)
Education level	Not attending school = 1, Elementary school = 2, Junior high school = 3, Senior high school = 4, College and above = 5	2.836 (1.000)	2.832 (0.847)	0.004 (−0.064)
Health level	Very healthy = 5, relatively healthy = 4, commonly = 3, relatively unhealthy 2, very unhealthy = 1	3.747 (1.021)	3.953 (0.965)	−0.206*** (3.233)
Village cadres	Yes = 1, no = 0	0.235 (0.424)	0.253 (0.435)	−0.018 (0.674)
Household population	2 or less = 1, 3-5 = 2, 6–8 = 3, 9 or more = 4	2.379 (2.595)	2.478 (2.436)	−0.099* (1.840)
Number of part-time employees in the family	Number of labour force engaged in both agricultural and non-agricultural work simultaneously	0.036 (1.649)	0.040 (0.904)	−0.024 (−1.165)
Number of elderly farmers	Number of elderly people aged 65 and above working in agriculture at home	0.638 (0.841)	0.513 (0.805)	0.125** (−2.385)
E-commerce training participation	Household members have received training in e-commerce, yes = 1, no = 0	0.084(0.011)	0.125(0.016)	−0.042** (2.097)
Production technology information requirements	Family's level of demand for production technology information (rating)	6.382 (0.117)	7.338 (0.131)	−0.956*** (5.249)
Digital technology application	Digital technologies such as the Internet of Things, drones, and artificial intelligence are used in production, yes = 1, no = 0	0.069 (0.010)	0.234 (0.021)	−0.165*** (6.768)
Cooperative participation	Participation in farmers' cooperatives, yes = 1, no = 0	0.194 (0.016)	0.284 (0.022)	−0.089*** (3.236)
Paddy fields	1.64 or less acres = 1, 1.64–3.29 acres = 2 3.29–4.92 acres=3, 4.92 or more acres =4	1.136 (0.018)	2.388 (0.066)	−1.252*** (13.560)
Paddy fields fertility	Very good=5, relatively good=4, average=3, relatively poor=2, very poor=1	3.363 (0.809)	3.291 (0.825)	0.073(−1.395)
Household income	Household's disposable income in 2022(Yuan) Below 30,000 = 1;30,000–50,000 = 2;50,000–80,000 = 3;80,000–120,000 = 4, above 120,000 = 5	2.360 (1.397)	2.704 (1.399)	−0.344*** (3.808)
Financing support	Financing obtained from the bank, yes = 1, no = 0	0.243 (0.429)	0.352 (0.478)	−0.109*** (3.692)
Agricultural socialised services	Utilisation of agricultural social services, yes = 1, no = 0	0.799 (0.401)	0.936 (0.245)	−0.137*** (6.426)

Note:The values in parentheses for non-land transfer and land transfer are standard errors, while the values in parentheses for mean difference are T-values.

influencing adoption ; μ_{1j} and μ_{0j} represents the random error term. To address sample selection bias from unobservable factors, the model includes the inverse Mills ratio. λ_{1i} and λ_{0i} and its covariance $\rho_{\mu 1 v} = \text{cov}(\mu_0, v)$, $\rho_{\mu 0 v} = \text{cov}(\mu_0, v)$, Using the full information maximum likelihood method, the model estimates AGPTs adoption levels for both groups under real and counterfactual scenarios, calculating the average treatment effect of land transfer. The expected conditions for farmers in both land transfer scenarios are estimated as follows:

$$E(Y_{1i}|S_i = 1) = \beta_{1j}X_{1ij} + \rho_{\mu 1 v}\lambda_{1i} \quad (4)$$

$$E(Y_{0i}|S_i = 0) = \beta_{0j}X_{0ij} + \rho_{\mu 0 v}\lambda_{0i} \quad (5)$$

In the “counterfactual” scenario, the conditions where “farmers who transferred land do not transfer” and “farmers who did not transfer do transfer” are unobservable. Thus, an endogenous switching model is used to estimate farmers’ AGPTs adoption behaviour in this scenario:

$$E(Y_{0i}|S_i = 1) = \beta_{0j}X_{1ij} + \rho_{\mu 0 v}\lambda_{1i} \quad (6)$$

$$E(Y_{1i}|S_i = 0) = \beta_{1j}X_{0ij} + \rho_{\mu 1 v}\lambda_{0i} \quad (7)$$

The average treatment effect on the treated (ATT) for farmers with land transfer can be expressed as the difference between Eq. (4) and Eq. (6):

$$ATT = E(Y_{1i}|S_i = 1) - E(Y_{0i}|S_i = 1) = (\beta_{1j} - \beta_{0j})X_{1ij} + (\rho_{\mu 1 v} - \rho_{\mu 0 v})\lambda_{1i} \quad (8)$$

Similarly, the average treatment effect on the untreated (ATU) for farmers without land transfer can be expressed as the difference between Eq. (5) and Eq. (7):

$$ATU = E(Y_{1i}|S_i = 0) - E(Y_{0i}|S_i = 0) = (\beta_{1j} - \beta_{0j})X_{0ij} + (\rho_{\mu 1 v} - \rho_{\mu 0 v})\lambda_{0i} \quad (9)$$

ATT and ATU represent the potential outcomes of the adoption of AGPTs in agriculture based on counterfactual scenarios.

Mediating effect model

Land transfer indirectly influences farmers’ adoption of AGPTs by increasing household income, financing support, and improving agricultural socialised services. To test this hypothesis, a mediation effect model is established.:

$$Y_i = \theta_0 + \theta_1 S_i + \theta_2 X_i + \sigma_1 \quad (10)$$

$$M_i = \tau_0 + \tau_1 S_i + \tau_2 X_i + \sigma_2 \quad (11)$$

$$Y_i = \omega_0 + \omega_1 S_i + \epsilon_i M_i + \omega_2 X_i + \sigma_3 \quad (12)$$

In the formula: Y_i represents the degree of adoption of AGPTs by farmers, S_i represents land transfer, M_i represents the mediating variables, namely household income, financing support, and agricultural socialised services. X_i represents the control variable, $\theta_1, \tau_1, \omega_1, \epsilon_i, \theta_2, \tau_2, \omega_2$ and are the coefficients to be estimated, $\sigma_1 \sim \sigma_3$ is a random interference term. Equations (10) and (12) represent the Oprobit estimation regression, and Eq. (11) selects the Oprobit model and Probit model based on the type of mediator variable.

Empirical results

Analysis of the factors influencing land transfer and farmers’ adoption of AGPTs. Table 5 presents the regression results of the ESR and Oprobit models. The estimates from the Oprobit model indicate that land transfer significantly increases the adoption rate of AGPTs; specifically, farmers who transfer land have a 30.7% higher adoption rate compared to those who do not engage in land transfer. However, the chi-square statistic for the likelihood ratio test in the ESR model is 2.79 ($p = 0.098$), indicating selective bias

Table 5 The estimated impact of land transfer on the adoption of AGPTs by farmers.

Variable	Endogenous transformation regression model (ESR)			Oprobit
	Selection equation	Result equation		
	Whether to transfer land	Land transfer	No Land transfer	Adoption of AGPTs
Gender	−0.094 (0.128)	0.056 (0.185)	−0.083 (0.115)	−0.028 (0.102)
Age	−0.062 (0.057)	0.042 (0.071)	0.072 (0.047)	0.064 (0.040)
Education level	0.074 (0.047)	0.260*** (0.080)	−0.001 (0.052)	0.073* (0.044)
Health level	−0.047 (0.047)	−0.023 (0.065)	0.071 (0.045)	0.042 (0.037)
Village cadres	−0.003 (0.059)	−0.050 (0.143)	0.048 (0.107)	0.058 (0.084)
Household population	0.777*** (0.057)	−0.082 (0.074)	0.025 (0.049)	0.004 (0.042)
Number of part-time employees in the family	−0.051 (0.057)	0.012 (0.067)	0.041 (0.042)	0.006 (0.037)
Number of elderly farmers	0.143 (0.112)	−0.108 (0.081)	−0.092* (0.055)	−0.107** (0.047)
E-commerce training participation	−0.128 (0.114)	0.301 (0.189)	−0.070 (0.158)	0.104 (0.117)
Production technology information requirements	0.054 (0.053)	0.052** (0.023)	0.035** (0.016)	0.062*** (0.013)
Digital technology application	0.227 (0.160)	0.610*** (0.160)	0.568*** (0.173)	0.509*** (0.109)
Cooperative participation	0.050 (0.052)	0.017 (0.140)	0.100 (0.109)	0.033 (0.085)
Cultivated area of paddy fields	0.287* (0.154)	−0.155* (0.088)	−0.019 (0.165)	0.026 (0.038)
Fertility of paddy fields	0.038** (0.017)	0.203*** (0.073)	0.057 (0.053)	0.117*** (0.044)
Evaluation of grain purchase prices	0.090* (0.050)			
Land transfer				0.307*** (0.084)
Constants	0.090* (0.050)	−0.759 (0.740)	−0.839* (0.465)	0.307*** (0.084)
Wald test	62.16***			
LR test	2.79*			140.78***
Log-likelihood	−2036.086			−1286.820
Ins1		0.217*** (0.047)		
Ins2			0.005 (0.029)	
r1		−0.412** (0.168)		
r2			0.030 (0.275)	

Notes: The levels of significance are denoted by ***, **, and *, which signify statistical significance at the 1%, 5%,and 10% thresholds, respectively.

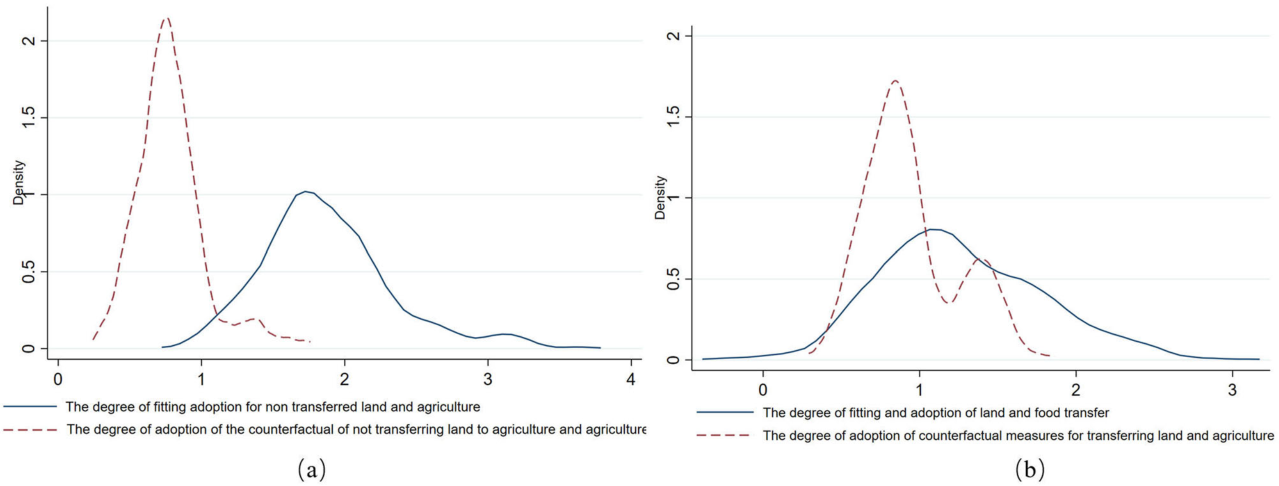


Fig. 4 Probability density of farmers' adoption of AGPTs under different land transfer scenarios. a Adoption levels under land transfer. The blue solid line represents farmers' adoption of AGPTs, while the red dashed line shows the counterfactual. The peak of the dashed line shifts to the left compared to the solid line, indicating that farmers have a significantly lower adoption rate in the counterfactual scenario (without land transfer). **b** Adoption levels under no land transfer. The blue solid line represents farmers' adoption of AGPTs without land transfer, while the red dashed line shows the counterfactual. The peak of the solid line shifts to the left compared to the dashed line, indicating that farmers would show a significant increase in adoption if land were transferred.

Table 6 The ATT of land transfer on the adoption of AGPTs by farmers.

Matching method	Treatment group	Control group	ATT	Standard error	*T* value
Unmatched	1.262	0.784	0.478	0.073	6.53***
One-to-one matches	1.234	0.764	0.470	0.172	2.72***
Caliper matching	1.234	0.671	0.562	0.164	3.43***
Kernel matching	1.234	0.672	0.561	0.165	3.40***
Local linear regression matching	1.234	0.684	0.549	0.172	3.19***
Average value	1.234	0.698	0.534	0.168	3.18***

Notes: The levels of significance are denoted by ***, **, and *, which signify statistical significance at the 1%, 5%,and 10% thresholds, respectively.

and endogeneity at the 10% significance level. Due to the non-random nature of farmers' decisions regarding land transfer, selection bias is present, which the Oprobit model cannot eliminate. As a result, the estimation of the causal relationship between land transfer and farmers' adoption of AGPTs may be biased.

From the selection equation, household size, number of paddy fields, field fertility and evaluation of grain prices positively correlate with land transfer decisions. The result equation indicates that there are differences in the adoption of AGPTs between farmers who engage in land transfer and those who do not. Education significantly increases AGPTs adoption behaviour among land-transferred farmers but not for non-transferred ones. Economic and resource constraints hinder adoption, but scale economies and contiguous land from transfers help mitigate these. Elderly farmers negatively impact adoption among non-transferred farmers but not those with land transfers. Demand for production technology information positively correlates with AGPTs adoption behaviour for both groups. Among land-transferred farmers, the number of paddy fields negatively affects adoption, likely due to field heterogeneity, while paddy field fertility boosts adoption. From both the selection and result equations, the aforementioned common factors can lead to biased estimates of the impact of land transfer on farmers' adoption of green production technologies.

Estimation of the average treatment effect of land transfer on the adoption of AGPTs by farmers

To assess the impact of land transfer on farmers' adoption of AGPTs, this study utilises the ESR model to correct for sample selection bias from unobservable factors and estimate the average treatment effect of land transfer. Specifically, the level of adoption for land-transferred and non-transferred groups was calculated after correcting for sample selection bias using Eqs. (4) and (5). The "counterfactual" levels of adoption were then estimated using Eqs. (6) through (9). Results show an ATT of 0.431 and an ATU of 1.088.

Figure 4 illustrates the probability density distributions for both groups. In Fig. 4a, the curve for land-transferred farmers shifts left if they had not transferred land, indicating a reduction in AGPTs adoption (ATT = 0.431). In Fig. 4(b), the curve for non-transferred farmers shifts right in the hypothetical scenario of land transfer, indicating increased adoption (ATU = 1.088). These findings suggest that land transfer significantly boosts AGPTs adoption, supporting H1.

Robust test

Propensity score matching. To ensure robustness, the propensity score matching (PSM) method was applied to estimate the impact of land transfer on farmers' adoption of AGPTs. PSM mitigates selection bias using four techniques: nearest-neighbour matching, caliper matching (0.05 range), kernel matching (default functions and bandwidth), and local linear regression matching. Table 6 shows that the ATT of land transfer on farmers' adoption of AGPTs is significantly positive, consistent with the ESR model findings, confirming their robustness.

Replacing explanatory variables and models

This study replaces the binary land transfer variable with transferred land size. Table 7 shows the results: column (1) reflects the impact of the land transfer on farmers' adoption of AGPTs, while column (2) examines the effect of the land transfer scale. The scale has a significant positive impact on farmers' adoption of AGPTs, consistent with column (1). Columns (3) and (4) use Poisson regression, confirming the significance and consistent impact direction. These findings show that land transfer significantly boosts farmers' adoption of AGPTs, even across model variations.

Mediation effect analysis

This study further analyses the mechanisms through which land transfer promotes farmers' adoption of AGPTs, incorporating a detailed examination of household income, financing support, and agricultural socialised services.

Land transfer promotes the adoption of AGPTs by farmers by increasing household income and increasing financing support. The estimation results in Table 8, column (1) indicate that land transfer significantly enhances the adoption of AGPTs among farmers. Column (2) reveals that land transfer notably increases household income. In Column (3), which includes both land transfer and household income, both factors exhibit a significant positive impact on farmers' adoption of AGPTs, confirming a significant mediating effect of household income. In addition, results from models (1), (4), and (5) indicate that land transfer significantly improves financing support, and when both land transfer and financing support are considered, each positively impacts AGPTs adoption behaviour, thereby validating H2 regarding the significant mediating effect of financing support.

Land transfer promotes the adoption of AGPTs by farmers by increasing agricultural socialised services. A mutually reinforcing relationship between land transfer and agricultural socialised services results in estimation bias due to endogeneity. To address this, the instrumental variable method will be used, with biological disasters—specifically, wild boar damage to agriculture—as the instrumental variable (Qu and Zhao, 2021). In Table 9, Column (1) shows that biological disasters significantly negatively impact land transfer. Column (2) indicates that land transfer positively influences agricultural socialised services, suggesting that increased land transfer enhances these services. The Wald test value of 2.79 confirms the overall statistical significance of the model. Column (3) demonstrates that land transfer and agricultural socialised services positively affect AGPTs adoption, implying that land transfer enhances agricultural production scale and productivity through socialised services, hereby lending support to H3.

Heterogeneity analysis

Heterogeneity under different transition scenarios. It examines the effects of different transfer contracts, term lengths, and rents on the adoption of AGPTs. Land transfer contracts can be categorised into no contract, oral and written agreements. In line with the study's framework, undetermined transfer periods are classified into short-term (below 1), middle-term (1–4 years), and long-term (over 5 years) categories. Furthermore, land transfer rents are categorised as zero rent (no payment), low rent (up to 100 yuan), moderate rent (100–500 yuan), and high rent (above 500 yuan).

Table 7 Replace variables and replace model.

Variables	(1) Oprobit	(2) Oprobit	(3) Poisson regression	(4) Poisson regression
Land transfer	0.307*** (0.084)		0.310*** (0.077)	
The scale of land transfer		0.125*** (0.035)		0.106*** (0.020)
Control variable	Controlled	Controlled	Controlled	Controlled
Constants			−1.715*** (0.310)	−1.585*** (0.312)
Pseudo R^2	0.052	0.051	0.060	0.058
N	1020	1020	1020	1020

Notes: The table presents standard errors in parentheses. The levels of significance are denoted by ***, **, and *, which signify statistical significance at the 1%, 5%, and 10% thresholds, respectively.

Table 9 Analysis of the mechanism of agricultural socialised service.

Variables	(1) The first stage: land transfer	(2) the second stage	(3) Adoption of AGPTs
Land transfer		2.769* (1.577)	0.287*** (0.085)
Biological disasters	−0.022*** (0.008)		
Agricultural socialised services			0.214** (0.101)
Control variable	Controlled	Controlled	Controlled
Pseudo R^2			0.053
Wald test		2.79*	
N	1020	1020	1020

Notes: The table presents standard errors in parentheses. The levels of significance are denoted by ***, **, and *, which signify statistical significance at the 1%, 5%, and 10% thresholds, respectively.

Table 8 Analysis of the mechanism of household income and financing support.

Variables	(1) Adoption of AGPTs	(2) Household income	(3) Adoption of AGPTs	(4) Financing support	(5) Adoption of AGPTs
Land transfer	0.307*** (0.084)	0.137* (0.083)	0.298*** (0.085)	0.186* (0.105)	0.299*** (0.084)
Household income			0.082*** (0.027)		
Financing support					0.165** (0.080)
Control variable	Controlled	Controlled	Controlled	Controlled	Controlled
Pseudo R^2	0,052	0.058	0.055	0.078	0.053
N	1020	1020	1020	1020	1020

Notes: The table presents standard errors in parentheses. The levels of significance are denoted by ***, **, and *, which signify statistical significance at the 1, 5, and 10% thresholds, respectively.

Table 10 The impact of land transfer on the adoption of AGPTs by farmers under different transfer scenarios.

Variable		Land transfer	No Land transfer	ATT	Standard error	*T* value	Sample size
Land Transfer Contract	No contract	0.981	0.800	0.181	0.151	1.20	759
	Oral contract	1.124	0.580	0.548	0.212	2.59***	761
	Written contract	1.750	0.550	1.200	0.364	3.30***	694
Land transfer period	Short-term	1.000	0.725	0.275	0.154	1.78**	829
	Middle-term	1.319	0.739	0.580	0.336	1.73**	701
	Long-term	1.579	0.825	0.754	0.309	2.44***	684
Land transfer rent	Zero rent	1.040	0.787	0.253	0.155	1.64	762
	Lower rent	0.944	0.756	0.188	0.298	0.63	682
	Medium rent	1.472	0.669	0.803	0.337	2.39***	789
	Higher rent	1.800	0.600	1.200	1.095	1.10	499

Note: The levels of significance are denoted by ***, **, and *, which indicate statistical significance at the 1%, 5%, and 10% thresholds, respectively.

Table 11 The impact of land transfer on the adoption of AGPTs by farmers under different land endowments.

Variable		Land transfer	No Land transfer	ATT	Standard error	*T* value	Sample size
Paddy field area	Small farmers	1.139	0.973	0.167	0.111	1.51	850
	Large-scale	1.340	0.613	0.727	0.396	1.83**	80
Paddy field fertility	Low score group	0.793	0.586	0.206	0.338	0.61	138
	High score group	1.310	0.762	0.548	0.176	3.11***	822
Land fragmentation	Low score group	1.309	0.604	0.705	0.236	2.99***	647
	High score group	1.103	0.673	0.430	0.162	2.65***	383

Note: The levels of significance are denoted by ***, **, and *, which indicate statistical significance at the 1%, 5%, and 10% thresholds, respectively.

Table 10 shows that compared with other land transfer contracts, written contracts have significantly promoted the adoption of AGPTs, increasing by 1.200 percentage points respectively. Compared with other land transfer periods, the long-term significant transfer promoted the adoption of AGPTs, increasing by 0.754 percentage points. Regarding rent categories, moderate rent notably boosts adoption, while low and high rents show no significant effect. This aligns with Zhang et al. (2022), which found that zero rent decreases land efficiency, whereas high rent increases operational costs, limiting financial resources for green investments.

Heterogeneity of land endowments among different farmers. In this research, farmers are further categorised based on paddy field area, fertility, and land fragmentation. Paddy fields are classified as small (less than 2 hectares) or large-scale (more than 2 hectares). Paddy field fertility is measured on a five-point scale, with scores below 3 considered low and above 3 considered high. Land fragmentation is assessed by the ratio of paddy field area to the number of field blocks, divided by the mean, above 1.130 is high, and below 1.130 is low.

According to Table 11, land transfer significantly promotes adoption among large-scale farmers. Paddy field fertility, reflecting natural land endowment, also influences adoption. Land transfer significantly promotes adoption among farmers with higher fertility. Land fragmentation affects the unit cost of technology adoption. Compared to those with high fragmentation, land transfer significantly promotes adoption increases by 0.705 percentage points for farmers with low fragmentation.

Discussion, implications, and conclusion

Based on a large-scale survey conducted in July 2023 among farmers in Jiangxi Province, China, this study analyses grain farmers' adoption of AGPTs, the characteristics of farmland operation rights transfer, and the profiles of farmers and investigates the relationship between land transfer and AGPTs adoption behaviour by using the ESR model. The results indicate that farmers acquiring additional land are more likely to adopt AGPTs. Land transfer, a key aspect of China's rural land system reform, provides an important pathway for farmers to engage in agricultural production and expand their operations (Zhou et al., 2020). Acquiring additional land reallocates resources and inputs, creating favourable conditions for adopting AGPTs, while enabling farmers to pursue clearer agricultural goals and efficient, sustainable development (Zhang et al., 2022).

Previous studies have largely explored the connection between land scale and farmers' green production practices, specifically how land management scale affects orchard farmers' adoption of AGPTs (Zhang & Liu, 2021). However, less is understood about the impact of land transfer on farmers' adoption of AGPTs. This study reveals that land transfer supports farmers' adoption of AGPTs by increasing household income, offering financing support, and enhancing agricultural socialised services. While high costs and resource limitations hinder AGPTs adoption, acquiring additional land helps farmers overcome these barriers (Adnan et al., 2019a). Greater income and access to low-interest loans and subsidies further enable farmers to invest in AGPTs and assume associated risks (Zeng, 2023). Additionally, agricultural socialised services facilitate information dissemination of AGPTs, and as farmers expand their land, they receive increased support through professional assistance, strengthening their knowledge and application of AGPTs (Gao et al., 2023).

This study further reveals that farmers' adoption of AGPTs varies by land transfer type and the characteristics of land endowments. This aligns with the literature suggesting that written contracts, extended transfer periods, and fair rental fees encourage the adoption of AGPTs (Zhang et al., 2024a). Written contracts and long-term land transfers provide stable land use rights that reduce investment uncertainty, encouraging long-term investment and new production methods, while appropriate rental fees lower operational costs, increase profitability, and promote the adoption of AGPTs (Li et al., 2024).

Furthermore, land transfer significantly impacts large-scale farmers, those with higher rice field fertility, and farmers with lower land fragmentation. Large-scale farmers typically have greater economic strength and technical capability, enabling more effective resource utilisation (Qu et al., 2023). By acquiring additional land, they can adopt new technologies to maintain soil fertility's economic and ecological advantages, ensuring higher output and better product quality (Turner, 2016). With more concentrated resources, farmers facing lower land fragmentation can achieve scalable management in green technology applications, simplifying management and improving resource efficiency (Guo and Wang, 2024).

Implications

This research has important theoretical and practical significance. Promoting sustainable agricultural production is conducive to food security and environmental protection, especially in developing countries where agriculture is seriously polluted (Adnan et al., 2019b). The economic effect of land transfer drives farmers to adopt the circulation of agricultural contractual management rights. Theoretically, this study has deepened the understanding of the green production effect and its mechanism of land transfer.

Consequently, policymakers should enhance the land transfer market, encouraging capable farmers to transfer land while ensuring that adjustments in land management rights optimise resource allocation. Establishing special green production subsidies can motivate land transferors to adopt sustainable technologies. Strengthening the technical support of agricultural social services will equip farmers with the knowledge and skills needed for adopting agricultural production technologies.

Moreover, standardising land transfer contracts, ensuring the long-term nature of land leases, and maintaining reasonable land rent is essential for expanding land management scales and encouraging the adoption of agricultural contractual management rights. Finally, providing tailored technical training based on farmers' land endowments will help ensure that they can effectively implement technologies suited to their specific conditions.

Conclusion

The study demonstrates that farmers who have acquired land through transfer adopt AGPTs at a significantly higher rate than those who have not. Land transfer facilitates the adoption behaviour of AGPTs by increasing household income, providing financing support, and enhancing agricultural socialised services. Specifically, land transfer scenarios involving written contracts, long-term agreements, and moderate rent significantly promote farmers' adoption of AGPTs. Furthermore, land transfer has a more pronounced effect on farmers' adoption of AGPTs among large-scale farmers, those with higher paddy field fertility, and farmers with less fragmented land.

Data availability

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions
YP drafted the initial manuscript and analyzed the data, and YP and JG conceptualised and designed the study. YL and LL analyzed the data and reviewed the manuscript, and LL and SJ carried out the initial analysis, YL and YT reviewed and revised the manuscript. YP and YT revised and polished the manuscript. JG and YT provided supervision on the manuscript. All authors approved the final manuscript.

Competing interests
The authors declare no competing interests.

Ethical approval
This study has been ethically reviewed and approved by the Jiangxi Agricultural University Science and Technology Ethics Committee (No. JXAULL-2023-05-07, approval date: 21 May 2023). All procedures in this study were in accordance with the institutional research guidelines and the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent
The researchers analysed survey data collected from the School of Economics and Management at Jiangxi Agricultural University in July and August 2023. All participants provided written informed consent before completing the questionnaire. Anonymity was fully ensured, and participants were informed that the survey's purpose and data usage were solely for academic research. No personal identifying information was collected, ensuring the confidentiality of participants. Participation was voluntary, with the option to withdraw at any time, and there were no conflicts of interest or potential risks. The study excluded vulnerable groups, limiting participation to individuals who met specific criteria.

Additional information
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