

Article

Why Do Farmers Leave Land Idle? Unpacking the Role of Farmland Fragmentation and Mechanization Constraints in Farmland Abandonment Behavior

Peng Cheng ^{1,2}, Yuru Wang ¹, Ke Liu ^{3,*}, Xuesong Kong ⁴, Houtian Tang ^{5,*}, Yu Cheng ¹ and Jinrun Chen ¹

- ¹ School of Management, Wuhan Institute of Technology, Wuhan 430205, China; chengpeng1141@wit.edu.cn (P.C.); wangyuru@stu.wit.edu.cn (Y.W.); 22506010011@stu.wit.edu.cn (Y.C.); 22506010054@stu.wit.edu.cn (J.C.)
- ² Research Center for Coordinated Development of Enterprises and Environment, Key Research Institute of Humanities and Social Sciences in Hubei Province, Wuhan Institute of Technology, Wuhan 430205, China
- ³ School of Public Administration, Huazhong Agricultural University, Wuhan 430070, China
- ⁴ School of Resource and Environmental Sciences, Wuhan University, Wuhan 430079, China; xuesongk@whu.edu.cn
- ⁵ School of Public Affairs, Xiamen University, Xiamen 361005, China
- * Correspondence: kliu@webmail.hzau.edu.cn (K.L.); tanghoutian@stu.xmu.edu.cn (H.T.)

Abstract

Under the dual pressures of increasing fragmentation of farmland and profound changes in the agricultural labor force, the problem of abandoned farmland in rural China has become increasingly prominent, posing a serious threat to food security. Previous studies have mainly focused on the impact of socioeconomic factors on farmland abandonment behavior; however, there remains a lack of systematic investigations into the underlying mechanisms through which farmland fragmentation influences farmers' land-use decisions. Therefore, this study applies behavioral theory to construct a "fragmentation–mechanization–abandonment" analytical framework to analyze the potential mechanisms of land-use decision-making. Using micro-level household survey data from multiple provinces across China, we conduct empirical tests through Probit models and Karlson Holm and Breen (KHB) mediation effect analysis. Our findings include: (1) Farmland fragmentation significantly increases the probability of farmland abandonment, which remains robust across multiple tests. (2) Farmland fragmentation indirectly influences abandonment behavior through the mediating variable of agricultural mechanization level, but this mechanism plays only a partial mediating role. (3) Heterogeneity tests indicate that the positive effect of farmland fragmentation is significantly stronger among households with low access to finance than among those with high access to finance. This influence is also stronger among households with high farmland accessibility. This study indicates that abandonment governance requires moving beyond a singular focus on land consolidation and shifting toward a synergistic approach that combines differentiated regional strategies with targeted support for smallholders. From a micro-mechanism perspective, this study provides empirical evidence for targeted implementation of land consolidation and livelihood support for smallholders, offering important policy implications for achieving agricultural modernization.

Keywords: farmland fragmentation; agricultural mechanization level; farmland abandonment behavior; impact path; China

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1. Introduction

According to the United Nations World Population Prospects 2024 report, the global population had reached nearly 8.2 billion by mid-2024 and is projected to increase by another 2 billion over the next 60 years, feeding this growing population poses significant challenges to global cropland systems [1,2]. Farmland, as the fundamental resource for agricultural production, provides multiple services including food supply, ecological regulation, and social security [3–5]. However, rapid urbanization and industrialization have driven a large rural labor force shift to non-agricultural industries [6], leading to farmland abandonment in many regions globally, particularly in mountainous areas and regions with low agricultural production efficiency [7]. This transition in land-use not only directly reduces effective food supply [8] but also intensifies the dual pressures of population growth and resource constraints [9,10]. Furthermore, it may trigger ecosystem degradation, such as accelerated soil erosion [11], biodiversity loss, and rural landscape fragmentation [12]. Against this backdrop, optimizing land resource allocation and enhancing farmland utilization efficiency have become critical challenges faced by countries worldwide [13,14]. China feeds nearly 20% of the world's population with only 9% of the arable land, yet its food security faces increasingly severe structural challenges [15,16], and the trends of declining quantity, deteriorating quality, and spatial fragmentation of arable land resources remain fundamentally unresolved [17]. More critically, due to historical factors and rising production costs, the fragmentation of farmland is widespread across China, posing a crucial structural obstacle constraining agricultural modernization and inducing farmland abandonment [18,19].

Farmland abandonment, as an extreme negative form of land utilization, has become a severe challenge in many regions globally, particularly in mountainous and marginal agricultural areas [20–22]. Previous studies have revealed the driving mechanisms behind farmland abandonment from multiple dimensions, including natural constraints [23], socioeconomic changes [24], low comparative efficiency in agricultural production, and institutional factors [25,26]. Among these, farmland fragmentation is widely recognized as a key factor inducing or exacerbating farmland abandonment due to its profound impact on agricultural production costs, efficiency, and farmer decision-making [27].

Farmland fragmentation generally refers to the division of land into spatially dispersed small plots [28,29], whose formation is influenced by multiple factors including natural geographical conditions, land tenure systems, and socioeconomic transformations [30–32]. In specific contexts, such as high ecological heterogeneity, dense populations, imperfect markets, and market-oriented agricultural systems, moderate fragmentation may promote crop diversification [33], thereby increasing ecological resilience [34], dispersing production risks [35], and adapting smallholder livelihood strategies to enhance agricultural production resilience [36,37]. However, farmland fragmentation can also have negative impacts on agricultural efficiency, as it is indicated to increase production costs, limit mechanization [38], and reduce land productivity [39,40], ultimately leading to the waste of arable land resources and undermining agricultural production and food security [41]. Existing studies have primarily established the linkage between farmland fragmentation and farmland abandonment from a cost–benefit perspective, suggesting that fragmentation increases the time costs, labor inputs, and management difficulties of agricultural production. This further reduces economies of scale and economic returns in farming, thereby raising the probability of farmers abandoning their farmland [42,43]. However, the specific mechanisms through which farmland fragmentation influences farmer decisions and the heterogeneity of its effects remain to be explored through in-depth theoretical frameworks and rigorous empirical testing.

Agricultural mechanization constitutes a key pathway for enhancing labor productivity, reducing production costs, and addressing labor shortages [16,44], and is also regarded as an effective means of curbing the abandonment of farmland [45]. However, farmland fragmentation directly increases the time costs and fuel consumption associated with transferring machinery between fields, reduces the applicability of large-scale and high-efficiency agricultural equipment, and even increases operational difficulty and losses due to numerous field boundaries, further inhibiting the adoption of agricultural mechanization [46]. When this critical pathway for labor substitution is impeded, the pressure of rising labor costs becomes difficult to mitigate through technological means, and the risk of farmland abandonment increases accordingly. Although existing literature has preliminarily explored the impact of farmland fragmentation on land-use degradation, empirical testing of the critical transmission pathway of “fragmentation–mechanization–farmland abandonment” remains insufficient. Most studies either analyze the direct impact of fragmentation on farmland abandonment in isolation or examine the role of mechanization in agricultural productivity, lacking a quantitative assessment of mechanization’s mediating role in the “fragmentation–abandonment” relationship. During this process, household access to finance determines whether farmers can mobilize working capital for machinery services, hired labor, transportation, and temporary operating losses. Farmland accessibility, in turn, shapes the spatial costs of reaching, supervising, and coordinating dispersed plots. These two dimensions represent distinct but complementary household and production constraints that may alter the marginal effect of fragmentation. Against this background, this study aims to address three questions: (1) Does farmland fragmentation directly drive farmers’ abandonment decisions, and to what extent? (2) To what extent does agricultural mechanization mediate the effect of farmland fragmentation on abandonment? (3) Does the effect of fragmentation vary with household access to finance and farmland accessibility? By addressing these questions, this study aims to re-frame farmland fragmentation from a targeted efficiency-loss perspective to a distributional one, revealing the structural inequality underlying farmland abandonment, and providing theoretical foundations and empirical supports for optimizing land-use and formulating differentiated farmland protection policies.

2. Theoretical Framework and Research Hypothesis

According to farmland household behavior theory, farmers, as bounded-rational decision-makers, follow the fundamental principle of “cost–benefit” trade-offs in production decisions. When expected returns from farmland management exceed costs, farmers tend to maintain cultivation. However, when costs persistently rise and returns are continuously squeezed, farmers may choose to reduce inputs or even abandon cultivation [47,48]. As a prominent feature of China’s agricultural management system, farmland fragmentation profoundly impacts farmers’ cost structures and profit expectations. From the cost perspective, fragmented plots directly increase farming difficulty, raising management, labor coordination, and machinery transfer costs, thereby reducing farmland management efficiency. On the revenue side, fragmentation constrains mechanization adoption, economies of scale, and factor allocation, thereby reducing potential output. When rising costs and declining revenues jointly squeeze operating profits, rational farmers may choose to abandon their farmland. Within this framework, this study systematically elucidates the theoretical logic of how farmland fragmentation influences farmland abandonment behavior through direct, indirect, and heterogeneous effects (Figure 1).

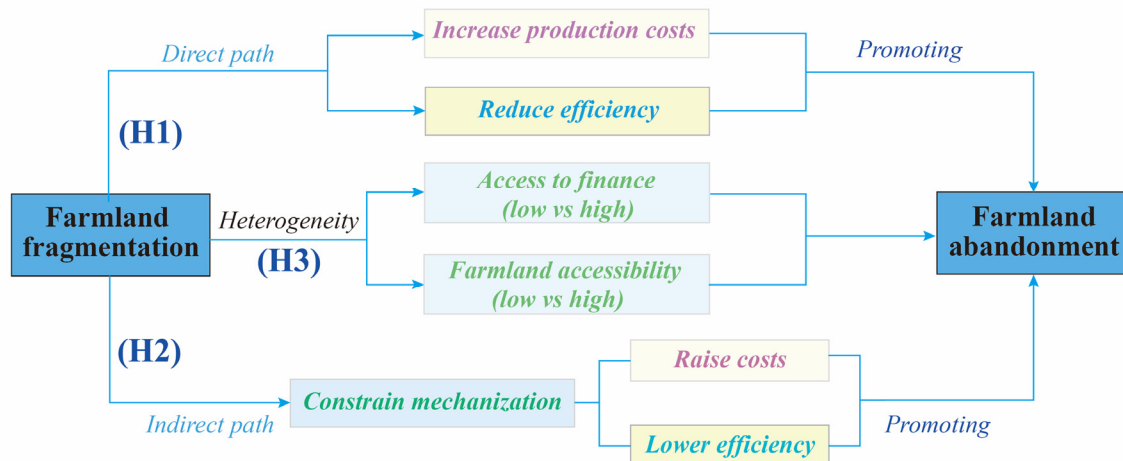


Figure 1. Theoretical framework.

2.1. Direct Impact of Farmland Fragmentation on Farmland Abandonment Behavior

Farmland fragmentation directly increases the physical difficulty and overall costs of cultivation, thereby influencing farmers' operational decisions. Fragmented plots significantly extend farmers' travel time between fields and increase the scheduling costs of agricultural machinery. These additional factor inputs directly raise production costs per unit area [49,50]. Simultaneously, fragmented plots constrain the effective coverage of standardized farmland development and modern irrigation facilities [51,52], reducing farmland's resilience to risks and its potential output. When the marginal costs of supervision, coordination, and transportation for managing fragmented plots consistently exceed the marginal benefits, rational households will reduce or abandon cultivation. They will instead allocate limited labor or capital to higher-return activities including non-agricultural employment. Therefore, we propose the following hypothesis:

Hypothesis 1. *A higher degree of farmland fragmentation means a greater likelihood that farmers will abandon their farmland.*

2.2. Indirect Effects of Farmland Fragmentation on Farmland Abandonment Behavior

Fragmented farmland not only increases direct costs but also indirectly contributes to farmland abandonment behavior by constraining the efficient allocation of key production factors. As a crucial pathway for enhancing labor productivity, reducing production costs, and addressing labor shortages, agricultural mechanization is likely to serve as a mediating variable linking fragmentation to farmland abandonment behavior [53,54]. Limited adoption of agricultural mechanization and the resulting efficiency losses represent one of the key pathways. Mechanization can effectively alleviate labor shortages and sustain farmers' willingness to cultivate, preventing abandonment of farmland. As non-agricultural employment opportunities increase and the opportunity cost of agricultural labor rises, mechanization serves as a vital means for farmers to address labor constraints and maintain continuous farmland operation. However, a fundamental contradiction exists between the spatial patterns created by fragmented farmland and the contiguous, level conditions required for mechanized operations. Fragmentation leads to time-consuming and fuel-intensive transfers among plots for farm machinery, while also complicating negotiations between farmers and machinery service providers, making quality supervision of operations more difficult [55]. Even if improving mechanization conditions proves to be an effective strategy for alleviating farmland abandonment in mountainous

areas, its effectiveness largely depends on whether the farmland meets the basic conditions for contiguous operations, which fragmented farmland often fails to satisfy [56]. Although technological innovation and socialized agricultural machinery services can partially mitigate these conflicts, the economic costs and technical barriers to mechanization on fragmented farmland are generally higher. Under these circumstances, operational efficiency and economic returns often fall significantly below those of contiguous land [57,58], severely dampening farmers' willingness and ability to adopt mechanization as a labor substitute. This impeded mechanization prevents agricultural production from achieving economies of scale, hinders effective labor substitution, and maintains high reliance on manual labor. Consequently, labor costs per unit of output remain elevated, further eroding operating profits and diminishing the economic value of farmland. Fragmented farmland continuously weakens profitability through the chain of "inhibiting mechanization adoption–raising production costs–reducing operational efficiency", making abandonment a rational exit strategy. Based on this, we propose the following hypothesis:

Hypothesis 2. *Fragmentation of farmland indirectly increases the probability of farmers abandoning their farmland by reducing the level of agricultural mechanization.*

2.3. Heterogeneous Effects Under Financial and Accessibility Constraints

Farmers facing similar degrees of farmland fragmentation may not make identical land-use decisions because their capacity to absorb additional operating costs and the spatial conditions of production differ. Within the household decision framework, fragmentation changes the relative costs and returns of continued cultivation, while household access to finance and farmland accessibility determine whether these additional costs can be absorbed or become binding constraints. The two factors therefore constitute complementary boundary conditions for the relationship between farmland fragmentation and abandonment.

Household access to finance shapes farmers' capacity to undertake productive agricultural investment under credit and risk constraints [59]. Operating dispersed plots requires payments for machinery services, hired labor, transportation, input delivery, and field supervision. These expenditures may intensify seasonal liquidity pressure. Experimental evidence shows that easing lean-season liquidity constraints increases on-farm labor input and agricultural output [60]. Fragmentation may consequently force farmers to reduce inputs or withdraw from cultivation even when expected agricultural returns remain positive over the full production cycle. By contrast, households with high access to finance can hire machinery and labor, maintain necessary inputs, and absorb short-term losses, thereby reducing the likelihood that additional fragmentation costs lead directly to abandonment. Evidence from rural finance research further shows that access to institutional finance increases both the probability and extent of agricultural technology adoption [61]. Research on mechanization-service systems also indicates that service-provider models can improve smallholders' access to appropriate mechanization [62].

Farmland accessibility affects the baseline spatial costs of managing dispersed plots. Low farmland accessibility raises the time and transportation costs of reaching dispersed plots and makes remote parcels more difficult to manage. Evidence from mountainous China shows that parcels located farther from agricultural laborers' residences are more likely to be abandoned [63]. Its interaction with fragmentation, however, is not necessarily unidirectional. Where poor access already constitutes the dominant constraint on cultivation, abandonment may be driven primarily by road conditions and field-entry barriers, leaving comparatively little marginal variation to be explained by fragmentation. Once basic access conditions improve, repeated movement among plots, machinery scheduling,

and cross-plot coordination may become more salient in farmers' operating decisions, making fragmentation a more visible constraint. Site-specific evidence further identifies land quality, proximity to forest edges, and distance from the farm as strong determinants of farmland abandonment [64]. Multi-scale evidence from mountainous China shows that the determinants of abandonment differ across spatial scales, cropland fragmentation and distance to the nearest settlement are influential at the local scale, whereas distance to the county center and agricultural mechanization are more relevant at the regional scale [27]. Because these mechanisms imply no unambiguous ex ante direction, the effect of farmland accessibility is specified as a non-directional heterogeneity hypothesis.

Hypothesis 3. *The effect of farmland fragmentation on farmland abandonment varies with household access to finance and farmland accessibility.*

Hypothesis 3a. *The positive effect of farmland fragmentation on abandonment is stronger among households with low access to finance than among those with high access to finance.*

Hypothesis 3b. *The effect of farmland fragmentation on abandonment differs between households with low and high farmland accessibility.*

3. Data and Statistical Description

3.1. Study Area

China feeds nearly 20% of the world's population with only about 9% of the world's arable land, placing immense pressure on protecting its farmland resources. China has a total arable land area of about 128 million hectares, but the per capita arable land is less than 0.1 hectares, far below the global average. Influenced by the historical evolution of the household responsibility system and complex topographical conditions, China faces a particularly acute problem of fragmented farmland. This is especially pronounced in hilly and mountainous regions, where typical characteristics include a high number of plots per household, small average plot sizes, and scattered distribution. This severely constrains the development of large-scale agricultural operations and the adoption of modern production factors. Concurrently, rapid urbanization and industrialization have driven continuous labor migration from agriculture to non-agricultural sectors, resulting in an aging and feminized agricultural workforce. Against this backdrop, selecting China's hilly and mountainous regions as the research area holds significant theoretical and practical value. First, these areas epitomize multiple challenges confronting contemporary Chinese agriculture, including farmland fragmentation, structural labor shifts, rapid mechanization development, and rising risks of farmland abandonment, making them the concentrated and globally representative regions for these contradictions. Second, the household-contracted land tenure system has shaped a vast and a large population of smallholder decision-makers. Exploring the mechanisms of farmland fragmentation on household behavior within this institutional framework helps deepen our understanding of the interactive dynamics between farmland tenure structures and factor allocation, thereby broadening the theoretical horizons of land economics. Finally, the widespread and complex causes of farmland abandonment in hilly and mountainous areas offer profound insights from a Chinese case study for agricultural transformation in analogous global regions.

3.2. Variable Selection and Data Sources

3.2.1. Variable Definitions

(1) Dependent variable

Following existing literature [65], this study selects “farmland abandonment behavior” as the dependent variable to estimate the impact of core explanatory variables and control variables on such behavior. Drawing on the Land Administration Law of the People’s Republic of China and related research [66], this study defines “farmland abandonment behavior” as that farmland under household contract or management has remained unseeded or unmanaged for one or more consecutive seasons for a complete agricultural year preceding the survey date, excluding cases involving intentional agronomic practices such as crop rotation or fallowing. According to the descriptive statistics reported in Table 1, approximately 49.2% of the surveyed households reported having abandoned farmland. This proportion reflects the characteristics of the hilly and mountainous sample areas examined in this study, such regions feature complex topography, severe fragmentation of farmland, and abundant non-agricultural employment opportunities. Historically, these areas have been prone and high-incidence zones for farmland abandonment, providing ample data sources for identifying the impact mechanism of fragmentation on farmland abandonment behavior in this research.

Table 1. Variable definitions and descriptive statistics.

Variable Type	Indicator Settings	Indicator Definition	Mean	Standard Deviation
Dependent variable	Farmland abandonment behavior	Whether farmers abandon farmland: 1 = Yes, 0 = No	0.492	0.500
Explanatory variable	Farmland fragmentation	Number of farmland plots/Total managed area (mu)	1.260	1.181
Mediating variable	Agricultural mechanization level	Farmers’ comprehensive capacity to access mechanization services 1 = No machinery, relying on manual labor; 2 = Almost no equipment, occasional hiring/renting when necessary; 3 = Only a small amount of simple equipment; 4 = Some types available; 5 = Multiple types available	1.951	1.060
Control variables	Gender	Gender of the respondent: 1 = Male, 0 = Female	0.594	0.491
	Age	Age of the respondent: 1 = 30 and below; 2 = 31–40; 3 = 41–50; 4 = 51–60; 5 = 61 and above	3.852	1.166
	Educational level	Respondent’s educational attainment: 1 = Elementary school or below; 2 = Junior high school; 3 = High school/vocational school/technical school; 4 = Junior college; 5 = Bachelor’s degree or above	1.788	0.964
	Political affiliation	Whether the respondent is a member of the Communist Party of China: (1 = Yes; 0 = No)	0.093	0.291
	Number of household laborers	Total number of household labor force	3.175	1.460
	Cadre	Whether any household member has served as a village cadre: 1 = Yes; 0 = No	0.186	0.389

Agricultural technical training	Access to agricultural technical training: 1 = Not interested at all; 2 = Want to participate but lack opportunity; 3 = No recollection; 4 = Occasionally participate; 5 = Frequently participate	2.867	1.017
Fertility	Soil fertility of cultivated land: 1 = Extremely infertile; 2 = Poor; 3 = Average; 4 = Fairly fertile; 5 = Extremely fertile	3.325	0.823
Irrigation	Irrigation conditions of cultivated land: 1 = Very poor; 2 = Poor; 3 = Average; 4 = Fairly good; 5 = Very good	2.912	1.152
Topography	1 = Mountainous; 2 = Hilly; 3 = Terraced; 4 = Plain	2.154	1.220

(2) Core explanatory variable

This study selects “farmland fragmentation” as the core explanatory variable. Fragmentation reduces agricultural economic efficiency by increasing production costs, thereby prompting farmers to abandon farmland. Existing studies commonly measure farmland fragmentation using indices such as the Global Land Fragmentation Index, Simpson Index, Januszewski Index, or the number of farmland parcels managed by households [67]. Drawing on prior literature [68] and considering data availability, this study employs the ratio of “number of parcels/total area” as the fragmentation measure. A higher ratio indicates more parcels per unit area and greater fragmentation.

(3) Mediating variable

To explore the underlying mechanism linking farmland fragmentation to abandonment, this study, drawing on existing research and considering data availability [69], introduces the “agricultural mechanization level” as the mediating variable. This indicator comprehensively reflects both farmers’ equipment ownership and access to socialized services. In the absence of precise data on mechanized operation areas, it reasonably approximates the actual mechanization level experienced by farmers. Based on the types of agricultural machinery owned by farming households and their access to commercial agricultural services, this study developed an ordinal scale ranging from 1 to 5. The gradient from “no machinery at all” to “multiple types of equipment” reflects the incremental advancement in farmers’ agricultural mechanization level. It should be noted that farmers who access hired or rented services may achieve higher levels of mechanization through a well-developed service market, and their actual level of mechanization may exceed that of farmers who “own a small amount of simple equipment”. This is an inherent limitation and will be interpreted with caution in subsequent analyses in light of the theoretical framework. To verify the measurement quality of this scale, this study conducted tests in three areas, including predictive validity, discriminant validity, and robustness. The results show that the level of agricultural mechanization is significantly negatively correlated with farmland abandonment behavior ($OR = 0.741, p < 0.001$) and exhibits a monotonically decreasing trend, indicating that the scale possesses good predictive validity. The level of agricultural mechanization is significantly negatively correlated with farmland fragmentation ($\rho = -0.201, p < 0.001$), consistent with theoretical expectations, indicating good discriminant validity. These indicate that conclusions remain robust after binary coding and controlling for covariates. Since the scale is a single-item ordinal measure, Cronbach’s α is not applicable. Overall, this scale demonstrates good validity and robustness as a measure of agricultural mechanization levels.

(4) Control Variables

To isolate the influence of other potential factors on farmland abandonment behavior, this study introduces control variables at three levels, including individual farmer characteristics, household characteristics, and farmland endowment characteristics. Each variable is grounded in theoretical rationale and empirical evidence. Individual characteristics, such as the respondent's gender, age, education level, and the political status, may influence abandonment decisions through pathways affecting cultivation willingness, labor capacity, risk preferences, and policy responsiveness. Households with more laborers typically maintain cultivation longer, while households in which members have served as village officials or received agricultural training often have advantages in accessing policy information, agricultural subsidies, and technical support, which can reduce the tendency to abandon farmland. At the land endowment level, factors such as soil fertility, irrigation conditions, and terrain can influence farmers' decisions to abandon farmland by affecting land productivity potential and cultivation difficulty.

3.2.2. Data Sources

The data for this study were collected during field surveys conducted in rural areas by more than 50 faculty members and students during the winter and summer breaks from January to February 2025 and July to August 2025. The surveys covered typical hilly and mountainous regions in Hubei, Hunan, Jiangxi, Fujian, Henan, and Guangxi and other representative agricultural provinces in China (Figure 2). These regions feature complex topography and a high degree of farmland fragmentation, and they are characterized by widespread labor outflow and limited non-agricultural employment opportunities, making them ideal areas for studying the relationship between farmland fragmentation and abandonment. The sampling process combines stratified and random sampling methods, taking into account both topographical features and economic development levels to ensure balanced coverage of the sample. Using a systematic random sampling method, counties across the province were divided into three groups based on per capita Gross Domestic Product (GDP), and one county was randomly selected from each group as a sample county. Within each sample county, townships and villages were selected according to the same criteria. This design ensures balanced coverage of the sample in terms of regional distribution and economic development levels. Before the formal survey, the research team developed a standardized, structured questionnaire, established guidelines for interpreting the questions and response options, and trained the survey administrators to ensure consistency in data collection. Data collection employed a combination of structured questionnaires and face-to-face interviews, yielding a total of 1094 questionnaires. After rigorous data cleaning to exclude invalid questionnaires due to missing information or logical inconsistencies, 1064 valid questionnaires were ultimately obtained, representing a valid-questionnaire rate of 97.26%. This provided reliable data support for subsequent empirical analysis.



Figure 2. Overview map of the research areas. Note: The base map was produced using the standard map of the Ministry of Natural Resources, China (Review No. GS (2024) 0650), and there are no modifications to the base map.

3.3. Model Specification

3.3.1. Baseline Regression Model: Probit Model

The Probit model is a standard nonlinear probability model for handling binary discrete dependent variables. It assumes the existence of a continuous latent variable linearly related to the explanatory variables, with the random error term following a standard normal distribution. When the latent variable exceeds a certain threshold, the observable binary outcome is determined. Through maximum likelihood estimation, this model provides effective estimates of the marginal effects of core explanatory variables on the probability of outcome occurrence [70]. Farmland abandonment behavior is treated as a binary dummy variable following a binomial distribution, thus the Probit model is employed to examine the impact of farmland fragmentation on abandonment. The baseline regression model is as follows:

$$Y_i^* = \beta_0 + \beta_1 X_i + \sum_{k=1}^K \gamma_k C_{ki} + \varepsilon_i, \quad \varepsilon_i \sim N(0,1) \quad (1)$$

$$Y_i = \begin{cases} 1 & \text{if } Y_i^* > 0 \\ 0 & \text{if } Y_i^* \leq 0 \end{cases} \quad (2)$$

$$P(Y_i = 1 | X_i, C_i) = \Phi \left(\beta_0 + \beta_1 X_i + \sum_{k=1}^K \gamma_k C_{ki} \right) \quad (3)$$

Equation (1) represents the latent variable equation. Y_i^* denotes the unobservable propensity of farmer i to abandon land; X_i is the core explanatory variable representing the degree of farmland fragmentation; C_{ki} is the k th control variable encompassing individual farmer, household, and land endowment characteristics; β_0 is the constant term; β_1 and γ_k are the parameters to be estimated; and ε_i represents the random disturbance term, following a standard normal distribution and $\varepsilon_i \sim N(0,1)$. The observed outcome Y_i (whether farmer i engages in farmland abandonment) is determined by the rules in

Equation (2). When the latent variable Y_i^* is greater than zero, the observable outcome is farmland abandonment behavior ($Y_i = 1$); otherwise, it is non-abandonment ($Y_i = 0$).

Equation (3) represents the Probit model. $\Phi(\cdot)$ denotes the cumulative distribution function of the standard normal distribution, while other variables and parameters retain their previously defined meanings. This model employs maximum likelihood estimation for parameter estimation. Subsequent analyses primarily report the average marginal effect (AME) of variables to provide intuitive interpretations of the economic impacts of farmland fragmentation and other factors.

3.3.2. Mediating Effect Model

To examine the mediating pathway through which farmland fragmentation influences farmers' farmland abandonment behavior via agricultural mechanization level, this study focuses on potential transmission channel of agricultural machinery equipment level and constructs corresponding mediation models for verification. Following the standard academic paradigm for mechanism testing [71], this research confirms the mediating variables' transmission role by separating the total effect, direct effect, and indirect effect of the independent variable on the dependent variable. However, since the baseline model employs the Probit model, which is a nonlinear probability model, directly applying the traditional three-step method based on linear regression assumptions would lead to biased mediation effect estimates due to incomparable latent variable scales across equations. To address these issues and ensure robustness in mechanism testing, this study employs the Karlson Holm and Breen (KHB) method proposed by Karlson et al. [72] for mediation analysis. This method employs residualization to place the full model including the mediator and the simplified model excluding the mediator on the same latent variable scale. This enables an unbiased decomposition of the total effect and direct effect, while accurately calculating the magnitude of the indirect effect and its standard error. The specific model specification is as follows:

$$P(Y_i = 1 | X_i, Z_i, C_i) = \Phi(\theta_0 + \theta_1 X_i + \theta_2 Z_i + C_i' \gamma) \quad (4)$$

$$Z_i^* = \alpha_0 + \alpha_1 X_i + C_i' \delta + \epsilon_i, \quad \epsilon_i \sim N(0,1) \quad (5)$$

$$P(Y_i = 1 | X_i, \tilde{Z}_i, C_i) = \Phi(\beta_0 + \beta_1 X_i + \beta_2 \tilde{Z}_i + C_i' \eta) \quad (6)$$

Equation (4) represents the full Probit model incorporating the mediator variable Z_i , used to estimate the direct effect of the core explanatory variable X_i on the outcome variable Y_i after controlling for the mediator. Y_i denotes the decision to leave farmland fallow for household i (fallow = 1, not fallow = 0); X_i denotes the degree of farmland fragmentation; Z_i represents the mediating variable of agricultural mechanization level; C_i is the control variable; $\Phi(\cdot)$ denotes the standard normal cumulative distribution function; θ_0 is the constant term; and θ_1 and θ_2 are the parameters to be estimated, measuring the direct effect of farmland fragmentation and the net impact of agricultural mechanization level, respectively.

Equation (5) describes the generation process of the mediator variable Z_i . Since Z_i is an ordered categorical variable, it is underpinned by a continuous latent variable Z_i^* . This latent variable is linearly explained by the core explanatory variable X_i and the control variable C_i , with the error term ϵ_i following a standard normal distribution. The observed ordered variable Z_i is associated with the latent variable through a set of thresholds ($\kappa_1 < \kappa_2 < \dots$): $Z_i = m$, where $\kappa_{m-1} < Z_i^* \leq \kappa_m$. The parameter α_1 measures the effect of farmland fragmentation X_i on the latent variable of machinery equipment Z_i^* , constituting the first half of the mediating path.

Equation (6) is key to unbiased mediation effect estimation. Here, $\tilde{Z}_i$ is not the original mediating variable but the residual term obtained from the auxiliary regression in Equation (5), $\tilde{Z}_i = Z_i^* - (\hat{\alpha}_0 + \hat{\alpha}_1 X_i + C_i' \hat{\delta})$. This represents the portion of agricultural mechanization level that is independent of farmland fragmentation and control variables. Equation (6) is the reduced model in the KHB decomposition. The introduction of $\tilde{Z}_i$ aims to control for variance in Z_i that is unrelated to X_i . This ensures that the coefficient β_1 for X_i in this model is on the same latent variable scale as the coefficient θ_1 in the full model (Equation (4)), enabling direct comparison.

Within the KHB framework, unbiased estimates are obtained from the combination of model coefficients regarding the mediating effect of farmland fragmentation on fallow decisions via agricultural mechanization level yields. The total effect is reflected in the coefficient β_1 of the reduced model, the direct effect is shown in the coefficient θ_1 of the full model, and the indirect effect is reflected in $\beta_1 - \theta_1$. This estimator is statistically equivalent to a consistent estimate of the path product $\alpha_1 \times \theta_2$ after controlling for scale differences. The empirical analysis in this study reports the standard error and confidence interval of the indirect effect calculated via 1000 bootstrap resamples, providing a robust inference on the statistical significance of the mediating path. The KHB decomposition is implemented using the `khb` command in Stata 18.

4. Empirical Results

4.1. Comprehensive Impact of Farmland Fragmentation on Farmland Abandonment Behavior

4.1.1. Baseline Regression Analysis

To assess multicollinearity among variables in the model, this study employed Stata 18 to examine the variance inflation factor (VIF) for each independent variable. Results indicate that VIF values for all variables ranged between 1.03 and 1.42, substantially below the conventional threshold of 10, and corresponding tolerance values ($1/\text{VIF}$) ranged from 0.71 to 0.9. Although the Probit model employs maximum likelihood estimation which differs from the assumptions of linear regression, the low VIF values suggest the absence of severe multicollinearity among explanatory variables, thereby mitigating concerns regarding estimation stability to some extent. Under the condition that all other factors remain unchanged, the probability of farmland abandonment will increase by about 5.27 percentage points for each unit increase in farmland fragmentation index.

Table 2 reports the baseline regression results before and after incorporating control variables. Without control variables, the AME of farmland fragmentation on farmland abandonment behavior probability is 0.0591 ($p < 0.01$). After controlling for a series of potential influencing factors, the AME of fragmentation decreases slightly to 0.0527 ($p < 0.01$). However, at the 1% statistical level, its positive impact remains highly significant. This small change in magnitude and consistent direction indicates that the driving role of farmland fragmentation in farmland abandonment behavior is robust.

Furthermore, the inclusion of control variables significantly enhances the model's explanatory power. The model's pseudo R^2 increases from 0.0136 to 0.0479, while the significance of the farmland fragmentation coefficient remains unchanged, indicating that the model has robustness. Among the control variables, agricultural technical training and soil fertility exerted significant inhibitory effects on farmland abandonment behavior, highlighting the positive role of human capital enhancement and soil fertility maintenance in stabilizing agricultural production. Educational attainment, however, exhibited a slight pro-abandonment effect. Other variables such as gender, age, and household labor force size showed insignificant effects, suggesting that modern agricultural decisions may be driven more by economic rationality than traditional demographic characteristics. In summary, the baseline regression results strongly support research Hypothesis 1.

Table 2. Impact of farmland fragmentation on farmland abandonment behavior.

Variable	Model 1		Model 2	
	Probit	Dy/dx	Probit	Dy/dx
Farmland fragmentation	0.1504 *** (0.0382)	0.0591 *** (0.0146)	0.1391 *** (0.0390)	0.0527 *** (0.0145)
Gender			−0.0388 (0.0813)	−0.0147 (0.0308)
Age			−0.0119 (0.0398)	−0.0045 (0.0151)
Education level			0.1010 ** (0.0487)	0.0382 ** (0.0183)
Political affiliation			0.0334 (0.1503)	0.0127 (0.0569)
Number of household laborers			−0.0398 (0.0274)	−0.0151 (0.0104)
Cadre			0.0635 (0.1108)	0.0240 (0.0419)
Agricultural technology training			−0.2186 *** (0.0401)	−0.0828 *** (0.0145)
Fertility			−0.1359 ** (0.0526)	−0.0514 *** (0.0197)
Irrigation			−0.0010 (0.0374)	−0.0004 (0.0141)
Topography			−0.0551 * (0.0332)	−0.0208 * (0.0125)
Constant	−0.2070 *** (0.0598)		1.0061 *** (0.2983)	
N	1064	1064	1064	1064
R-squared	0.0136		0.0479	

Note: All values are reported to four decimal places; values in parentheses indicate robust standard errors; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.1.2. Robustness Test for Baseline Regression

To ensure the reliability of the baseline regression conclusions, this study conducts three methodological approaches. First, considering that the functional form of the binary choice model may affect estimation results, the baseline Probit model is replaced with the Logit model for re-estimation. Second, to examine whether conclusions are affected by the measurement method of the dependent variable, the binary dependent variable (farmland abandonment behavior) is replaced with a continuous variable (degree of farmland abandonment), defined as the proportion of abandoned farmland area relative to total household farmland area and estimated using the Tobit model, which is suitable for handling truncated data. Finally, to eliminate potential estimation bias from extreme outliers, all continuous variables undergo winsorization at the 1% level at both tails and are re-estimated using the Probit model. All robustness tests included the same set of control variables as the baseline model, covering 10 variables across three dimensions, including individual characteristics, household characteristics, and farmland endowment.

Table 3 reports the robustness results. The farmland fragmentation variable maintained 1% statistical significance across all three methods, with coefficients of 0.2344, 0.1068, and 0.1556, respectively. All coefficients indicated a significant positive effect, consistent with the direction observed in the baseline model. Model 3 presents Logit model

estimates, showing high consistency with Probit results, indicating that the baseline conclusion is insensitive to the specific functional form of the binary choice model. Model 4 presents Tobit model results after replacing the dependent variable, where the marginal effect of farmland fragmentation on the degree of farmland abandonment is 1.02%, also significant at the 1% level. Model 5 presents the estimated results of the Probit model after winsorization. The fragmentation coefficient is 0.1556, with a marginal effect of 5.88%, significant at the 1% level. These results closely align with the baseline model, indicating that the conclusions are not driven by extreme outliers. Overall, after conducting various robustness tests, the positive effect of farmland fragmentation on farmland abandonment behavior remained consistent. This further strengthens the reliability of the study's findings, indicating that Hypothesis 1 is robustly supported.

Table 3. Robustness tests: Model substitution and dependent variable replacement.

Variable	Model 3		Model 4		Model 5	
	Logit	Dy/dx	Tobit	Dy/dx	Probit	Dy/dx
Farmland fragmentation	0.2344 *** (0.0606)	0.0548 *** (0.0138)	0.1068 *** (0.0267)	0.0102 *** (0.0025)	0.1556 *** (0.0374)	0.0588 *** (0.0138)
Control variables	Yes		Yes		Yes	
Constant	1.5101 *** (0.4086)		0.7812 *** (0.1981)		0.9859 *** (0.2984)	
N	1064	1064	1064	1064	1064	1064
R-squared	0.0483		0.0335		0.0488	

Note: All values are reported to four decimal places; values in parentheses indicate robust standard errors; *** $p < 0.01$.

4.1.3. Endogeneity Tests

To mitigate potential endogeneity issues associated with farmland fragmentation variable, this study selects “average farmland fragmentation of other farmers in the same village, excluding the household itself” as an instrumental variable. This variable is a macro variable at the village level, and it is unlikely to directly affect individual farmers’ decision to abandon farming after removing their own samples. Simultaneously, farmers within the same village share similar topographical conditions, land allocation history, and agricultural infrastructure, which may lead to similar degree of land fragmentation. To further alleviate potential threat to the exogeneity of the instrumental variable posed by village-level common shocks, this study incorporates a farmland topography variable into the model to absorb village-level factors that may simultaneously affect both the instrumental variable and the outcome variable. Nevertheless, the exogeneity of this instrumental variable may still be affected by unobservable village characteristics, such as economic development, local institutional effectiveness, or the development of land transfer markets. In summary, “average farmland fragmentation of other farmers in the same village, excluding the household itself” serves as an instrumental variable that satisfies the requirements of correlation and exogeneity to a certain extent, and subsequent interpretation of the results should be approached with caution.

This paper employs IV-2SLS for estimation and reports the results of the Wald exogeneity test and the Durbin–Wu–Hausman test to diagnose endogeneity. Table 4 reports the endogeneity test results. The first-stage estimation reveals that the instrumental variable is positively correlated with farmland fragmentation at the 1% level, with an F-statistic of 174.87, far exceeds the 10% critical value of 16.38 for the Stock–Yogo weak instrumental variable test. It indicates no weak IV problem. Both the Wald exogeneity test and the Durbin–Wu–Hausman (DWH) test are significant at the 1% level, rejecting the null hypothesis that “farmland fragmentation is exogenous”. After correcting for endogeneity

bias, the second-stage analysis reveals that the regression coefficient for farmland fragmentation on farmers' farmland abandonment behavior is 0.1665, significant at the 1% level. Since a linear probability model is used in the second stage, the regression coefficient can be directly interpreted as a marginal effect. The marginal effect estimated via IV is approximately three times that of the average marginal effect (0.0527) in the baseline Probit model. This difference primarily stems from diversities in the identification parameters. The baseline Probit model reports the average marginal effect across the full sample, whereas the IV-2SLS identifies the Local Average Treatment Effect (LATE) for those influenced by the instrumental variable, whose magnitude is typically higher than the average effect across the entire sample [73]. Meanwhile, the instrumental variable method helps mitigate measurement error and omitted variable bias, which may also lead to the upward coefficient. These results indicate that higher levels of farmland fragmentation significantly increase the probability of farmland abandonment. In summary, the instrumental variable is valid, and the test results are robust. This approach alleviates endogeneity concerns to a certain extent and enhances the credibility of the core conclusions.

Table 4. Endogeneity test results.

Variable	Stage 1 (Farmland Fragmentation)	Stage 2 (Farmland Abandonment Behavior)
Mean fragmentation of other farmers' farmland	0.8743 *** (0.0661)	
Farmland fragmentation		0.1665 *** (0.0240)
Control variables	Yes	Yes
Constant term	0.3234 (0.2565)	0.6487 *** (0.1402)
R-squared	0.3797	0.4823
Wald exogeneity test (p)		0.0000
DWH endogeneity test		$\chi^2 = 32.79$ ($p = 0.0000$)
Weak instrumental variable test (F)	174.87 > (16.38, 10% Stock-Yogo)	

Note: All values are reported to four decimal places; values in parentheses indicate robust standard errors; *** $p < 0.01$.

4.2. Mediating Effect Analysis

4.2.1. Mediating Effect Results

To uncover the mechanism through which farmland fragmentation influences farmland abandonment behavior, this study introduces agricultural mechanization level as a mediating variable (Table 5). The KHB method decomposition reveals that the total effect coefficient of farmland fragmentation on farmland abandonment behavior is 0.1386 and significant at the 1% level, with a direct effect of 0.1248 ($p < 0.01$) and an indirect effect of 0.0139 ($p < 0.05$). Table 6 reports the impact of farmland fragmentation on agricultural mechanization level. The ordered Probit model estimation results show that farmland fragmentation has a significant negative effect on agricultural mechanization level. Table 7 summarizes the validation results of robustness tests from multiple methods. In the model without control variables, the indirect effect is 0.0248 ($p < 0.01$), with the same direction. The indirect effect estimated via KHB decomposition is 0.0139, and it remains significant at the 1% level even after applying robust standard errors, indicating that this effect is not driven by heteroscedasticity. However, the indirect effect accounts for only 10% of the total effect. This result suggests that the level of agricultural mechanization plays a partial mediating role between farmland fragmentation and farmland abandonment behavior, and that impeded mechanization is merely one of the many transmission

pathways through which farmland fragmentation leads to abandonment. The estimated directions of the AME decomposition and the ordered Probit model align with the main test. It should be noted that the KHB decomposition reports indirect effects on the latent variable scale, whereas the average marginal effect decomposition reports indirect effects on the probability scale. As they have different scales of measurement, the numerical values should not be directly compared. The multicollinearity test shows a maximum VIF of 1.420, indicating no severe multicollinearity issues. In summary, the mediation analysis partially confirms Hypothesis 2, farmland fragmentation indirectly increases the probability of farmland abandonment behavior to some extent by reducing the level of agricultural mechanization. However, the effect size of this mediation pathway is small, and it represents only a partial transmission mechanism.

Table 5. Mediating effect test results.

Effect	Estimated Coefficient	Standard Error	Z-Value	95% Confidence Interval	
				Lower Limit	Upper Limit
Total effect	0.1386 ***	0.0354	3.96	0.0700	0.2074
Direct effect	0.1248 ***	0.0353	3.53	0.0556	0.1940
Indirect effect	0.0139 **	0.0055	2.53	0.0031	0.0247

Note: All values are reported to four decimal places; *** $p < 0.01$, ** $p < 0.05$.

Table 6. Impact of farmland fragmentation on agricultural mechanization level.

Variable	Coefficient	Standard Error	Z-Value
Farmland fragmentation	−0.1310 ***	0.0356	−3.68
Control variables	Yes	Yes	Yes
N	1064	1064	1064
Pseudo R ²	0.0451		

Note: All values are reported to four decimal places; *** $p < 0.01$.

Table 7. Results of robustness tests for mediating effects.

Test Method	Indirect Effect (Latent Scale)	Indirect Effect (Probability Scale)	Indirect Effect Proportion
KHB decomposition	0.0139 **		10.0340%
Robust standard error KHB	0.0139 ***		10.0340%
Model without control variables	0.0248 ***		16.4722%
Average marginal effects decomposition		0.0052	10.0340%
Ordered Probit model	−0.1310 ***		
Multicollinearity test	VIF(max) = 1.4200		

Note: All values are reported to four decimal places; *** $p < 0.01$, ** $p < 0.05$.

4.2.2. Reverse Causality Sensitivity Test

To mitigate potential reverse causality between the mediating variable and the dependent variable, this study conducts two sensitivity analyses. Table 8 shows that among non-abandoning households, the coefficient for the effect of farmland fragmentation on agricultural mechanization level is significantly negative, suggesting the “farmland fragmentation–agricultural mechanization level” pathway exists independently of farmland abandonment behavior. After excluding the 25% of samples with the highest abandonment intensity (Model 7), the KHB indirect effect decreases from 0.0139 to 0.0086 and becomes insignificant, indicating that this mediating path is somewhat sensitive to extreme outliers. However, the direction of the effect does not reverse, and the overall direction of

the two sensitivity checks remains consistent, suggesting that the threat of reverse causality is limited and the core conclusions remain generally robust.

Table 8. Results of reverse causality sensitivity tests variable.

	Model 6	Model 7	
	Farmland Fragmentation → Agri-cultural Mechanization Level	KHB Indirect Effect	
	Households Not Abandoning Farmland	Full Sample	Excluding High-Abandonment Samples
Coefficient	−0.1354 ***	0.0139 **	0.0086
Standard error	0.0522	0.0055	0.0054
Z-value	−2.60	2.53	1.60
N	540	1064	798

Note: All values are reported to four decimal places; *** $p < 0.01$, ** $p < 0.05$.

4.3. Heterogeneity Analysis

To examine whether the effect of farmland fragmentation varies with household financial conditions and farmland accessibility, the sample is divided into low and high groups according to the values of these two indicators. Table 9 reports the subgroup Probit estimates, while Table 10 presents the corresponding within-group and between-group Wald tests.

The results first indicate significant heterogeneity in household access to finance. In the low-access group, the estimated coefficient of farmland fragmentation is 0.1920 and is positive at the 1% significance level, whereas the coefficient decreases to 0.0536 and becomes statistically insignificant in the high-access group. The between-group Wald statistic is 3.8628, with an associated p -value of 0.0494, confirming that the difference between the two coefficients is statistically significant at the 5% level. This finding suggests that households with limited access to external finance are less able to absorb the additional expenditures generated by fragmented cultivation, including machinery services, hired labor, transportation, and field management. Consequently, farmland fragmentation is more likely to induce abandonment among financially constrained households. Hypothesis 3a is therefore supported.

Farmland accessibility also produces a statistically identifiable difference. In the low-accessibility group, the estimated coefficient of farmland fragmentation is 0.0594 and does not reach conventional significance levels. In contrast, the coefficient rises to 0.1996 in the high-accessibility group and is significant at the 1% level. The Wald statistic for the between-group comparison is 3.1203, and its p -value is 0.0773, indicating that the coefficient difference is significant at the 10% level. One possible interpretation is that in places where basic traffic conditions remain poor, road constraints and difficulties in reaching cultivated plots will lead to abandonment decisions, weakening the marginal explanatory role of fragmentation. Once farmland becomes relatively accessible, repeated movement between dispersed plots, machinery scheduling, and cross-plot coordination will become more prominent operating constraints. Hypothesis 3b is thus supported, although the statistical evidence is weaker than that for household access to finance.

Taken together, the results confirm Hypothesis 3. The effect of farmland fragmentation on abandonment is conditioned by both households' financial capacity and the spatial accessibility of cultivated land, rather than being uniformly distributed across the sample.

Table 9. Heterogeneity analysis results.

Variable	Full Sample	Low Access to Fi- nance	High Access to Fi- nance	Low Farmland Ac- cessibility	High Farmland Accessibility
Farmland fragmentation	0.1391 *** (0.0351)	0.1920 *** (0.0522)	0.0536 (0.0646)	0.0594 (0.0510)	0.1996 *** (0.0584)
Gender	−0.0388 (0.0809)	−0.0675 (0.0975)	−0.0110 (0.1494)	−0.0371 (0.1207)	−0.0481 (0.1110)
Age	−0.0119 (0.0396)	0.0031 (0.0471)	−0.0357 (0.0721)	0.0657 (0.0611)	−0.0717 (0.0525)
Educational level	0.1010 ** (0.0485)	0.1578 *** (0.0588)	0.0040 (0.0879)	0.1359 * (0.0757)	0.0923 (0.0651)
Political affiliation	0.0334 (0.1510)	0.0015 (0.1967)	0.1404 (0.2144)	0.0138 (0.2356)	−0.0236 (0.2057)
Number of household la- borers	−0.0398 (0.0281)	−0.0281 (0.0210)	−0.0066 (0.0445)	−0.0576 ** (0.0255)	−0.0183 (0.0301)
Cadre	0.0635 (0.1102)	0.0028 (0.1373)	0.2561 (0.1883)	0.1260 (0.1719)	0.0409 (0.1509)
Agricultural technology training	−0.2186 *** (0.0397)	−0.1922 *** (0.0498)	−0.2996 *** (0.0720)	−0.2036 *** (0.0653)	−0.2411 *** (0.0536)
Fertility	−0.1359 ** (0.0533)	−0.2189 *** (0.0652)	0.0685 (0.0976)	−0.2722 *** (0.0791)	−0.0001 (0.0730)
Irrigation	−0.0010 (0.0382)	−0.0162 (0.0473)	0.0548 (0.0652)	0.0019 (0.0594)	0.0282 (0.0514)
Topography	−0.0551 * (0.0329)	−0.0627 (0.0418)	−0.0229 (0.0571)	−0.0575 (0.0548)	−0.0421 (0.0434)
Constant	1.0061 *** (0.2971)	1.1131 *** (0.3610)	0.4403 (0.6170)	1.4223 *** (0.4936)	0.5311 (0.4126)
N	1064	742	322	484	580
R-squared	0.0479	0.0645	0.0505	0.0509	0.0584

Note: All values are reported to four decimal places; values in parentheses indicate robust standard errors; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 10. Within- and between-group difference tests for the heterogeneity analysis.

Heterogeneity Dimension	Test Type	Test Item	Wald χ^2	p-Value
Household access to finance	Within-group test	Low access to finance group: coefficient of farmland fragmentation = 0	13.5567	0.0002
Household access to finance	Within-group test	High access to finance group: coefficient of farmland fragmentation = 0	0.6867	0.4073
Household access to finance	Between-group test	Low access to finance group vs. high access to finance group	3.8628	0.0494
Farmland accessibility	Within-group test	Low farmland accessibility group: coefficient of farmland fragmentation = 0	1.3577	0.2439
Farmland accessibility	Within-group test	High farmland accessibility group: coefficient of farmland fragmentation = 0	11.6882	0.0006
Farmland accessibility	Between-group test	Low farmland accessibility group vs. high farmland accessibility group	3.1203	0.0773

Note: The within-group tests examine whether the coefficient of farmland fragmentation differs significantly from zero within each subgroup. The between-group tests are based on full-sample Probit models with interaction terms, and Wald tests are used to assess whether the coefficients differ significantly across groups. All Wald tests have one degree of freedom.

5. Discussion

This study empirically examines the direct impact of farmland fragmentation on farmland abandonment behavior, its mediating effects, and heterogeneous mechanisms using micro-level household survey data from multiple provinces across China. By treating households as micro-level decision-makers and delving into the logic behind their behaviors, we aim to uncover the underlying reasons why current farmland protection policies have not fully achieved their intended outcomes.

5.1. Persistent Fragmentation Continues to Drive Farmland Abandonment Behavior

The baseline regression results indicate that farmland fragmentation is a key driver of farmers' decisions to abandon cultivation. Fragmented plots significantly increase the marginal costs of agricultural production by raising farmers' commuting time costs, labor coordination costs, and agricultural machinery scheduling costs. When the marginal costs generated by fragmented plots erode or even completely offset cultivation returns, rational farmers tend to abandon cultivation. This study validates the pattern of marginal land withdrawal from production due to farmland fragmentation in the context of Asian smallholder economies [74]. Notably, most survey areas are located in mountainous and hilly regions, with a high proportion of elderly laborers among sampled households, a demographic structure consistent with China's macro trend of rural labor force aging [75]. For this segment of the workforce, the high-intensity field commuting required by fragmented farmland creates an objective contradiction with their gradually declining labor capacity, potentially amplifying the marginal impact of cultivation costs on abandonment decisions. This suggests that the negative effects of fragmentation are significantly context-dependent, intertwined with specific demographic structures, labor market conditions, and topographical features. However, despite the continuous financial support provided by governments at all levels in land consolidation and related policies in recent years, there is still a certain degree of fragmentation of farmland, which remains a key driver of farmland abandonment behavior [76].

5.2. The Dilemma of Mechanization Constraints

This study's mediation analysis reveals that farmland fragmentation suppresses agricultural mechanization, forming a chain of "farmland fragmentation–mechanization constraints–farmland abandonment". This study has confirmed a significant negative relationship between fragmented farmland and agricultural mechanization [77], quantifying the mediating effect of mechanization barriers between fragmentation and farmland abandonment behavior. However, this indirect effect accounted for only about 10% of the total effect and ceased to be significant after excluding samples with high rates of abandonment, indicating that the suppression of mechanization is merely one of many transmission pathways through which fragmentation induces farmland abandonment. The constraints imposed by fragmented farmland on mechanization are multidimensional. At the technical feasibility level, small plots hinder the large-scale deployment of medium-to-large agricultural machinery. For example, in plain regions, field ridges and ditches can significantly reduce mechanized operation efficiency. In hilly and mountainous areas, topographical constraints and land fragmentation combine to create a double barrier, significantly diminishing the economic viability of mechanization as a labor substitute [78]. Economically, small-scale machinery suited for fragmented plots faces challenges including insufficient research and development, high costs, and lengthy investment recovery cycles, and agricultural socialized service markets remain underdeveloped in fragmented regions because of high operational costs and scheduling difficulties [79], dampening

farmers' purchasing interest. Therefore, the suppression of mechanization caused by fragmented land can be regarded as one of the structural barriers to improving agricultural productivity growth.

The limited influence of the mediating effect also implies that fragmentation induces farmland abandonment may not be "mechanization constraints", but rather the more direct pathway of "labor outflow–declining farming willingness–farmland abandonment". This finding aligns closely with the characteristics of the sample in this study. The surveyed areas are predominantly hilly and mountainous regions, with a notable aging and feminization of the farming population. The shortage of labor supply itself constitutes a core constraint on farming. Even with improved mechanization conditions, the ability and willingness of an aging labor force to adopt new technologies remain a practical bottleneck [24].

5.3. Financial and Spatial Boundary Conditions of the Fragmentation Effect

The heterogeneity results indicate that the abandonment effect of farmland fragmentation depends on households' financial capacity and the spatial conditions of agricultural production. The significantly stronger effect among households with low access to finance is consistent with the following evidence, binding credit and risk constraints restrict agricultural investment [59], rural finance affects agricultural technology adoption [61], and access to formal and informal credit shapes the adoption of mechanized technologies [80]. The present study extends this scope by demonstrating that financial conditions also determine whether the additional costs associated with fragmented cultivation are converted into land abandonment. Operating dispersed plots requires repeated expenditures on machinery services, hired labor, transportation, input delivery, and field supervision, while agricultural returns are generally realized only after harvest. Households with limited financing channels have less capacity to bridge this temporal mismatch between current expenditure and future income. Temporary liquidity shortages may therefore lead to delayed operations, reduced inputs, or withdrawal from cultivation. By contrast, households with high access to finance can mobilize external funds, purchase socialized agricultural services, and absorb short term operating losses, thereby weakening the transmission of fragmentation costs into abandonment decisions. Access to finance consequently functions as a cost buffering condition rather than eliminating the technical efficiency consequences associated with fragmented plot organization [81].

Farmland accessibility exhibits a different pattern. The fragmentation effect is stronger among households with high farmland accessibility, which differs from the conventional expectation that poor accessibility should intensify the adverse effects of fragmented land. Existing studies identify location, distance to settlements or service centers, road accessibility, and other site specific spatial conditions as important determinants of farmland abandonment [27,64]. Our findings suggest that accessibility may also alter the relative importance of fragmentation within the broader production constraint structure. When farmland is difficult to reach, poor roads, high travel costs, and machinery entry barriers may constitute binding constraints, leaving limited additional variation to be explained by fragmentation. Once basic accessibility improves, repeated movement among dispersed plots, machinery scheduling, and cross plot coordination become more prominent sources of operating inefficiency. Thus, high accessibility will not promote abandonment. Rather, it makes the independent constraint imposed by fragmented plot organization more visible. Taken together, the findings distinguish a financial buffering mechanism from a spatial constraint switching mechanism, showing that the consequences of fragmentation depend jointly on household resource capacity and the spatial context in which fragmented plots are managed [82].

5.4. Research Contributions and Limitations

This study reveals the pathways through which farmland fragmentation influences farmers' abandonment behavior, offering theoretical and practical marginal contributions in the following aspects: (1) Based on farmland household behavior theory, this study constructs an analytical framework of "fragmentation–mechanization–abandonment", enhancing the theoretical explanatory power of fragmentation issues in land-use change research. (2) By identifying agricultural mechanization level as the key mediating variable, this study reveals the underlying mechanism through which farmland fragmentation influences abandonment behavior by constraining technology adoption. Beyond the "cost–benefit" pathway to include technology adoption constraints, this study enriches the mechanistic understanding of the socioeconomic consequences of fragmentation. (3) By introducing household access to finance and farmland accessibility as heterogeneity dimensions, this study identifies the financial and spatial boundary conditions of the fragmentation effect.

This study also has its limitations. (1) Cross-sectional data constraints prevent capturing the dynamic evolution and bidirectional feedback between fragmentation and farmland abandonment behavior. Furthermore, the non-agricultural income variable used in this study is subject to self-selection bias with regard to farmers' decisions to abandon farmland, making it difficult to accurately identify the direct contribution of non-agricultural employment opportunities to farmland abandonment. (2) The focus on economically rational drivers overlooks socio-cultural mechanisms such as weakened emotional attachment to farmland and diminished community governance capacity. Future research could integrate longitudinal panel data with spatial analysis methods, introduce instrumental variables or exogenous variables such as county-level non-agricultural wages, and combine institutional analysis with social network perspectives to explore the social acceptability of land consolidation policies and farmer participation mechanisms, thereby providing stronger theoretical support for addressing farmland fragmentation and enhancing rural resilience.

6. Conclusions and Policy Implications

6.1. Conclusions

This study employs micro-level household survey data to construct a theoretical framework for empirical testing, systematically analyzing the pathways and mediating effects of farmland fragmentation on abandonment behavior while revealing heterogeneous impacts across different farm sizes. The results include: (1) Fragmentation significantly promotes farmland abandonment behavior. Fragmentation constitutes a direct pathway to farmland degradation by raising cultivation management and coordination costs, thereby squeezing operational profits. (2) Agricultural mechanization level plays a mediating role between fragmentation and farmland abandonment behavior, with indirect effects accounting for approximately 10% of the total effect, indicating that mechanization serves as one of the pathways through which farmland fragmentation leads to abandonment. (3) The effect of farmland fragmentation on abandonment varies with household access to finance and farmland accessibility. It is stronger among households with low access to finance and those with high farmland accessibility, indicating that the consequences of fragmentation depend on both households' capacity to absorb additional operating costs and the spatial conditions of agricultural production. In summary, farmland abandonment induced by fragmentation reflects not only the mismatch between dispersed landholdings and mechanized production but also the interaction between household financial capacity and the spatial conditions of agricultural production.

6.2. Policy Implications

Based on these findings, in addition to uniform land consolidation, policies aimed at reducing fragmentation-induced farmland abandonment could also coordinate plot reorganization, mechanization services, and household financial support, and improve farmland accessibility. Specifically, (1) It is suggested to coordinate plot reorganization with improvements in mechanization and farmland accessibility to reduce farmers' land management costs. In areas with low farmland accessibility, priority should be given to improving field roads, bridges, drainage crossings, and machinery-entry conditions. Where basic accessibility is already high, additional road construction alone may not reduce the costs of fragmentation. Plot exchange, boundary adjustment, coordinated machinery scheduling, and agricultural socialized services should therefore be promoted to reduce repeated movement and cross-plot management costs. (2) Targeted financial support could be established for households with low access to finance. Seasonal operating loans, credit guarantees, interest subsidies, and agricultural service vouchers should be linked to machinery hiring, labor substitution, input purchases, and the maintenance of fragmented plots. The policy focus could be placed on easing temporary liquidity constraints and lowering the transaction costs of fragmented production, rather than simply expanding the scale of general agricultural lending. (3) It is suggested to improve the collaborative governance and dynamic assessment system. A dynamic monitoring system for farmland abandonment based on remote sensing and field survey could be established through integrating resources from departments such as natural resources, agriculture and rural affairs, and finance. After that, a differentiated evaluation mechanism could be established based on this system. Specifically, plain grain-producing regions should prioritize the stability of planted area and the proportion of contiguous farmland, while hilly and mountainous areas should focus on arable land utilization rates and improvements in smallholder farming conditions. Additionally, a special fund for farmland abandonment governance should be set up to direct resources toward fragmented areas dominated by smallholders, with policy instruments adjusted dynamically based on evaluation results.

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