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The extent, drivers and production loss of farmland abandonment in China: Evidence from a spatiotemporal analysis of farm households survey

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ABSTRACT

The uncertainty of the global food supply has increased, and land abandonment has affected food security. Based on nationally representative farm households in 1995, 2002, 2008 and 2020, this paper systematically reveals the extent, drivers, and production loss of farmland abandonment in China, providing a scientific basis for the comprehensive management of land abandonment. The extent of farmland abandonment has been increasing since 1995; 1/5 of farmers have abandoned their farmland, and 1/10 of farmland has been abandoned. The number of counties recording farmland abandonment increased from 34 (11.15%) at the beginning of the study period to 224 (73.44%) by the end, and these counties were mainly distributed in the hilly and mountainous areas along the Yangtze River as well as in Southeast, Southwest, Northwest, and Northeast China. Farmland abandonment is the result of a combination of multiple factors, including basic farmland conditions and socio-economic and ecological factors, among which the low agricultural comparative income caused by agricultural labour shortages and poor-quality farmland conditions is the root cause. In 2020, for example, the ratio of farmland abandonment in major grain-producing and non-grain-producing regions was 7.38% and 16.94%, respectively, resulting in a total loss of 49.23 million tons of grain, which is 7.36% of the total national grain output. The production loss experienced by China could feed 123 million people based on the per capita annual food consumption estimates of 400 kg. Currently, farmland abandonment poses a threat to China's food security, and the government should gradually improve the quality of farmland through comprehensive land management, improve rural infrastructure and develop small-scale machinery suitable for hilly and mountainous areas.

1. Introduction

Food security serves as the material foundation for and guarantee of social stability and economic development, and many countries have raised the issue of food security to an unprecedented strategic level (Chen et al., 2021; Liu and Zhou, 2021; George and Adelaja, 2022). To ensure that China's food supply is adequate and stable, the central government has traditionally prioritized addressing agricultural management and rural development. Doing so has been the country's top strategic task, and China has formed an important theoretical system for food security and the protection of cultivated land (He et al., 2019; Su et al., 2020; Zhou et al., 2021). With the migration of many rural labourers to China's cities, "rural decline" has become an increasingly prevalent phenomenon in the country. This trend encompasses a range of social, economic, and demographic challenges, including the ageing of and decrease in the rural population and the shift away from traditional agricultural practices towards non-agricultural industries. These factors have limited food production capacity and thus pose a great challenge to food security (Liu and Li, 2017; Wang et al., 2020a,b). In addition, the transformation and upgrading of the consumption structure of residents set higher requirements for China's grain production capacity (Yu et al., 2021). Under the background of the intensification of the contradiction between global grain supply and demand, the grain production problem in China appears to be particularly important (Fischer and Connor, 2018; George and Adelaja, 2022).

As the foundation of food production, farmland plays an essential role in ensuring an adequate food supply (Deng et al., 2019a; Deng et al., 2019b; Li and Liu, 2021). Unfortunately, urbanization and

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industrialization have caused a mass rural exodus, which has resulted in the marginalization of farmland and has ultimately led to the large-scale abandonment of marginal farmland. This trend is particularly evident in developed countries such as those in Europe, the United States and Japan. However, the mountainous areas of China, Latin America, and Southeast Asia have also experienced this phenomenon (Estel et al., 2015; Ito et al., 2016; Kolecka et al., 2017; Castro et al., 2020; He et al., 2020). Farmland abandonment is one of the most critical land use changes in the world today, and it significantly impacts sustainable development and the global environment. Vegetation succession, environmental problems, and socioeconomic impacts are some of the main consequences of farmland abandonment (Li et al., 2018). This phenomenon has global impacts and can lead to a decline in grain production capacity and extensive grain imports, often resulting in deforestation in other countries (Li et al., 2021). The problem of farmland abandonment has recently attracted considerable attention from scholars worldwide, with a particular focus on the issue of food security, which arises from farmland abandonment (Baysse-Lainé and Perrin, 2018; S. Chen et al., 2022). However, what are the trends in the scale and distribution of land abandonment in China since 1995? What are the causes of abandonment? What is the amount of grain production lost due to land abandonment? Understanding the extent of the changes in and driving factors of farmland abandonment and the amount of loss in production in China is crucial for abandoned land management. By clarifying these factors, we can gain insights into the causes of farmland abandonment in China and its impact on food production, and we can develop strategies to mitigate its subsequent impacts on food security.

The issue of farmland abandonment, which has centred on several aspects, has been a topic of interest among scholars for some time. First, several scholars have utilized meta-analysis, remote sensing and household surveys to investigate the issue of farmland abandonment (Sirami et al., 2008; Estel et al., 2015; Dara et al., 2018), with study areas being concentrated in Europe, Japan, and the Mediterranean (Herrando et al., 2014; Ito et al., 2016; Kolecka et al., 2017; Quintas--Soriano et al., 2022). This phenomenon was first reported in China in the late 1980s. By the late 20th century, farmland abandonment had become increasingly severe in Chongqing, Hubei, Ningxia and Jiangxi, and its extent continued to expand (Yan et al., 2016; Han and Song, 2019; Xu et al., 2019; He et al., 2020; Liang et al., 2020; Wang et al., 2020a,b). Second, a county-level survey found that in 2015, the ratio of farmland abandonment in mountainous counties was 14.32%, with the highest rate occurring in the mountainous regions along the Yangtze River (Li et al., 2018). Additionally, remote sensing surveys have shown that the extent of farmland abandonment is increasing in some counties, with abandonment ratios exceeding 10% in Wusheng County in Sichuan Province and Wushan and Youyang Counties in Chongqing city (Shi et al., 2018). Furthermore, the variation in land abandonment across regions is a result of the differences in the natural environment, socio-economic status and policy. Third, scholars have also explored the driving mechanisms underlying this phenomenon, finding that changes in natural geographical conditions and socio-economic development drive farmland abandonment (Dolton-Thornton, 2021; Yan et al., 2016; Zhang et al., 2016). Finally, scholars have recently started to pay attention to the impact of farmland abandonment on grain production capacity. By examining the relationship between farmland abandonment and grain output from the perspective of the quantity and quality of cultivated land (Li et al., 2021), scholars have enhanced our scientific understanding of the relationship between farmland abandonment and food security.

In summary, although the literature has reported on the extent, spatial distribution and drivers of farmland abandonment, certain gaps remain. First, previous studies have focused on typical case area studies with a short time span and strong regional dimension. Second, few studies have explored the driving mechanisms of farmland abandonment at the micro-farmer level. Finally, quantitative studies on the impact of farmland abandonment on food production are lacking. As a result, it is challenging to answer specific questions about the extent of farmland abandonment, the driving mechanisms underlying this phenomenon, and the impact on grain production in China over the past 20 years.

This study aims to address these gaps by explicitly focusing on three main objectives. First, this research aims to provide a comprehensive and systematic analysis of the extent and spatial distribution of farmland abandonment in China over the course of nearly three decades. By utilizing nationally representative farm household sampling surveys conducted in 1995, 2002, 2008, and 2020, we employ spatial analysis to clarify the extent of farmland abandonment at the national scale. Second, we aim to investigate the driving mechanisms of farmland abandonment at the micro-farm household level. Previous studies have often overlooked this level of analysis, which is crucial for understanding the individual factors and decision-making processes contributing to abandonment. By delving into the micro-level dynamics, we can gain a deeper understanding of the root causes of farmland abandonment in China. Finally, this study seeks to quantify the impact of farmland abandonment on grain production, and we assess the production loss resulting from abandonment in major grain-producing and non-grain-producing regions of China. This analysis provides valuable insights into the implications of farmland abandonment for food security in the country. By achieving these objectives, our study contributes to the development of effective policies for managing abandonment and improving food security in China.

2. Materials and methods

2.1. Data

The data were obtained from the Chinese Household Income Project (CHIP) (http://www.ciidbnu.org/chip/), involving data from five rounds of national sample surveys conducted in 1988, 1995, 2002, 2008 and 2014 (CHIP1988, CHIP1995, CHIP2002, CHIP2008 and CHIP2014, respectively). The sample covered over 300 counties in 22 provinces across China, resulting in a total of more than 70,000 families. The following describes the basic cleaning process for the sample. First, samples not involving farmland abandonment were removed, such as CHIP1988. Second, a sample of urban households, numbering nearly 40,000, was excluded. Finally, the remaining sample of rural households covered 305 counties in 22 provinces, i.e., Beijing, Hebei, Henan, Shandong, Shanxi, Anhui, Jiangsu, Zhejiang, Sichuan, Chongqing, Shaanxi, Gansu, Liaoning, Jilin, Guangdong, Guangxi, Guizhou, Yunnan, Hunan, Jiangxi, Hubei and Xinjiang (Fig. 1), with more than 30,000 households. Beijing, Liaoning, Jiangsu, Zhejiang, Shandong and

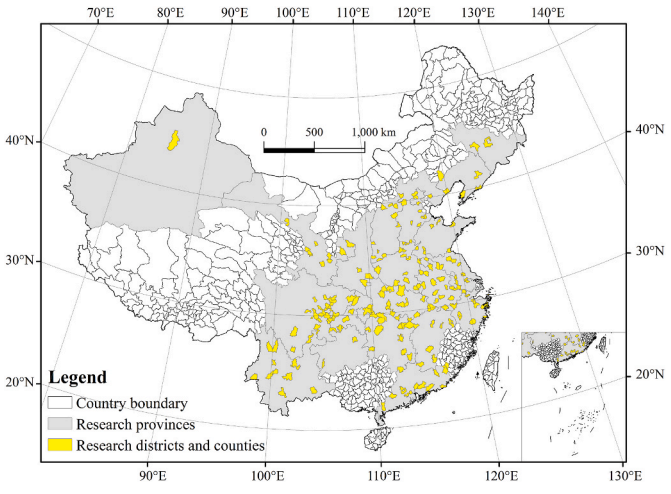

Fig. 1. Schematic diagram of the study area.

Guangdong represent the eastern coastal region, while Hebei, Shanxi, Jilin, Anhui, Jiangxi, Henan, Hunan and Hubei represent the central region, and Sichuan, Chongqing, Guizhou, Yunnan, Shaanxi, Gansu and Xinjiang represent the western region. This sample is nationally representative due to the marked differences in socioeconomic status, resource endowments and household circumstances among these regions. The questionnaire included information on demographics, income and expenditure, household assets and agricultural operations, and farmland abandonment.

Notably, CHIP1995, CHIP2002 and CHIP2008 all cover 305 counties in 22 provinces across the country with consistent coverage, while CHIP2014 covers only 234 counties in 15 provinces. To ensure consistency in survey coverage, we conducted a farm household survey in 2020 for the 305 counties covered in the previous period. The detailed process involved several steps. First, we chose the method in which rural university students returned to their hometown to participate in the survey, which has been proven to be fast and effective compared to the conventional field surveys used in previous studies, which require labour and financial resources (Li et al., 2018). Second, university students majoring in land science and geographical science were selected as researchers and then trained. The questionnaire surveys were carried out by these university students returning to their hometowns from June to August 2020. Meanwhile, we marked the geographical coordinates of each survey sample to ensure the completion of the survey for the expected counties. Third, four supplementary surveys in some regions where there was an insufficient number of samples were conducted in September and October 2020, and the questionnaires were also checked to ensure that the responses were free from errors. Finally, we named the survey data of rural university students returning to their hometowns CHIP2020. The main data of this study consisted of four rounds of national rural farm household sampling survey data, namely, CHIP1995, CHIP2002, CHIP2008, and CHIP2020. In addition, we cleaned the data by excluding samples of landless households, which did not contain the indicators required for the study, and by excluding samples with a negative average age of family members. Samples with a proportion of agricultural fixed assets or non-agricultural fixed assets in the household greater than 1 were excluded, and samples without an important index were also excluded. Ultimately, the sample sizes of the four surveys were 7064, 8269, 7480 and 8593 households, totalling 31,406 households (Fig. 2).

2.2. Methods

2.2.1. Calculation of the farmland abandonment ratio

The extent of farmland abandonment is generally measured with one of two methods. One is the ratio of farmers who abandoned farmland to the total number of farmers, and the other is the ratio of the area of abandoned farmland to the total farmland area of a family. The formula for calculating the ratio of farmers who abandoned farmland to the total number of farmers is as follows:

$$R_{1i} = [N_a / (N_a + N_{na})] \times 100\% \quad (1)$$

where R_{1i} is the ratio of farmers who abandoned farmland to the total number of farmers and N_a and N_{na} are the number of farmers who abandoned farmland and did not abandon farmland, respectively.

The formula for calculating the ratio of the area of abandoned farmland to the total area of farmland of a family is as follows:

$$R_{2i} = [A_a / (A_a + A_{na})] \times 100\% \quad (2)$$

where R_{2i} is the ratio of the area of abandoned farmland to the total area of farmland of a family and A_a and A_{na} are the area of abandoned farmland and the area of nonabandoned farmland, respectively.

2.2.2. Identification of the drivers of farmland abandonment

The dependent variable in this paper is whether or not farmland abandonment occurred for farm households. A value of 1 is assigned to farmers who abandoned their farmland and a value of 0 is assigned to those who did not. Farmland abandonment is influenced by multiple factors, and this study selected driving factors, such as labour, agricultural production conditions and socio-economic development, with which to identify the factors affecting farmland abandonment. Table 1 presents the definitions and basic descriptive statistics of the variables (Chen et al., 2022; Shao et al., 2015; Xu et al., 2019). The results show

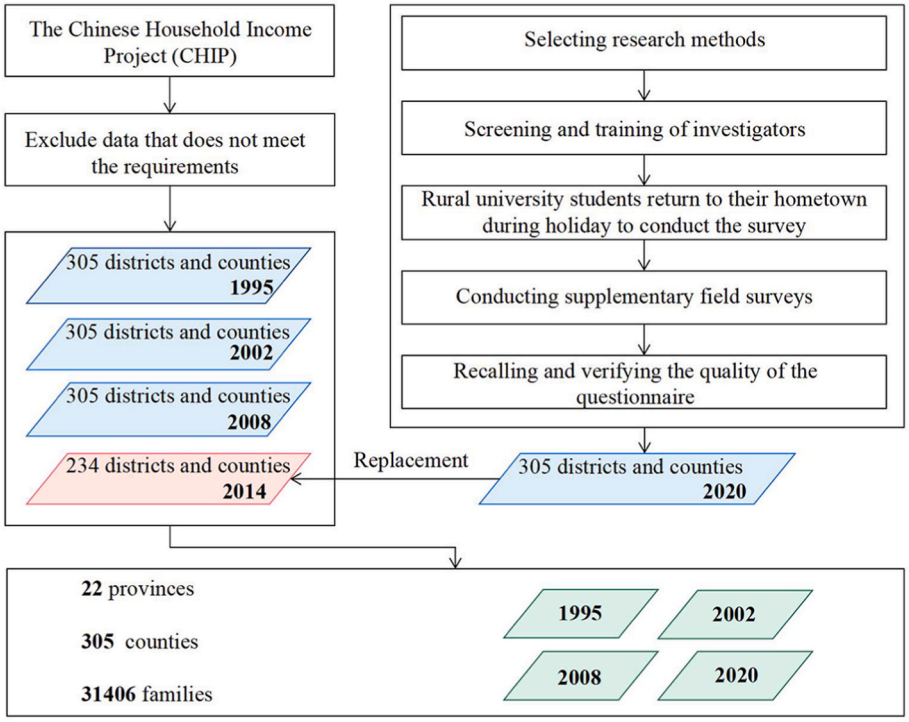

Fig. 2. The process of data collection.

Table 1
Definitions and descriptive statistics of the variables.

Variable	Definition	Average	SD	Number
Is there abandonment	Yes = 1, no = 0	0.17	0.26	31406
Area of abandoned farmland	Area of family abandoned farmland in ha	0.16	0.22	5339
Age of the householder	The age of the head of household in years	51.29	12.97	31406
Sex of the householder	Male = 1, female = 0	0.95	0.22	31406
Marital status of the householder	Married = 1, unmarried = 2, divorced = 3, widowed = 4, other = 5	1.14	0.61	31406
Educational level of the householder	Illiterate or semi-illiterate = 1, third grade and below = 2, fourth grade and above = 3, middle school = 4, high school = 5, vocational = 6, college and above = 7	3.64	1.05	31406
Working in the province	Yes = 1, no = 0	0.37	0.48	31406
Working outside the province	Yes = 1, no = 0	0.16	0.36	31406
Total farmland area of family	Total farmland area of a family in ha	0.52	0.51	31406
Total nonfarm income	Nonfarm income of all family members in yuan	18895.87	31895.93	31406
Total productive assets	Total value of all productive asserts for household in yuan	4691.16	21711.16	31406
Access to credit	Yes = 1, no = 0	17810.91	49374.26	31406
Topography	Plain = 1, hilly = 2, mountainous = 3	2.25	0.80	305
Land titling	Yes = 1, no = 0	0.27	0.31	305
Level of farmland transfer rent	Average annual rent per ha in yuan/ha	5975	3469	305

that the ratio of farmers who abandoned farmland to the total number of farmers was 17%. Additionally, the average abandoned farmland area was 0.156 ha for farmers who abandoned farmland.

Logit model. The dependent variable is a non-linear and binary discrete variable that does not conform to a normal distribution, does not satisfy the linear regression condition, and cannot be used for least squares estimation. Therefore, the logit model is a binary discrete choice model that regards the logit distribution as a random error term. It can be used to simulate utility maximization problem selection behaviour. The qualitative variable Y_i is introduced into the study. When a farmer abandoned farmland, $Y_i = 1$; when a farmer did not abandon farmland, $Y_i = 0$. The explanatory variables are X_{ii}, X_{hi}, X_{vi} and X_{di} (Hahn et al., 2020). Logit regression analysis is named after the logit transformation applied to the outcome variable. Rather than directly regressing a dichotomous outcome variable, the logit transformation is used to transform it to the logit scale. This approach introduces the concept of odds, which are directly modelled by the logit model. The odds are the ratio of the probability of an event occurring (p) to the probability of an event not occurring ($1 - p$). They reflect the relative advantage of an event occurring compared to an event not occurring. By using the logit transformation to model odds, logistic regression can effectively capture the relationship between the predictor variables and the odds of the outcome variable occurring. The odds ratio (OR) represents how the incidence ratio of the predictor variable changes when it is increased by one unit when all other variables remain constant. This means that the odds of the outcome variable occurring will be e(p) times higher for each unit increase in the predictor variable. The econometric logit model is constructed as follows:

$$Odds = \frac{p}{1-p} \tag{3}$$

$$\log it = \log\,(Odds) = \alpha_0 + \beta_1 X_{ii} + \beta_2 X_{hi} + \beta_3 X_{vi} + \beta_4 X_{di} + \varepsilon_i \tag{4}$$

$$Odds\ ratio(OR) = \frac{Odds_1}{Odds_2} \tag{5}$$

where Y_i is 1 if a farmer has abandoned his farmland and Y_i is 0 otherwise. X_{ii}, X_{hi}, X_{vi}, and X_{di} denote a set of factors, namely, householder characteristics, household characteristics, village characteristics and dummy variables that affect farmland abandonment, respectively. These factors belong to different levels, such as the individual, household or village level, and they can affect whether household farmland is abandoned and the scale of abandonment at different levels. Therefore, each of these four types of factors needs to be considered in this study. ε_i is the error term. β_1, β_2, β_3, and β_4 are the parameters to be estimated.

Tobit model. Because the dependent variable is a non-negative number indicating the area of farmers' abandoned farmland, there is left-merging at zero. Thus, regression analysis of the restricted dependent variable conducted by a Tobit model can effectively avoid estimation bias (Chen and Zhou, 2011). The econometric model is as follows:

$$AF_i = \delta_0 + \gamma_1 X_{ii} + \gamma_2 X_{hi} + \gamma_3 X_{vi} + \gamma_4 X_{di} + \theta_i \tag{6}$$

where AF_i is the area of farmland abandoned by farmer i. X_{ii}, X_{hi}, X_{vi}, and X_{di} denote a set of factors, namely, householder characteristics, household characteristics and village characteristics and dummy variables that affect farmland abandonment, respectively. θ_i is the error term, and γ_1-γ_4 are the parameters to be estimated.

2.2.3. Estimation of production loss

The national production loss is the sum of the production loss of each province. Therefore, the provincial farmland abandonment ratio, which is the area-weighted farmland abandonment ratio in the counties under the jurisdiction of a province, should first be estimated. The calculation formula is as follows:

$$AF_p = W_{p1}AF_{p1} + W_{p2}AF_{p2} + \cdots + W_{pn}AF_{pn} \tag{7}$$

where AF_p is the area-weighted farmland abandonment ratio in province p and W_{pi} and AF_{pi} are the proportion of the farmland area and the abandonment ratio in county i of province p, respectively.

To assess the production loss caused by farmland abandonment in China, this study used the average grain yield per ha and the total national grain production in 2020 as the standard (Li et al., 2021). The calculation formula is as follows:

$$GL_p = AF_p \times CL_p \times U_p \tag{8}$$

where GL_p is the production loss caused by farmland abandonment in province p in 2020; AF_p is the farmland abandonment ratio in province p; CL_p is the amount of farmland retained in province p; and U_p is the grain yield per unit area in province p, that is, the ratio of the total grain output to the sown area. Studies have shown that China's overall grain demand is expected to reach approximately 610 million tons, with each person consuming an average of approximately 400 kg of food (Yi, 2021). This study can estimate the number of people who can be supported by abandoned farmland based on per capita grain consumption.

3. Results

3.1. Changes in the extent of farmland abandonment in China

Fig. 3 shows the extent of farmland abandonment in different periods. In the 1990s, 1.32% of farmers abandoned their farmland, and since then, the ratio of farmland abandonment has grown rapidly, reaching 3.84% in 2002, 10.55% in 2008 and 20.79% in 2020. Over the past 20 years, the ratio of farmers abandoning their farmland has

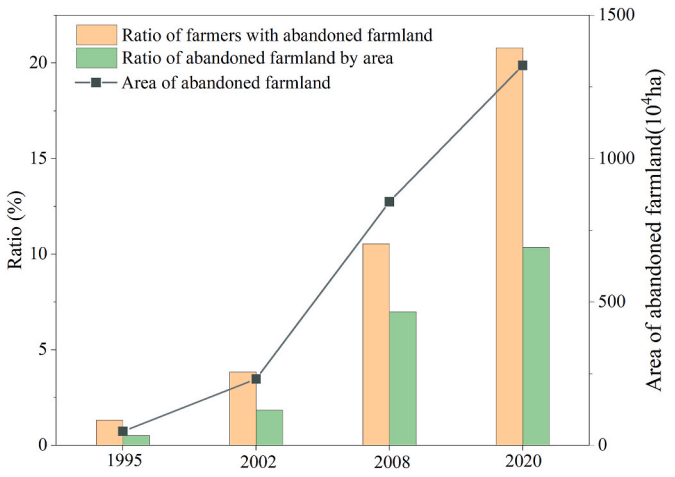

Fig. 3. Extent of farmland abandonment during the years of 1995–2020.

increased by nearly 15 times. In other words, more than 1/5 of farmers nationwide have abandoned their farmland. Meanwhile, the ratio of the abandoned farmland area increased from 0.52% to 10.36% by the end of the study period, an increase of nearly 19 times. Currently, more than 1/10 of the farmland in rural China is abandoned, accounting for approximately 13.4 million ha of farmland.

3.2. Spatial distribution of farmland abandonment in China

Fig. 4 shows the spatial distribution of farmland abandonment during the study period. In 1995, the number of counties with records showing farmland abandonment was 34, and that number increased to 224 by the end of the period. Based on the 305 participating counties, the proportion of counties that recorded farmland abandonment in the early stage was 11.15%, and that proportion rose to 73.44% in the late stage. The counties were mainly distributed in the mountainous areas along the Yangtze River and in Northwest and Southwest China, such as Chongqing, Hubei, Hunan, Jiangxi, Shaanxi and Yunnan. Farmland abandonment has been increasing since 1995, and it has spread to most of the hilly and mountainous counties in the country in recent years.

In terms of the ratio of abandoned farmland area, only Minle County in Gansu Province exceeded 10%, while the ratios in the remaining 33 counties were all less than 10% in 1995. Starting in 2008, the ratio of the area of abandoned farmland in all counties began to increase rapidly. Among them, the ratios in Boluo, Qingtian, Shaoxing, Xiangshan, Dabu and Qijiang Counties all exceeded 20%, with the areas of abandoned farmland being concentrated in the hilly and mountainous areas of Chongqing, Zhejiang, Guangdong and Anhui. At the end of the study period, the number of counties with an abandonment ratio exceeding 10% reached 48, accounting for 21.43% of the total study counties. Among them, the abandonment ratio rose high enough to exceed 30% in the Wansheng District, Linyi County and the Kaizhou District, while the ratio exceeded 20% in the Hengqu, Pinglu District, Shaoxing, Xinjiang County, Xiangshan County, Pinglu County, Dabu County and Qijiang County. These counties are concentrated in Chongqing, Hunan, Guangdong, Zhejiang, Shaanxi and Shanxi. In short, farmland abandonment across the country has continued to intensify since 1995, and the more serious areas of farmland abandonment are concentrated in the hilly and mountainous areas along the Yangtze River as well as in Southeast, Southwest, Northwest and Northeast China.

3.3. Driving mechanism of farmland abandonment

The variance inflation factor (VIF) was used to test multicollinearity between the variables. The results showed no significant collinearity, with a maximum VIF of 1.35 and a mean VIF of 1.16. Year and region variables were added, and the coefficients and significance remained robust. The area under the receiver operation characteristic (ROC) curve (AUC) was used to judge the goodness of fit of the model, and the AUC value of Model 3 was 0.858, indicating a well-set model. Then, we set up three models, where Model 1 incorporated householder, family and location characteristics, while Model 2 and Model 3 gradually incorporated the year and region virtual variables based on Model 1, providing more robust results. Model 3 presents the results of the robustness estimates incorporating all variables.

Table 2 presents the results with regard to the drivers of farmland abandonment. The age of the householder has a typical U-shaped relationship with farmland abandonment, with a turning point at 55.77

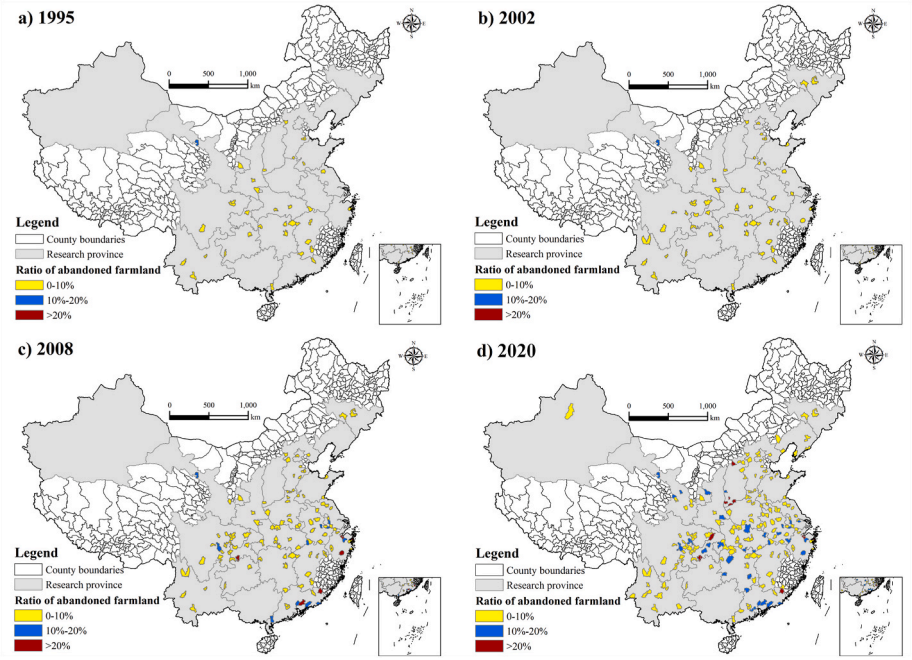

Fig. 4. Spatial distribution of farmland abandonment at the county level.

Table 2
Drivers of farmland abandonment based on the logit model.

Variables	Model 1		Model 2		Model 3	
	Coefficient	Odds ratio	Coefficient	Odds ratio	Coefficient	Odds ratio
Age of householder	−0.055***	0.056	−0.035**	0.065	−0.029*	0.097
	(-3.46)		(-2.11)		(-1.72)	
Age of householder ^2	0.00016	0.998	0.00032**	0.825	0.00026*	0.971
	(1.21)		(2.37)		(1.93)	
Working outside the province	0.286***	0.331	0.294***	0.466	0.279**	0.253
	(4.12)		(4.20)		(2.03)	
Working in the province	0.123**	0.131	0.383***	0.341	0.226***	0.084
	(2.07)		(6.24)		(3.47)	
Educational level of householder	0.007	0.234	−0.090***	0.213	−0.050*	0.028
	(0.24)		(-3.07)		(-1.65)	
Log (Total nonfarm income)	0.058***	0.062	0.008**	0.077	0.018**	0.067
	(7.24)		(1.99)		(2.17)	
Log (Total productive assets)	−0.112***	0.118	−0.077***	0.271	−0.068***	0.212
	(-15.19)		(-10.67)		(-8.59)	
Access to credit	−0.200*	0.246	−0.035	0.232	0.222*	0.189
	(-1.79)		(-0.31)		(1.91)	
Topography	0.207***	0.299	0.025*	0.215	0.222**	0.123
	(7.51)		(1.72)		(2.03)	
Land titling	−0.130**	0.312	−0.122**	0.156	−0.110**	0.098
	(-2.22)		(-2.21)		(-2.23)	
Log (Level of farmland transfer rent)	−0.077**	0.122	−0.085**	0.112	−0.082**	0.078
	(-2.03)		(-2.17)		(-2.01)	
Constant	−4.796***		−2.921***		−3.794***	
	(-9.74)		(-5.75)		(-7.10)	
Other variables	Yes		Yes		Yes	
Year dummies variables	-		Yes		Yes	
Region dummies variables	-		-		Yes	
Pseudo R2	0.301		0.432		0.576	
AUC	0.753		0.796		0.858	
Number of samples	31406		31406		31406	

Note: T statistics in parentheses. * $p < 0.1$, * * $p < 0.05$, * * * $p < 0.01$. Individual-level variables such as the gender of the head of household and the marital status of the head of household were included in Models 1–3. However, these variables were not significant, and after removing them, there was no significant effect on other variables in the model. The estimation results of these variables are not shown in Table 2 because of the simplicity of the model. In addition, farmland abandonment is also influenced by biophysical and economic factors, which are difficult to obtain, both year and region dummy variables are included in this study to mitigate the bias of results due to omission of the above factors. The same processes are performed in Table 3.

years old. When the householder is less than 55.77 years old, the probability of farmland abandonment decreases, and when the householder is older than 55.77 years old, the probability of farmland abandonment increases. Of the sample, the number of householders younger than this threshold is 21,239, accounting for 67.63%, while the number of householders older than this threshold is 10,167, accounting for 32.37%. However, the increase in the average age of the householder suggests that more farmers will abandon their farmland in the future, which will exacerbate the phenomenon of farmland abandonment in China. Working outside the province and working in the province have coefficients of 0.279 and 0.226, respectively, and are significant at the 5% and 1% levels, respectively, indicating that households employing migrant workers are more likely to abandon their farmland. Non-farm income has a positive coefficient that is significant at the 5% level and an odds ratio of 0.067, suggesting that for every unit increase in household non-farm income, the probability of abandonment of household farmland increases by 6.7%. On the other hand, the coefficients of total productive assets, land titling, and the level of farmland transfer rent are negative and significant at the 5% level or higher with odds ratios of 0.212, 0.098, and 0.078, respectively. These results mean that farmers with higher total productive assets and confirmed land property rights are less likely to abandon their farmland. Furthermore, every unit increase in the level of total productive assets or farmland transfer rent decreases the probability of abandoning farmland by 21.2% or 7.8%, respectively, while confirming land titles reduces the probability of abandonment by 9.8%.

In summary, the age of the householder, working outside the home, the proportion of non-farm income, the proportion of productive assets, topography, land titling, and the land transfer market are all decisive factors affecting farmers' land abandonment. Farmers who are a young householder, with family members who work outside the home, with a high proportion of non-farm income, and who are in hilly and mountainous areas are more likely to abandon their farmland. On the other hand, those who are an older householder, with no workers outside the home, with a high proportion of productive assets, and who have completed land titling are less likely to abandon their farmland. The land system contributes to farmland abandonment to a certain extent by causing a mismatch of farmland resources among farmers.

Table 3 shows the results of the drivers of the abandoned farmland area. Model 4 includes the characteristics of the householder, family and location. Models 5 and 6 gradually include the year and region dummy variables on the basis of Model 4, and Model 6 provides a robustness check with regard to the inclusion of all the variables. The results show that there is also a U-shaped relationship between the age of the householder and the abandoned farmland area. The turning point is 47.92 years old. That is, when the householder is less than 47.92 years old, the area of farmland abandonment is smaller. In contrast, when the householder is over 47.92 years old, the area of farmland abandoned by farmers increases. Meanwhile, farmers who work outside the province, receive a high proportion of non-farm income and live in hilly and mountainous areas are more likely to abandon their farmland. In contrast, farmers whose total productive assets are high, whose land rights have been confirmed and whose land transfer market is well developed are less likely to abandon their farmland.

These findings suggest that labour shortages, coupled with an increase in non-farm income, are crucial factors driving farmers to abandon their farmland. Fig. 5 shows the change pattern of non-farm wages and the rural residential population in China from 1995 to 2020. Nonfarm wages rose continuously during the study period from 11.30 yuan per day in 1995 to 139.23 yuan in 2020, representing an increase

Table 3
Drivers of abandoned farmland area for farmers based on the Tobit model.

Variables	Model 4	Model 5	Model 6
Age of householder	−0.003	−0.003***	−0.0023***
	(-0.64)	(-3.33)	(-2.68)
Age of householder ^2	0.000017	0.000029***	0.000024***
	(0.38)	(3.57)	(2.99)
Working outside the province	0.034	0.026***	0.021***
	(1.18)	(5.04)	(4.07)
Working in the province	0.089***	0.029***	0.020***
	(3.93)	(6.55)	(4.60)
Educational level of household head	−0.016	−0.006***	−0.005**
	(-1.54)	(-3.08)	(-2.49)
Log (Total nonfarm income)	−0.001	0.001	0.001**
	(-0.24)	(-0.40)	(2.48)
Log (Total productive assets)	−0.019***	−0.007***	−0.006***
	(-6.47)	(-12.94)	(-10.78)
Access to credit	−0.266***	−0.006	0.008
	(-5.36)	(-0.67)	−0.91
Topography	0.068**	0.005	0.021***
	(2.35)	(0.82)	(3.32)
Land titling	−0.035**	−0.035**	−0.035**
	(-2.29)	(-2.31)	(-2.21)
Log (Level of farmland transfer rent)	−0.063***	−0.008***	−0.008***
	(-3.61)	(-2.71)	(-2.76)
Constant	0.224	0.134***	0.082***
	(1.45)	(4.87)	(2.89)
Other variables	Yes	Yes	Yes
Year dummies variables	-	Yes	Yes
Region dummies variables	-	-	Yes
LR chi2	231.71	1836.58	2583.51
Pseudo R2	0.113	0.582	0.818
Number of samples	31406	31406	31406

Note: T statistics in parentheses. * p < 0.1, * * p < 0.05, * * * p < 0.01.

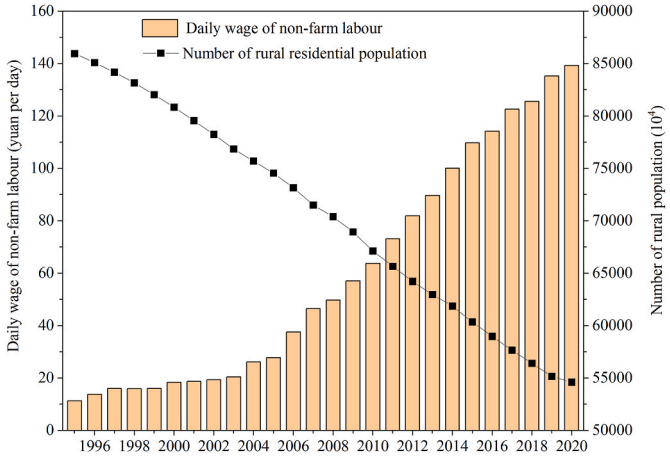

Fig. 5. Rural population and non-farm wages from 1995 to 2020.

of nearly 12 times. Meanwhile, the residential population in rural areas declined from 859.47 million in 1995 to 546 million in 2020, representing a drop of 314 million (36.47%) over the past 20 years. Notably, non-farm employment wages rose exponentially from 2003 to 2010. Combining the analyses of Figs. 2 and 3, we find that the ratio of farmland abandonment rose the fastest from 2002 to 2008. The relationship among farmland abandonment, the increase in non-farm wages and the decrease in the residential population in rural areas shows a synergistic evolutionary nature.

3.4. Production loss caused by farmland abandonment

To quantitatively evaluate the production loss caused by farmland abandonment, this paper first calculates the farmland abandonment ratio at the provincial level by applying the area-weighted method to the surveyed counties. Then, the production loss caused by farmland abandonment is estimated based on the provincial grain yield per unit area. Fig. 6a shows that the provinces with large areas of abandoned farmland in the major grain-producing areas are Hunan, Hubei, Sichuan, Shandong and Anhui, which are located mainly along the Yangtze River. Fig. 6b shows that the provinces with large areas of abandoned farmland in the non-major grain-producing areas are Xinjiang, Shanxi, Gansu, Yunnan and Chongqing, which are mainly distributed in the hilly and mountainous areas of Northwest, Southwest and Southeast China.

Table 4 shows that the ratio of abandoned farmland in the major grain-producing areas was 7.38%, of which the ratios in Hunan and Hubei were generally higher than 10%. The ratio of abandoned farmland in the non-major grain-producing areas was 16.94%, with the highest ratios in Chongqing, Shanxi, Zhejiang and Xinjiang (in that order), all of which exceeded 20%, with Chongqing reaching 26.37%. In 2020, the area of abandoned farmland was 4.48 million ha in major grain-producing areas and 6.43 million ha in nonmajor grain-producing areas, among which Hunan and Xinjiang were the largest. In terms of production loss, the scale of production loss caused by farmland abandonment in major grain-producing areas and non-major grain-producing areas was 29.05 million tons and 20.18 million tons, respectively, accounting for 4.34% and 3.02% of the total output (669.50 million tons in 2020), respectively, for a total of 7.36%. In short, farmland abandonment has become very common in both major and non-major grain-producing areas. The production loss caused by farmland abandonment amounts to 49.23 million tons, accounting for 7.36% of the total grain output in 2020. It is estimated that the scale of grain reduction caused by farmland abandonment in China could feed 123 million people based on the per capita annual food consumption estimates of 400 kg.

4. Discussion

4.1. Urgency of farmland abandonment management

In the context of global changes, global food security is facing serious challenges, and the production loss caused by farmland abandonment poses a great threat to food security. Studies show that serious farmland abandonment has occurred in both major food-producing and non-food-producing areas due to accelerated urbanization, which has increased nonfarm wages and decreased the permanent rural population. Excluding the high-yield provinces of Inner Mongolia and Heilongjiang, major grain-producing areas and nonmajor grain-producing areas lost 29.05 million tons and 20.18 million tons of grain, respectively. These losses represent 7.36% of China's total grain production and 34.26% of its total grain imports in 2020. These losses could feed 123 million people, based on an international estimate of 400 kg of per capita annual grain consumption. Notably, according to the Food and Agriculture Organization (FAO) of the United Nations, nearly 690 million people worldwide were already facing food shortages and hunger in 2019, even before COVID-19. Furthermore, the world is currently experiencing an era of multiple crises and compound risks, with frequent and significant impacts from factors such as the Newcastle pneumonia epidemic, economic depression, regional conflicts, climate change, and extreme weather. Agriculture and food systems have become incredibly vulnerable, and the global food supply chain is unstable. Changes in food production have increased the risk of agricultural production (Li et al., 2021; George and Adelaja, 2022). Until there is a fundamental breakthrough in agricultural science and technology, farmland will remain the decisive factor in ensuring food production. Therefore, all sectors must pay greater attention to this issue and work together to develop effective strategies to mitigate the impacts of farmland abandonment on food production and security.

4.2. Comprehensive management of farmland abandonment

Various countries have implemented measures at the policy,

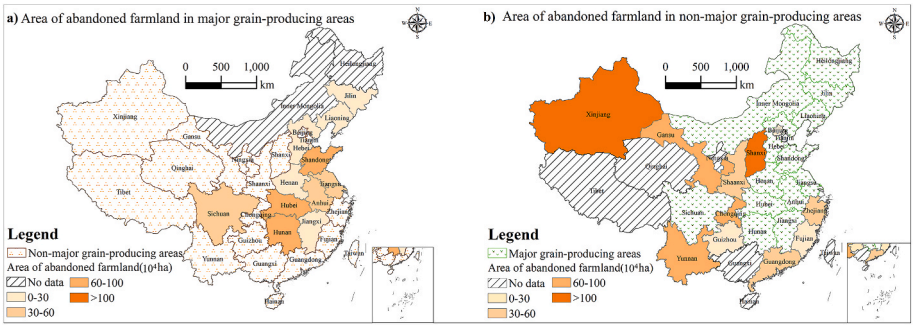

Fig. 6. Spatial pattern of farmland abandonment in major and nonmajor grain-producing areas.

Table 4
Production loss caused by abandoned farmland.

Provinces	Ratio of abandoned farmland (%)	Area of abandoned farmland (ha)	Production loss (Ten thousand tons)	Ratio of production loss (%)
Major grain-producing areas				
Liaoning	2.54	126324.54	59.22	0.10
Shandong	9.35	709878.00	502.66	0.81
Henan	2.82	229019.28	184.19	0.30
Anhui	9.04	530262.32	363.31	0.59
Jiangsu	8.83	403883.75	318.88	0.52
Hubei	13.20	691000.99	375.61	0.61
Sichuan	8.43	566886.56	294.09	0.48
Hunan	17.21	714383.63	489.81	0.79
Jilin	1.80	125668.90	74.72	0.12
Hebei	4.10	267507.68	157.13	0.25
Jiangxi	3.85	118872.16	85.58	0.14
Total	7.38	4483687.81	2905.21	4.34
Non-major grain-producing areas				
Xinjiang	20.00	1047920.00	296.94	0.48
Beijing	7.81	16694.59	3.21	0.01
Shanxi	25.27	1025087.91	342.45	0.55
Gansu	18.35	986835.64	202.96	0.33
Shaanxi	13.28	528767.34	158.54	0.26
Chongqing	26.37	624810.64	284.72	0.46
Yunnan	14.56	904727.56	268.42	0.43
Fujian	17.14	229183.43	83.52	0.14
Guangdong	18.72	486788.84	226.31	0.37
Guizhou	3.23	146039.69	40.15	0.06
Zhejiang	21.64	427844.73	110.39	0.18
Total	16.94	6424700.37	2017.62	3.02

technical and economic levels to address the challenges posed by farmland abandonment. First, countries have introduced policies to support farmers and encourage them to remain engaged in local farming (Li et al., 2017; Gao et al., 2005). China's Ministry of Agriculture and Rural Affairs has issued the Guidance on the Coordinated Utilization of Waste Land for the Development of Agricultural Production. This policy document outlines requirements to improve farming conditions on waste land, promote large-scale operations, ensure food security, and enhance the ecological environment. In doing so, it provides increased policy support for waste land improvement. Second, economic measures have been taken to address farmland abandonment. These include increasing subsidies for food production, raising the purchase price of food, and improving the social security system in rural areas (Chen et al., 2018). These economic interventions aim to incentivize farmers to continue farming and reduce the likelihood of farmland abandonment. At the technical level, efforts are focused on land remediation and infrastructure development. These efforts involve improving infrastructure facilities for irrigation, drainage, and transportation on farmland and enhancing farming conditions (Wang et al., 2014; Huang et al., 2020). Additionally, the development of farm equipment suitable for mountainous areas and the promotion of agricultural mechanization contribute to reducing the ratio of abandoned farmland. Intelligent technologies such as remote sensing, big data, and machine learning are also being utilized to dynamically monitor land use. These technical means play a vital role in identifying areas at risk of abandonment and implementing timely interventions to prevent it (X. Wang et al., 2023). The combination of policy support, economic incentives, and technological advancements ensures the promotion of sustainable agriculture and the reduction in abandoned farmland. Countries can effectively address the challenges associated with farmland abandonment.

4.3. Uncertainty of the results of this study

The study has some limitations due to data restrictions. For instance, not all provinces in China were covered, and Heilongjiang Province and Inner Mongolia were not included in estimating the production loss caused by abandonment due to the lack of relevant data. Notably, both provinces are among the top ten grain-producing provinces in China, which could lead to an underestimation of the amount of food lost. Additionally, the phenomenon of "invisible farmland abandonment" occurring in some areas could not be estimated in this study (Sun and Zhou, 2016; Guo et al., 2020). This phenomenon refers to situations where although no farmland abandonment occurred, the input of labour, capital, and other factors per unit of farmland decreased significantly, leading to a decrease in the output level. As a result, the level of production loss may be underestimated. We plan to explore these issues further in future studies to provide a more accurate estimate of the scale of production loss that has been caused by farmland abandonment.

Despite the data limitations, our study included the five major topographic regions of China, covering both major and non-major grain-producing areas. Thus, the survey is somewhat nationally representative. Moreover, the data estimated through sampling are consistent with those of related studies. A meta-analysis showed that as of 2017, 165 counties nationwide recorded farmland abandonment, indicating an increasing trend (Zhang et al., 2019). In 2015, a sample study of mountainous counties found a national farmland abandonment ratio of approximately 14.3%, which is consistent with our findings (Li et al., 2018). Similarly, the ratio of abandonment in major grain-producing areas was approximately 6%, closely matching the 5.04% ratio found in our study (Li et al., 2021). Additionally, remote sensing image interpretation found that the ratio of farmland abandonment in some mountainous areas of Chongqing was over 20%, which was close to the figure of 26.37% found in our study in 2020 (Wang et al., 2020a,b).

In conclusion, despite the limitations in data and methodology, our study provides valuable insight into the extent of farmland abandonment in China. Our survey is somewhat nationally representative, including both major and nonmajor grain-producing areas, and it complements existing studies that are based solely on remote sensing images. The data estimated in our study through sampling have scientific validity and are consistent with those of related studies, whether considering national or local ratios of abandonment. Our findings can inform future efforts to address farmland abandonment and ensure that

this vital resource is sustainably managed for the benefit of future generations.

4.4. Future research directions of this study

With the progress of socio-economic development, the role of farmland evolves after its land-use transition (Song et al., 2015). While it serves as a crucial source of food production, it has also come to play a significant role in providing social functions such as an aesthetic landscape, leisure activities, entertainment, tourism, and farming culture preservation (Peng et al., 2015). Consequently, farmland abandonment not only affects national food security but also leads to the deterioration of agricultural landscapes, the decline of villages, the loss of farmer livelihoods, and changes in biodiversity. Furthermore, studies have shown that there are regional differences in the ecological effects of farmland abandonment, and whether farmland abandonment is beneficial for biodiversity is a matter of concern (Aide et al., 2012; Y. Wang et al., 2023). Therefore, the effects of farmland abandonment could be the focus of future research.

A further concern is that in addition to the large-scale abandonment of sloping arable land in China's hilly mountainous regions, the high-quality farmland resources (terraced fields) in the mountains are currently at constant risk of being abandoned. Terraces play a significant role in enhancing food production compared to sloping land in mountainous areas. Moreover, terraces contribute to the reduction in runoff, improved soil fertility, and resilience against natural disasters. Unfortunately, the abandonment of terraced land has become a common occurrence in China. The large-scale abandonment of terraces not only results in the waste of human and material resources invested in their construction but also poses threats to food security. Moreover, it gives rise to a range of ecological and environmental issues, including increased soil erosion and alterations in landscape and biodiversity within mountainous areas. Therefore, conducting a comprehensive nationwide survey to assess the extent of terrace abandonment, investigate its causes, and protect terraces is a future research direction.

5. Conclusions and implications

5.1. Conclusions

In conclusion, this paper provides a systematic analysis of China's farmland abandonment from 1995 to 2020, using spatial analysis and econometric models to estimate the production loss. The study highlights that farmland abandonment has become increasingly prominent in rural China and that the number of counties with records of abandonment rose significantly over the study period. The phenomenon is primarily concentrated in hilly and mountainous areas along the Yangtze River, as well as Southeast, Southwest, Northwest, and Northeast China. Furthermore, the causes of farmland abandonment are complex and include factors such as farmland capacity and socio-economic and ecological factors. While farmland capacity is an internal factor, external driving forces such as labour shortages play a crucial role. Finally, the scale of grain reduction resulting from farmland abandonment in China is sufficient to feed nearly 100 million people, highlighting the impact on food security. Therefore, understanding the extent and drivers of farmland abandonment is vital for developing effective strategies to mitigate its impact on food security and to promote sustainable agricultural development in China. Additionally, our study provides valuable insights that can inform future policy decisions aimed at addressing this critical issue.

5.2. Policy implications

First, the government should strengthen the construction of farmland infrastructure, promote advanced technology, and improve the farming conditions of abandoned land. In short, the government should gradually improve the quality of farmland through comprehensive land management, improve rural infrastructure and develop small-scale machinery that is suitable for hilly and mountainous areas. In addition, it is worth noting that wildlife invasion has led to the abandonment of a large amount of farmland in hilly and mountainous areas. The government should strengthen the monitoring of wildlife, principally wild boars, and systematically assess the scale of abandoned farmland caused by wildlife.

CRediT authorship contribution statement

Yahui Wang: Data curation, Investigation, Methodology, Software, Writing – review & editing, Conceptualization, Supervision, Validation, Visualization, Project administration, Funding acquisition. **Aoxi Yang:** Investigation, Formal analysis, Roles, Writing – original draft, Writing – review & editing, Conceptualization, Investigation, Formal analysis, Methodology, Resources. **Qingyuan Yang:** Formal analysis, Roles, Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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