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The impact of government regulations on farmers' reduction of antimicrobial use: a survey of 1395 hog farmers in China

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Abstract

This study was based on a sample of 1,395 pig farmers from the fixed observation points in rural China in 2019. By applying a damage control model with an exponential distribution as the loss function, this study explored the marginal productivity of veterinary drug use among pig farmers in the four major pig - raising regions in China (the key - development region, the moderate - development region, the constrained - development region, and the potential - development region). Additionally, a binary Logit model was utilized to analyze the impacts of various factors on the excessive drug - use behavior of pig farmers in different regions. The estimation results of the damage - control model demonstrated that pig farmers in all four major farming regions had severe problems of excessive drug use. The proportions of excessive drug users in these regions were 47.4%, 66.1%, 67.2%, and 54.2% respectively. The regression results of the binary Logit model indicated that the regulatory and guiding behaviors of the government had a significant influence on the excessive drug - use behavior of pig farmers. However, the impacts differed across different regions. In moderately developed areas, part-time farming significantly inhibits excessive drug use by farmers. In potential development areas, joining agricultural cooperatives has the same effect. In restricted development areas, participating in farming training also has a significant inhibitory effect. Therefore, the government should strongly support the development of farmers' cooperatives and increase the scale and frequency of livestock training. Differentiated policies need to be formulated according to the different resource endowments in various livestock - raising regions.

Keywords Antimicrobial use, Damage control model, Marginal productivity, Regional heterogeneity, Hog farmers

Introduction

Reducing the use of veterinary drugs is of great significance for safeguarding national biosecurity and food safety. Since China implemented economic reforms in 1978, China's aquaculture and livestock breeding industries have been continuously developing and expanding. In 2020, China's live pig inventory was 406.2 million heads, accounting for 42.64% of the world's total [1]. In 2021, after being impacted by the African swine fever epidemic and the COVID-19 pandemic, China's live pig production recovered rapidly. The proportion of large-scale live pig farming reached 60% for the first time, and the number of live pigs slaughtered reached 671.3 million heads, an increase of 144.2 million heads compared with the previous year [2]. At the same time, the industry is facing serious threats from diseases such as swine fever, porcine reproductive and respiratory syndrome, and porcine pneumonia [3]. In 2019, the total economic losses

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caused by African swine fever to the pig farming industry accounted for 0.78% of China's GDP [4]. Veterinary drugs, as essential inputs in the breeding process, are widely used in pig farming. They can not only effectively reduce the risk of disease occurrence, ensure the output of livestock and poultry and breeding profits, but also significantly reduce the labor intensity of pig farming. However, there is a common phenomenon of excessive use of veterinary drugs by farmers during the breeding process [5]. China is already the world's largest producer and consumer of antibiotics, with an annual production of antibiotics exceeding 160,000 tons, of which more than 50% is used for animals [6]. Excessive use not only has poor effects on disease prevention and control but also leads to the emergence of serious biosafety issues such as zoonotic diseases and drug resistance in livestock and poultry [7]. International organizations such as the World Health Organization (WHO) are collaborating with various countries and local institutions, urgently advocating for actions to address the emergence and spread of antimicrobial resistance [8, 9]. Numerous scholars have conducted in-depth research on the factors influencing farmers' excessive use of antimicrobial drugs from different perspectives, aiming to promote farmers to reduce their drug use behavior.

However, there are differences in resource endowments, geographical locations, economic development levels, and cultural traditions among different breeding regions. A common view is that farmers' excessive drug use is closely related to the economic development level, population structure, employment situation, and geographical location of the regions they are in [10]. In coastal areas, due to frequent foreign trade, the risk of introducing exotic diseases is high, and farmers may excessively use antiviral veterinary drugs as a precaution. In economically developed areas, the degree of large-scale and intensive breeding is high, and there are high requirements for food safety and breeding standards. Therefore, farmers will use veterinary drugs in a standardized manner. These differences have led to heterogeneity in government regulatory behaviors aimed at reducing the use of antimicrobial drugs among different entities and regions. In order to establish the development of innovation, coordination, greening, opening and sharing, as well as to accelerate the transformation, upgrading and green development of the hog breeding industry, and ensure the effective supply of pork products, the Ministry of Agriculture and Rural Affairs issued the National hog Production Plan (2016–2020). This classification divides China's hog breeding regions into key development areas, constrained development areas, potential development areas, and moderate development areas. It also calls for the steady promotion of the reduction in the use of veterinary antimicrobial agents, with the aim of effectively enhancing the capacity and level of the safe, standardized, and scientific use of these agents in livestock and poultry breeding. Therefore, studying the influence of government regulation on veterinary antimicrobials use by farmers in different regions is of great practical significance to optimize the structure and regional layout of hog production and to promote farmers' reduction of antimicrobials use.

In view of this, in this study we use a large data sample from the China Rural Fixed Observatory 2019, comprising a total of 1395 hog farmers in 30 provinces across China, and divide China's hog breeding regions according to the National hog Production Development Plan (2016–2020) issued by the Chinese Ministry of Agriculture and Rural Affairs. Additionally, under the framework of a damage control model, we estimate the marginal productivity of veterinary antimicrobials in different farming regions and introduce a binary logit model to further analyze the factors affecting the overuse of veterinary antimicrobials by farmers in different farming regions.

Literature review and hypothesis development

Literature review

Scholars have extensively researched the potential hazards of the overuse of veterinary drugs and reached a consensus. The excessive use of veterinary antimicrobials not only leads to serious antimicrobial resistance issues, but also increases energy consumption and CO_2 emissions [11]. Moreover, research has been carried out to determine whether farmers engage in antimicrobial overdosing behavior [12]. Huang et al. utilized a two - stage damage control model to estimate the marginal productivity of pesticides in maize cultivation in China. The results indicated that the marginal productivity of pesticides was nearly zero [13]. Sun and Zhou applied a damage control model to calculate the marginal productivity of veterinary antimicrobials for hog farmers in Liaoning Province and found it to be close to zero [14].

To promote farmers to reduce the use of antibiotics, standardize disease prevention and control, domestic and foreign scholars have explored factors influencing farmers' adoption of green production practices from different perspectives. Some scholars have studied the impact of farmers' personal characteristics, family operational characteristics, cognitive perspectives, and social perspectives on their use of veterinary antibiotics. These factors include age [15], gender [16], level of education [17], number of hired workers [18], disease prevention and control knowledge and perception [19], and agricultural social services [20]. Additionally, some scholars believe that market demand is a crucial motivating factor for farmers' technology adoption [21], as the market stimulates farmers to adopt environmentally friendly production practices by increasing demand and prices for high-quality agricultural products [22]. While proper drug use by farmers also has environmental benefits, the market returns from proper drug use are the key incentive for stimulating their behavior and willingness, with market returns proving to be more effective than other policy measures [23]. However, recent studies indicate that achieving green and healthy development in the agricultural industry is challenging through self-regulation and market forces alone [24]. More scholars are beginning to examine the impact of government regulations on green production practices [25]. In terms of restrictive regulations, government oversight and penalties on farmers' production behavior have the most significant impact on promoting green production, as part of a comprehensive regulatory policy [26]. However, the current inadequacies in the government regulatory system have led to poor implementation of restrictive government regulations, resulting in frequent occurrences of behaviors such as excessive medication use and non-compliance with withdrawal periods by farmers [27]. In terms of incentive-based regulations, the government can provide farmers with appropriate compensation and rewards to alleviate production cost pressures to some extent and enhance farmers' motivation for proper drug use [28]. As for guidance-based regulations, the government can significantly improve farmers' awareness through knowledge training and educational activities, thereby promoting their adherence to proper production practices [29].

In summary, the majority of the existing literature relies on sample data from only a few provinces, and there is limited research on government regulation at the regional level. Given the diverse endowments, such as disparities in economic development levels, cultural backgrounds, and geographical conditions, among different farming regions, the results derived from studies using local - regional data may not accurately and scientifically represent the national scenario of farmers' veterinary drug use. Therefore, this study makes use of data from 1395 pig farms in fixed rural observation points across China. It classifies the pig - farming regions into key development areas, constrained development areas, potential growth areas, and moderately developed areas. Based on this classification, the study employs a loss - control model to calculate the marginal productivity of veterinary drug use by farmers in different regions. This allows for an assessment of the extent of excessive drug use by farmers in various regions and a further analysis of the impact of government regulatory policies on farmers' excessive drug - use behaviors in different farming regions. The objective is to furnish agricultural policymakers with references for formulating and implementing effective government regulatory measures and to propose policy recommendations for attaining high - quality development in the livestock industry.

Hypothesis development

Government involvement in the regulation of the farming industry mainly encompasses two types of regulatory approaches: incentive - based regulation and constraint - based regulation. Incentive - based regulation consists of activities such as awareness - raising, training, and the provision of subsidies. Constraint - based regulation, on the other hand, includes regulatory measures and penalties. The government's efforts in raising farmers' awareness and providing training can significantly enhance their knowledge of disease management and control, thereby promoting positive disease management and control behaviors among them [30]. Cash subsidies, on one hand, can strengthen farmers' ability to withstand risks, and on the other hand, they can reduce farmers' production costs. As a result, financial subsidies can increase farmers' inclination to reduce the amount of medications used. When government departments regulate the production process of farmers, it directly decreases the probability of farmers engaging in moral - hazard behaviors. Under strict regulation, farmers are compelled to reduce their use of certain substances. Policy - imposed penalties, by adding additional costs, indirectly discourage farmers from over - dosing [14]. Based on the above - mentioned analysis, the following hypotheses are proposed: Based on the above analysis, the following hypotheses are proposed:

H1: Government regulation behavior has a positive and significant effect on reducing the behaviour of over usage of VMPs by hog farmers.

In the process of agricultural production, the decision-making behavior of livestock farmers is influenced by factors such as policies, market demands, and resource conditions. However, it is important to recognize that different livestock regions have varying production foundations, environmental carrying capacities, resource endowments, consumer preferences, as well as slaughter and processing factors, which may affect how livestock farmers perceive and accept government regulatory policies. Therefore, even if the government implements similar regulatory policies across different regions, the responses and behaviors of livestock farmers may differ. Some scholars have found that when promoting green production behavior among farmers, policies should be tailored based on the agricultural production conditions and economic development levels of different regions [31]. Thus, when analyzing the impact of government regulatory policies on the behavior and compliance of livestock farmers, it is imperative to carefully consider the interactive relationships among the specific characteristics of each livestock area. Based on the above analysis, the following hypotheses are formulated:

H2: In different farming regions, government regulatory policies have different effects on the overdosing behavior of farmers.

Materials and methods

Theoretical analysis

The mechanism of veterinary medicine for hog breeding is different from traditional input factors such as capital, feed and labor. Veterinary medicine does not directly increase the production efficiency of hog breeding, but reduces the loss of production through the treatment and prevention of diseases. In this paper, we divided the mechanism of action of veterinary antimicrobials on hog farming into two stages by drawing on the work of Fox and Weersink [32], who introduced pesticide inputs into the production function. The first stage is when veterinary medicine comes into play in the event of an epidemic. Assume that when the amount of veterinary antimicrobials used is 0, the loss caused by the outbreak in the natural state is Z_0. When the amount of veterinary antimicrobials used is Q, then the effect of veterinary antimicrobials on the loss caused by the outbreak is C(Q). Then the expression of the damage control model due to the outbreak of the disease is:

$$Z = Z_0\left[1 - C\left(Q\right)\right] \tag{1}$$

C(Q) is a cumulative distribution function in the range of [0,1]. When C(Q) = 0, it means that the veterinary antimicrobials did not have any effect on the occurrence and spread of the disease; when C(Q) = 1, it means that the use of veterinary antimicrobials completely controlled the occurrence and spread of the disease and the loss of hog breeding was 0.

In the second stage, the use of veterinary antimicrobials does not fully control the occurrence and spread of epidemics, and outbreaks of epidemics affect the hog breeding industry. Assuming that Y_0 denotes the hog production without being affected by the epidemic, and D(Z) denotes the proportion of hog production being affected under the degree of epidemic impact Z. Then the expression of the loss control function is:

$$Y = Y_0\left[1 - D\left(Z\right)\right] \tag{2}$$

D(Z) is likewise a cumulative distribution function that lies in the range [0,1], then:

$$Y = Y_0\left[1 - D\left\{Z_0\left[1 - C\left(Q\right)\right]\right\}\right] \tag{3}$$

Model Building

Damage control model

The C-D production function is the most common form in general factor input production efficiency studies:

$$Y = \alpha\left\{\sum\nolimits_{i=1}^{n}\left[\left(X_i\right)^{\beta\,i}\right]\right\}\left(X_P\right)^{\delta} \tag{4}$$

Y is the hog production, XP is the amount of veterinary antimicrobials input, Xi is the i-th production factor input other than veterinary antimicrobials that can affect hog production, and α, β_i, δ are coefficients to be estimated.

To facilitate the identification of measurements, in this paper we set $r = 1$ in Eq. (5). Drawing on the expression for the damage control function proposed by Lichtenberg and Zilberman [33] in an existing study, we obtain:

$$Y = \alpha\left\{\sum\nolimits_{i=1}^{n}\left[\left(X_i\right)^{\beta\,i}\right]\right\}G\left(X_P\right)^{\gamma} \tag{5}$$

The above equation can be simplified as:

$$Y = F\left[X, G\left(X_P\right)\right] \tag{6}$$

Where F(·) denotes the C-D production function and G(·) is the damage control distribution function. G(Xp) is defined as a decimation function. We selected the loss control function in the form of exponential distribution based on the principles of simplicity of calculation, ease of understanding and better fit to the data.

Considering that, in the actual hog breeding process, different farmers use a wide range of veterinary antimicrobials with different prices, both injectable and oral, there are practical difficulties in counting the doses and prices of various types of veterinary antimicrobials as a single variable in the research process. Therefore, we constructed the marginal productivity of veterinary antimicrobials by analyzing the relationship between input costs and output benefits. Additionally, in order to compare the differences between the standard C-D production function and the loss control model, we established logistic regression equations for Eqs. (4) and (5) of the previous section:

$$ln\left(Y_n\right) = \alpha + \sum \beta_{\,i} ln\left(X_{in}\right) + \sum \theta_{\,j} M_{jn} + \delta\, ln\left(X_P\right) + V_n \tag{7}$$

$$ln\left(Y_n\right) = \alpha + \sum \beta_{\,i} ln\left(X_{in}\right) + \sum \theta_{\,j} M_{jn} + ln\left[G\left(X_P\right)\right] + V_n \tag{8}$$

where Yn is the hog farming income of the nth hog farming household; α, δ, β_i, θ_i are parameters to be estimated; V_n is the random error term; X_{in} is the cost of inputs except veterinary antimicrobials; and M is the control variable. For the standard C-D production function, we adopted a simple ordinary least squares (OLS) regression for estimation. Since the damage control model is nonlinear, we adopted the nonlinear least-squares (NLS) method for estimation.

By taking partial derivatives of Xp for each side of Eqs. (7) and (8), the marginal productivity of veterinary medicine (MVP) is defined as the farm income generated per unit of additional veterinary medicine. When MVP = 1, the veterinary antimicrobials input has reached the economic optimum. The equations are, respectively:

$$MVP\left(X_P\right) = \frac{\partial Y}{\partial X_p} = \beta \frac{Y}{X_p} \tag{9}$$

$$MVP = \frac{\partial Y}{\partial X_P} = \frac{Y}{G\left(X_P\right)} \times \frac{\partial G\left(X_P\right)}{\partial X_P} \tag{10}$$

Logit model

we constructed a logit model for regression analysis of the influencing factors of veterinary antimicrobials over-administration. The specific form is:

$$ln\frac{P\left(Y_n = 1\right)}{1 - P\left(Y_n = 1\right)} = \alpha + \sum \beta_{\,i} X_{in} + \varepsilon_{\,n} \tag{11}$$

In Eq. (11), Y_n represents whether the nth hog farmer over-administered veterinary antimicrobials. X_i is the independent variable affecting the over usage of veterinary antimicrobials by hog farmers in different farming regions.

In this paper, we drew on the existing research results and used 13 factors in three areas that affect the administration of veterinary antimicrobials by hog farmers as independent variables in the model (as shown in Table 8); that is, individual characteristic factors of hog farmers, including sex [15], age [14] and level of education [16]. We also considered hog farmers' household characteristics, including the main business of the household [34], the number of household laborers [35], the scale of household farming [36], whether they participate in farmers' cooperatives and whether they received training in farming [37]. Government policy factors were considered, including the number of times the relevant government departments supervised the use of veterinary antimicrobials by hog farmers [38], the number of fines imposed by the government on farmers for the illegal use of veterinary antimicrobials [39], the compulsory immunization subsidies granted by the government [40] and the number of government-organized campaigns for the reduction in veterinary antimicrobials use [41]. When calculating the marginal productivity of veterinary drug use, this paper refers to the existing research [42] and identifies six factors of production as input variables: piglet cost, feed cost, utility cost (water and electricity), veterinary drug cost, hired labor cost, and environmental protection cost. The income from hog farming is used as the output variable.

Data sources and descriptive statistics

Data sources

The micro-level farmer data used in this study are derived from the household survey data of the China Rural Fixed Observatory Points in 2019. The selection of sample livestock - breeding households is carried out as follows. First, government departments select sample villages across the country using the type - sampling method, taking into account different topographical features, levels of economic development, and types of economic regions. Subsequently, in the villages designated for fixed - point observation, 50–100 peasant households are chosen through the stratified - sampling method for long - term fixed - point observation. This selection is based on the upper, middle, and lower levels of household income. Data collection typically involves peasant households recording their daily production - related and living - related income and expenditure. Government investigators will regularly inspect and guide the peasants' book - keeping work to ensure its standardization and accuracy. After the data is compiled, it will be reviewed by the competent authorities. After cleaning the sample data by removing irrelevant values and missing data, a total of 1,395 pig farming households from 30 provinces and municipalities across China remained. These 30 provinces and municipalities are: Beijing, Tianjin, Jiangsu, Zhejiang, Fujian, Anhui, Jiangxi, Hubei, Hunan, Guangdong, Liaoning, Jilin, Heilongjiang, Inner Mongolia, Yunnan, Guizhou, Hebei, Shandong, Henan, Chongqing, Guangxi, Sichuan, Hainan, Shanxi, Shaanxi, Gansu, Xinjiang, Qinghai, Tibet, and Ningxia. Taking into consideration the production development foundation, environmental carrying capacity, resource endowment, consumption preferences, and slaughter processing, the Ministry of Agriculture and Rural Affairs of China has divided the national pig farming regions into key development areas, constrained development areas, potential growth areas, and moderately developed areas. Following the regional classification method of China's Ministry of Agriculture and Rural Affairs' "National Pig Production Development Plan (2016–2020)", the 30 provinces are divided into four major regions: Key Development Region, Constraint Development Region, Potential Development Region, and Moderate Development Region. The Key Development Region includes Hebei, Shandong, Henan, Chongqing, Guangxi, Hainan, and Sichuan. The Constraint Development Region includes Beijing, Tianjin, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Hunan, and Guangdong. The

Potential Development Region includes Inner Mongolia, Liaoning, Jilin, Heilongjiang, and Guizhou. The Moderate Development Region includes Yunnan, Shanxi, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, and Tibet(Fig. 1). The macro-level provincial data used in this study are sourced from the "China Livestock and Veterinary Yearbook" and the "China Agricultural Yearbook" of 2020.

Descriptive statistics of the sample

The data selected for this study from the nationwide fixed rural observation points can be divided into three parts: the first part includes individual statistical characteristics of pig farmers; the second part includes household statistical characteristics of pig farmers; and the third part includes specific breeding information of pig farmers, such as basic inputs and outputs of pig farming, including pig farming income, year-start livestock inventory, annual production volume, current year production and operating expenses, costs of piglets, disease prevention and control expenses, feed costs, labor inputs, etc. The data obtained from the "China Animal Husbandry and Veterinary Yearbook" and the "China Agricultural Yearbook" mainly include the number of government supervision inspections of pig farmers' veterinary drug use, the amount of fines imposed by the government for illegal veterinary drug use, the amount of compulsory immunization subsidies provided by the government, and the number of government-organized campaigns promoting reduced use of veterinary drugs. In this study, these four variables related to government regulation are categorized into constraint variables and guidance variables. The constraint variables are government supervision inspection frequency and fine amount, while the guidance variables are compulsory immunization subsidy amount and reduced medication promotion frequency.

Individual statistical characteristics

The individual statistical characteristics of the hog farmers in the four different farming regions are summarized in Table 1. As can be seen from Table 1, farmers are more likely to be male in all four different hog farming regions. In terms of age distribution, farmers in the four major breeding regions are mainly middle-aged and elderly, with 66.5% of hog farmers over 51 years old in

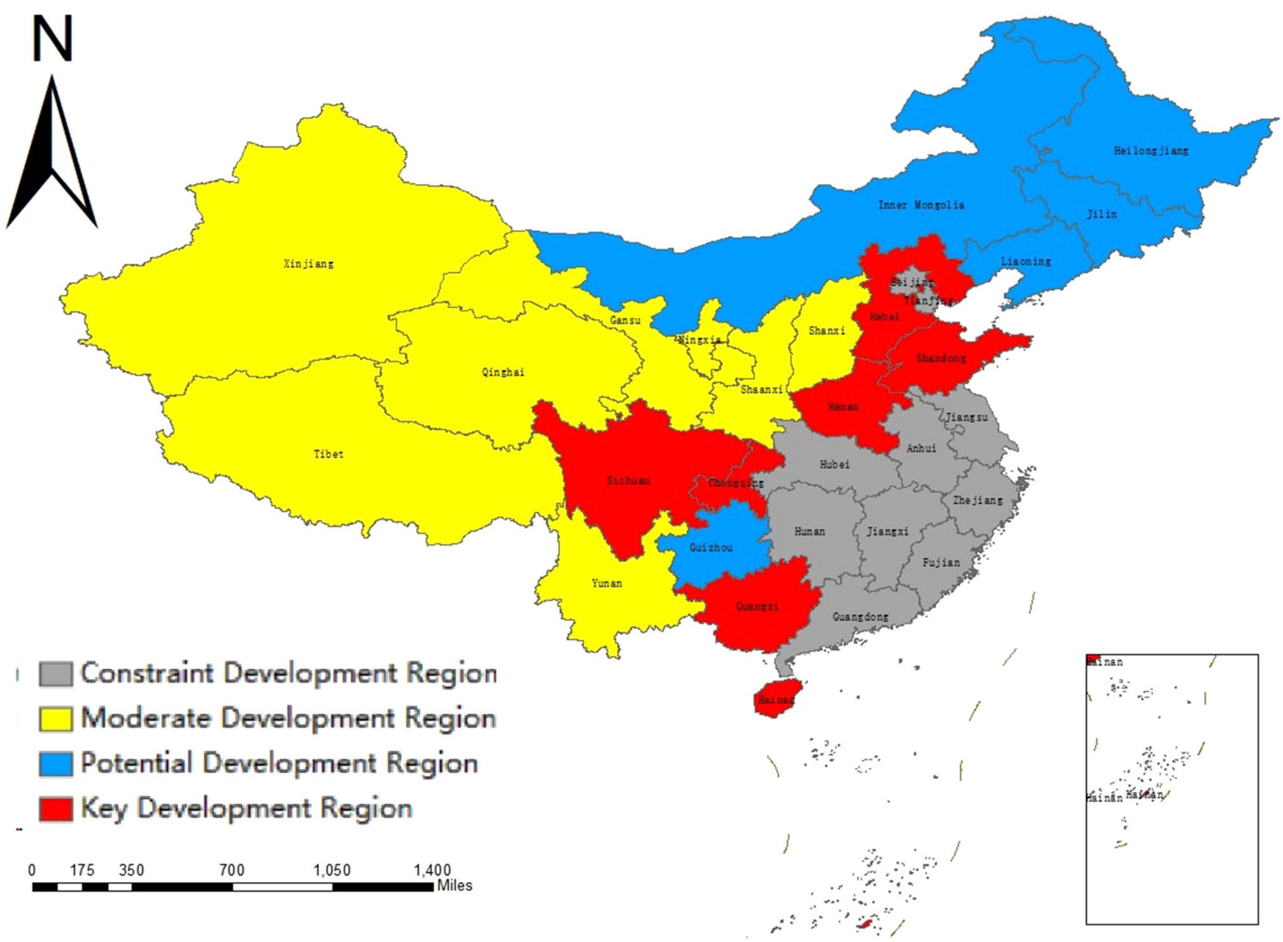

Fig. 1 Distribution of the four major farming regions

Table 1 Descriptive statistics of personal endowments of 1,395 sample livestock breeders in 2019

	Classification indicators	Number of samples			
		Key(%)	**Constraint(%)**	**Potential(%)**	**Moderate(%)**
Sex	Male	178(52.8)	148(55.6)	167(55.3)	247(50.4)
	Female	159(47.2)	118(44.4)	135(44.4)	243(49.5)
Age	20–30	23(6.8)	40(15.0)	52(17.2)	37(7.5)
	31–40	42(12.5)	24(9.0)	40(13.2)	70(14.3)
	41–50	48(14.2)	53(20.0)	47(15.6)	54(11.0)
	51–60	73(21.7)	45(17.0)	51(16.9)	111(22.7)
	61 years and older	151(44.8)	104(39.1)	112(37.1)	218(44.5)
Education level	Primary and below	134(39.8)	116(43.6)	121(40.1)	191(39.0)
	Middle School	167(50.0)	107(40.2)	148(49.0)	199(40)
	High School	22(6.5)	26(9.8)	21(70.)	62(12.7)
	College and above	14(4.2)	17(6.4)	12(4.0)	38(7.8)
Health conditions	Excellent	170(50.4)	157(59.0)	209(69.2)	315(64.2)
	Good	86(25.5)	62(23.3)	43(14.2)	90(18.3)
	Medium	43(12.7)	29(10.9)	16(5.2)	53(10.8)
	Poor	25(7.4)	12(4.5)	22(7.2)	20(4.0)
	Loss of labor	13(3.8)	6(2.2)	12(3.9)	12(2.4)
Agricultural training	Yes	305(90.5)	239(89.8)	250(82.7)	452(92.2)
	No	32(9.5)	27(10.2)	52(17.2)	38(7.8)

key breeding areas, 56.1% of farmers over 51 years old in bound breeding areas, 54.0% of farmers over 51 years old in potential development areas and 67.2% of farmers over 51 years old in moderate development areas. The education level of hog farmers in the four breeding regions is generally low, and the percentage of farmers with a higher education level is very small; the percentage of farmers with an education level of junior high school and below is 89.8% in the key development area, 73.8% in the constrained development area, 89.1% in the potential development area and 79.0% in the moderate development area. The physical condition of farmers in the four major breeding regions is generally good, with the percentage of farmers in excellent and good physical condition in the four major breeding regions being 75.9%, 82.3%, 83.4% and 82.5%, respectively. In general, the proportion of farmers in the four major hog breeding regions who received agricultural breeding training is very low.

Household statistical characteristics of hog farmers

Table 2 shows the statistical characteristics of the hog farming households. As can be seen from Table 2, the percentage of farmers who have farming as their main family business is very small in the four major farming regions, with 8% in the key development region, 12% in the constrained development region, 8% in the potential development region and 9% in the moderate development region. The number of farm household laborers in the four farming regions does not differ considerably, with mean values of 2.6, 2.6, 2.4 and 2.7, respectively. In different farming regions, the scale of hog farming varies due to factors such as resource endowment, land carrying capacity, urbanization level, market consumption potential and pork consumption capacity [35]. In general, the current scale of hog farming in China is relatively low, comprising mainly small- and medium-scale family farming. Overall, the development of farmers' cooperatives in China is low, and the number of farmers who know and join farmers' cooperatives is low, but there is a slight difference among the four major farming regions, with relatively more farmers joining farmers' cooperatives in the key development and potential development regions, accounting for 12% and 11%, respectively. In contrast, the percentages of farmers who joined farmers' cooperatives in the constrained development area and moderate development area were only 5% and 2%, respectively.

Characteristics of government regulation behavior faced by hog farmers

Table 3 illustrates the government regulation faced by pig farmers in different farming regions. According to Table 3, the total number of supervisory inspections of veterinary drug use by relevant government departments in key development areas, constrained development areas, and potential growth areas are 24,743, 35,472, and 22,626, respectively, while the least number of inspections is in moderately developed areas, at 7,244. Key development areas have the highest fines imposed by government departments for illegal veterinary drug use, with a total fine of 29.9 million RMB(Ren Min Bi, RMB), indicating stricter government regulation in these areas. Conversely, constrained development areas, potential growth areas, and moderately developed areas have relatively lower total fines for illegal drug use, at 16.3 million,

Table 2 Descriptive statistics of family endowments of 1,395 sample livestock breeders in 2019

Breeding area	Sample size	Farming as the main business				Number of laborers				Farming scale				Participation in cooperatives			
		Min	Max	Mean	S.D	Min	Max	Mean	S.D	Min	Max	Mean	S.D	Min	Max	Mean	S.D
Key	337	0	1	0.1	0.3	0	6	2.64	1.1	0	1300	24.63	115.8	0	1	0.1	0.3
Constraints	266	0	1	0.1	0.3	0	6	2.64	1.3	0	999	23.3	88.9	0	1	0.1	0.2
Potential	302	0	1	0.1	0.3	0	6	2.40	1.0	0	743	15.97	65.0	0	1	0.1	0.3
Moderation	490	0	1	0.1	0.3	0	7	2.72	1.0	0	300	11.63	36.4	0	1	0.1	0.2

Note: "Min" refers to the minimum value, "Max" refers to the maximum value, and "S.D." refers to the standard deviation

Table 3 Descriptive statistics of government supervision in four breeding regions in 2019

Breeding area	Number of supervisions (times)	Amount of fine (ten thousand yuan)	Amount of subsidy (ten thousand yuan)	Number of campaigns (times)
Key	24,743	2998	45,064	2293
Constraints	35,472	1630	76,779	9651
Potential	22,626	519	32,028	4229
Moderate	7244	1261	38,174	1154

5.2 million, and 12.6 million RMB, respectively. Constrained development areas have the highest expenditure on compulsory immunization subsidies, with a total amount of 767.8 million RMB, followed by key development areas and moderately developed areas, with total expenditures of 45.1 million and 38.2 million RMB, respectively. Potential growth areas have the lowest total expenditure at 32.0 million RMB. Constrained development areas and potential growth areas have the highest number of campaigns promoting reduced use of veterinary drugs, at 9,651 and 4,229 times, respectively, while key development areas and moderately developed areas have relatively fewer campaigns, at 2,293 and 1,154 times, respectively.

Estimated marginal productivity of veterinary antimicrobials

There are specific indicator settings and dimensions for each input variable on hog farming industry are shown in Table 4. From Table 4, it can be seen that hoglet inputs and feed inputs account for a greater proportion of the hog production process, while inputs in veterinary medicine account for a smaller proportion.

The damage control function has four forms of distribution functions. Its probability density function can converge rapidly to 0 and is within the range of 0 to 1. Therefore, it determines the extent of the damage caused by veterinary drugs (Xp) and the effectiveness of the control. Among the four distributions, the model in the Pareto distribution form implies the condition of constant output elasticity, which cannot accurately reflect the actual situation. Therefore, this distribution form is not adopted in this study. In empirical research, except for the Pareto distribution, the other three distributions have all been applied in empirical analysis. However, since there is no definite theoretical basis indicating which form is the best, one of the three distributions can be selected according to the principles of simplicity in calculation, ease of understanding, and good data fitting. In this study, because the damage control function with the Logistic distribution function does not converge during the iterative process, and the parameter α of the Weibull distribution is not significant, thus, based on the principles of simplicity in calculation, ease of understanding,

Table 4 Descriptive statistics of input - output variables of 1,395 sample livestock breeders in 2019

Variables	Variable description	Min	Max	Mean	SD
Breeding income	Continuous variable: Average revenue per pig (CNY/head)	0	6992	2304.4	1613.3
Piglet cost	Continuous variable: Cost of piglet inputs(CNY/head)	0	1900	382.8	372.4
Feed cost	Continuous variable: feed input cost (CNY/head)	0	2420	639.3	461.7
Water and electricity costs	Continuous variable: cost of water and electricity inputs (CNY/head)	0	337.5	6.3	23.6
Veterinary medicine costs	Continuous variable: veterinary input cost (CNY/head)	0	610	21.9	45.3
Labor costs	Continuous variable: breeding hired labor cost input (CNY/head)	0	214.3	2.2	17.3
Environmental costs	Continuous variable: Costs of farm manure treatment and environmentally sound treatment (CNY/head)	0	275	1.0	13.1

Note: “Min” refers to the minimum value, “Max” refers to the maximum value, and “S.D.” refers to the standard deviation, " CNY " refers to Chinese Yuan

Table 5 The regression results of the Cobb-Douglas production function in the four major aquaculture regions

Variables	C-D production function			
	Key	Constraints	Potential	Moderation
Livestock costs	0.144***(0.011)	0.068***(0.026)	0.107**(0.046)	0.148***(0.038)
Feed cost	0.647***(0.086)	0.933***(0.073)	0.702***(0.116)	1.008***(0.086)
Utility costs	-0.014(0.078)	-0.118**(0.052)	0.080(0.057)	0.006(0.172)
Veterinary cost	0.080(0.482)	0.039(0.047)	0.052(0.059)	0.269***(0.087)
Labor cost	0.632*(0.340)	0.333***(0.050)	-0.105(0.153)	-0.013(0.202)
Environmental costs	-0.147(0.106)	-0.945(0.896)	-0.106(0.069)	-1.967***(0.446)
Constants	2.572***(0.472)	1.360***(0.396)	2.470***(0.718)	0.132(0.470)
R^2	0.513	0.725	0.476	0.277
F-value	35.720	37.940	9.810	41.570

Note: The values in parentheses are standard errors. *** indicates significant at the 1% level.**indicates significant at the 5% level.*indicates significant at the 10% level. “——”means there are no data

R^2refers to the coefficient of determination, and α refers to the intercept

and good data fitting [43], this study selects the estimation results of the Cobb-Douglas (C-D) production function model and the damage control model with the Exponential distribution function for further analysis (as shown in Tables 5 and 6).

The results in Tables 5 and 6 show that for the four different farming regions, the C-D production function model and the damage control model with an exponential distribution function estimated similar magnitudes of the coefficients of the variables. The Tables 5 and 6 show that the impact of each input variable on hog farming income differs in different hog farming regions. Livestock costs and feed costs had a significant positive effect on hog farming income in all four hog farming regions. The effect of utility costs on hog farming income differs in different farming areas. For the constrained farming area, the input of utility costs has a negative effect on hog farming income. The cost of veterinary antimicrobials had a positive effect on the income of farmers in different regions, with the regression coefficients passing the 5% and 1% significance tests for key, constraints and moderate farming areas, respectively, indicating that disease control remains a crucial aspect of ensuring farming income and reducing losses, regardless of whether they are in the same farming area. In the key development area and the constrained development area, the hired labor cost of hog farmers has a positive and significant effect on farming income. The standard C-D production function regression results indicate that environmental costs in the moderate development area have a negative and significant effect on swine farming income. The results of the regression of the loss control model indicate that environmental costs in the moderate development area have a negative and significant effect on swine farming income.

In this study, based on the estimation results in Tables 5 and 6, the mean values of each input variable of hog farmers were introduced into Eqs. (6) and (7) to calculate the average marginal productivity of veterinary antimicrobials for the four farming regions. The average marginal productivity of veterinary antimicrobials for the four major farming regions was calculated to be 0 using the loss control function with the exponential distribution function, which indicates that the income from hog farming for each additional dollar of veterinary antimicrobials input is 0. This indicates that an increase in veterinary antimicrobials input by farmers will not increase farming income and will cause negative external effects, such as veterinary antimicrobials residues and harm to the ecological environment. The average productivity values of veterinary antimicrobials in the four major farming regions calculated using the C-D production function were 7.76, 3.03, 8.48 and 4.06, respectively. This result indicates that the marginal productivity of veterinary

Table 6 The regression results of the loss control functions of the exponential and the Weibull distribution

Variables	Damage control function							
	Exponential				Weibull			
	Key	Constraints	Potential	Moderation	Key	Constraints	Potential	Moderation
Livestock costs	0.146*** (0.034)	0.063** (0.025)	0.105*** (0.033)	0.127*** (0.036)	0.150*** (0.034)	0.064** (0.025)	0.103*** (0.032)	-0.152*** (0.037)
Feed cost	0.675*** (0.053)	0.933*** (0.044)	0.700*** (0.065)	0.986*** (0.086)	0.657*** (0.053)	0.921*** (0.043)	0.702*** (0.063)	1.060*** (0.084)
Utility costs	-0.003 (0.094)	-0.117** (0.061)	0.072 (0.080)	0.030 (0.170)	-0.077 (0.092)	-0.112* (0.061)	0.068 (0.077)	0.088 (0.138)
Veterinary cost	——	——	——	——	——	——	——	——
Labor cost	0.621* (0.380)	0.333*** (0.064)	-0.093 (0.260)	0.003 (0.685)	0.209 (0.364)	0.341*** (0.064)	-0.103 (0.258)	-0.132 (0.691)
Environmental costs	-0.142 (0.235)	-0.969*** (0.227)	-0.101 (0.124)	-1.632 (2.846)	-0.148 (0.238)	-0.944*** (0.227)	-0.105 (0.116)	1.954 (2.870)
Constants	2.856*** (0.348)	1.566*** (0.291)	2.695*** (0.418)	1.090* (0.559)	3.064*** (0.259)	1.825*** (0.231)	2.923*** (0.331)	0.526 (0.474)
α	1.371*** (0.711)	1.627** (0.800)	1.680 (1.088)	4.365*** (1.595)	0.408 (0.459)	0.315 (0.314)	0.322 (0.387)	0.433 (0.397)
R^2	0.512	0.725	0.475	0.284	0.494	0.721	0.475	0.265

Note: The values in parentheses are standard errors. *** indicates significant at the 1% level.**indicates significant at the 5% level.*indicates significant at the 10% level. "——"means there are no data

R^2refers to the coefficient of determination, and α refers to the intercept

antimicrobials calculated using the C-D production function is higher than that of the damage control model. This is also consistent with the assertion of existing studies that the C-D production function overestimates the marginal productivity of veterinary antimicrobials (or pesticides) [33]. Similarly, the marginal productivity of veterinary antimicrobials for a single farmer was calculated using a damage control function with an exponential distribution function. From the calculation results, the percentage of farmers overusing veterinary antimicrobials varied in different hog breeding regions. In general, among the four major hog breeding regions, the lowest percentage of farmers over-applying veterinary antimicrobials in the key development area was 47.4%, followed by the moderate development area, with 54.2% of farmers over-applying veterinary antimicrobials; the farming regions with the highest percentage of farmers over-applying veterinary antimicrobials were the constrained development area and the potential development area, reaching 66.1% and 67.2%, respectively. Although there are differences in the over usage of veterinary antimicrobials by farmers in the four major hog farming regions, in general, the over usage of veterinary antimicrobials is a common problem in the hog farming industry.

Results and discussion

Empirical analysis results

We further estimated the marginal productivity of veterinary antimicrobials for individual farmers in the four major hog farming regions based on the parameter estimation results of the damage control model with an exponential distribution function in Table 6. Using whether or not the use of veterinary antimicrobials is excessive as an explanatory variable, if the marginal productivity of the use of veterinary antimicrobials by an individual hog farmer is less than 0.01, which indicates that the hog farmer is overusing antimicrobials, the value is assigned to 1, conversely, the value is assigned to 0 [44].

Before conducting the logistic regression, this study performed tests for correlation and collinearity on the independent variables in Table 7. The test results indicate that there are no serious issues of correlation or collinearity. Based on the variable settings in Table 7, a logistic regression was conducted to estimate the factors influencing excessive use of veterinary drugs among pig farming households in the four major regions. The results are presented in Table 8.

From the Table 8, it can be seen that when farmers are in different farming areas, there are differences in the effects of different influencing factors on their overdose use. Moreover, it can be seen from Table 8 that the government's controlling and guiding behaviors have a greater impact on the over usage of veterinary antimicrobials by farmers in different regions, which shows that the government should actively play a macro-regulatory role in promoting farmers' regulation of disease and reduction in antimicrobials use.

In the key development areas and moderate development areas, the supervision by government departments has a significant negative impact on farmers' excessive use of antibiotics. For every one - unit increase in government department supervision, the probability of excessive drug use by farmers in key development areas

Table 7 Definition and assignment of explanatory variables and explained variables

Variables	Variable definitions and assignments
Whether veterinary antimicrobials were over-administered	Dummy variable: yes = 1, no = 0
Number of veterinary antimicrobials use supervisions (take logarithm)	Continuous variable: total number of veterinary antimicrobials administration supervisions by the relevant local government department where the farmer is located
Fines for violation of veterinary antimicrobials use (take logarithm)	Continuous variable: the total number of fines imposed by the relevant local government departments in the farmer's area for the illegal use of veterinary antimicrobials
Compulsory immunization subsidy (take logarithm)	Continuous variable: immunization subsidies granted by the local government where the farmer is located to support the farmer's disease control
Number of veterinary antimicrobials reduction campaigns (take logarithm)	Continuous variable: Number of veterinary antimicrobials use reduction campaigns organized by the local government where the farmer is located
Sex	Dummy variables: male = 1, female = 0
Age	Dummy variables: 20–30 = 1, 31–40 = 2, 41–50 = 3, 51–60 = 4, Above 60 = 5
Educational level	Dummy variables: elementary school and below = 1, middle school = 2, high school = 3, college and above = 4
Main family business	Dummy variable: farming as the main household business = 1, not farming as the main business = 0
Number of household laborers	Dummy variables: 1 person or less = 1, 2–3 persons = 2, 4–5 persons = 3, 6 persons or more = 4
Scale of breeding (take logarithm)	Continuous variable: Measuring farm size in terms of farmers' annual output
Farmer cooperatives	Dummy variables: joined farmers' cooperative = 1, not joined = 0
Farming training	Dummy variable: attended farming training = 1, not attended = 0

Table 8 Estimation results of logit model for factors influencing overdose use by farmers

Variables	Key	Constrained	Potential	Moderate
Number of veterinary antimicrobials use supervisions	-2.959*(1.667)	0.645(0.439)	0.772*(0.412)	-2.308*(0.890)
Fines for violation of veterinary antimicrobials use	-5.274***(1.767)	-0.807*(0.417)	-0.997***(0.366)	-0.211(0.188)
Compulsory immunization subsidy	0.365(0.309)	-0.090(0.225)	0.895***(0.271)	-0.038(0.153)
Number of veterinary antimicrobials reduction campaigns	-0.313(0.202)	-0.015(0.242)	-0.676*(0.362)	-0.559**(0.245)
Sex	-0.005(0.230)	-0.469*(0.281)	0.466(0.375)	-0.351*(0.199)
Age	-0.036(0.098)	-0.113(0.118)	-0.417(0.321)	0.050(0.102)
Educational level	-0.004(0.164)	-0.045(0.198)	-0.464**(0.235)	-0.073(0.141)
Main family business	-0.067(0.399)	-0.065(0.188)	-0.145(0.263)	-0.667*(0.384)
Number of household laborers	0.297(0.196)	0.326(0.204)	-0.023(0.211)	-0.162(0.182)
Scale of breeding	-0.012*(0.121)	-1.316***(0.273)	-1.816***(0.289)	0.186*(0.105)
Farmer cooperatives	-0.194(0.353)	-0.080(0.149)	-0.782*(0.447)	-0.115(0.832)
Farming training	-0.280(0.392)	-0.648*(0.358)	-0.012(0.376)	-0.197(0.369)
Constant term	-5.740(4.136)	-0.105(3.057)	-1.929(2.690)	-8.069***(2.861)

Note: The values in parentheses are standard errors. *** indicates significant at the 1% level. ** indicates significant at the 5% level. * indicates significant at the 10% level

Table 9 Synergies between subsidies and farm size

Variables	Key	Constrained	Potential	Moderate
Number of veterinary antimicrobials use supervisions	-0.509**(0.226)	0.594(0.478)	0.129 (0.199)	-0.772**(0.321)
Fines for violation of veterinary antimicrobials use	-0.713***(0.205)	-0.828*(0.452)	-1.038**(0.402)	0.047(0.127)
Compulsory immunization subsidy	0.404(0.245)	-0.075(0.233)	1.147***(0.297)	0.065(0.115)
Number of veterinary antimicrobials reduction campaigns	0.008(0.194)	-0.361(0.220)	-0.814**(0.379)	-0.042(0.187)
Subsidy × training	0.013(0.017)	-0.073(0.154)	-0.250**(0.103)	-0.014(0.012)
Other control variables	Controlled	Controlled	Controlled	Controlled
Constant term	-5.191(4.276)	0.468(3.080)	-1.367 (2.756)	-2.137(1.339)
R^2	0.085	0.061	0.088	0.041

Note: The values in parentheses are standard errors. *** indicates significant at the 1% level. ** indicates significant at the 5% level. * indicates significant at the 10% level will decrease by 2.959%, and that in moderate development areas will decrease by 2.308%. However, in potential development areas, the supervision by government departments has a significant positive impact on farmers' excessive use of antibiotics. For every one - unit increase in government department supervision, the probability of excessive drug use by farmers in potential development areas will increase by 0.772%. Fines imposed by the government on farmers for the illegal use of antibiotics have a significant negative impact on the excessive use of antibiotics by farmers in key development areas, restricted development areas, and potential development areas. For every one - unit increase in fines by government departments, the probability of excessive drug use by farmers in key development areas will decrease by 5.274%, that in restricted development areas will decrease by 0.807%, and that in potential development areas will decrease by 0.997%. In potential development areas, compulsory immunization subsidies have a significant positive impact on farmers' excessive drug - use behavior. For every one - unit increase in immunization subsidies by government departments, the probability of excessive drug use by farmers in potential development areas will increase by 0.895%. Government publicity has a significant negative impact on the excessive use of veterinary drugs by farmers in potential development areas and moderate development areas. For every one - unit increase in government publicity, the probability of excessive drug use by farmers in potential development areas will decrease by 0.676%, and that in moderate development areas will decrease by 0.559%. Therefore, Hypothesis 2 is verified.

There are some differences in the influence of the individual characteristics of hog farmers in different farming regions on their over usage of veterinary antimicrobials. In the key development area, constrained development area and moderate development area, the sex of the farmers had a negative effect on their over usage of veterinary antimicrobials, with the correlation coefficients of the constrained development area and moderate development area passing the 10% significance test. In all four farming regions, farmers' education levels had a negative effect on their overdose use, with the correlation coefficient passing the 5% significance test in the potential development area. There are also some differences in the influence of the household characteristics of the farmers in the different farming regions on their overdose use. Among the four major farming regions, farming as the main family business has a negative effect on the overdosing of veterinary antimicrobials by farmers. In the key development area, constrained development area and potential development area, the scale of farming had a negative and significant effect on the excessive use of veterinary antimicrobials by farmers, while in the moderate development area, the scale of farming had a positive and significant effect on the excessive use of veterinary antimicrobials by farmers. Participation in farmers' cooperatives had a negative effect on the over usage of veterinary antimicrobials by farmers in different farming regions, with the correlation coefficient passing the 10% significance test in the potential development area. Participation in farming training had a negative effect on the over usage of antimicrobials by farmers in different farming regions.

In order to explore the reasons why government subsidies have a significantly positive impact on the excessive use of drugs by farmers in the potential development area, this paper continues to test the interaction effect between subsidies and the scale of farming. The study found that in the potential development area, the interaction term between subsidies and the scale of farming has a significantly negative impact on the excessive use of drugs by farmers. This is undoubtedly a gratifying result. This indicates that the scale of farming can amplify the effect of subsidies. After large-scale farmers receive subsidies, they can make better use of their scale advantages and allocate the subsidy funds to introduce advanced epidemic prevention and control equipment, hire professional technicians, etc. These measures can more effectively control diseases and reduce the use of drugs. However, currently, the degree of large-scale farming in the potential development area is relatively low, which may be one of the reasons why subsidies have a significantly positive impact on the excessive use of drugs by farmers.

Robustness tests

In order to avoid estimation bias due to uncontrollable factors and to ensure that the logit regression results were convincing, we used a replacement measurement model approach for robustness testing. The binary probit model was used to estimate the data again and the results obtained are shown in Table 10. As can be seen from Table 10, the regression results of the probit model are basically consistent with those of the logit model, and the sign and significance of the coefficients do not change significantly, which indicates that the regression results in Table 8 are robust Table 10.

Discussion

Currently, the overuse of veterinary drugs has emerged as a prominent global public health concern. Many countries are implementing diverse measures to encourage farmers to curtail drug use, thereby safeguarding food safety and environmental security. In this context, this study computes the marginal productivity of veterinary drug use by livestock farmers in different regions to evaluate the extent of drug overuse among farmers in various areas. Moreover, it delves into the efficacy of government

Table 10 Estimation results of probit model for factors influencing overdose use by farmers

Variables	Key	Constrained	Potential	Moderate
Number of veterinary antimicrobials use supervisions	-0.871***(0.292)	2.525(1.398)	0.739***(0.255)	-1.965**(0.963)
Fines for violation of veterinary antimicrobials use	-0.866(0.911)	-0.581***(0.219)	-0.575**(0.255)	-1.752(0.777)
Compulsory immunization subsidy	0.078(0.244)	-0.042(0.134)	0.633***(0.167)	-0.082(0.078)
Number of veterinary antimicrobials reduction campaigns	-0.738(0.198)	-3.718(1.599)	-0.622***(0.231)	-2.143***(0.664)
Other control variables	Controlled	Controlled	Controlled	Controlled
Constant term	-11.454(7.668)	-0.620(3.046)	-0.763(1.135)	-5.800**(2.474)

Note: The values in parentheses are standard errors. *** indicates significant at the 1% level. ** indicates significant at the 5% level. * indicates significant at the 10% level

regulatory policies on the drug - overuse behavior of farmers in different livestock - raising regions. The aim is to furnish references for agricultural policymakers in formulating and implementing effective government regulatory measures and to put forward policy recommendations for the high - quality development of the livestock industry. Generally, the majority of Chinese hog farmers are small - scale farmers with decentralized operations. Although farmers' own awareness of green production serves as the internal driving force for the transformation and development of the farming industry, most of them are still in a state of passive adaptation [45]. Their green production behavior is not only associated with factors such as resource endowment [37], farmers' cognition, and information flow [46], but also relies more heavily on external incentives and constraints [47]. Consistent with the findings of Xiong et al. [48], we discovered that government supervision of veterinary antimicrobial use exerted a significantly negative impact on farmers' overdosing behavior in both key and moderately - developed areas. However, in potential development areas, government supervision has a significant positive impact on the excessive use of veterinary drugs. On one hand, although the potential development regions are endowed with abundant breeding resources, their industrial development is relatively backward, and the farming methods are rather traditional. Consequently, farmers in these regions have a relatively weak capacity to recognize and adapt to new policies and regulations. The intensification of government supervision may exert substantial short - term adaptation pressure on farmers. In the absence of adequate technical support and financial input, some farmers, out of fear of losses due to sick pigs, may instead increase the use of veterinary drugs. On the other hand, in potential development regions, due to factors such as vast territorial expanse, regulatory resources may be relatively scarce, making it difficult to achieve comprehensive and meticulous regulatory coverage. Moreover, the enforcement of supervision may weaken during the implementation process. This may lead some farmers to take chances, or fail to fully understand and implement regulatory requirements, thus resulting in the over - use of veterinary drugs.

Consistent with the findings of Yue et al. [49], the results of this study show that government fines on farmers for over usage had a negative effect on their over usage behavior. Policy penalties indirectly restrain farmers from environmentally unfriendly and inefficient production behaviors by increasing their additional costs, and farmers will be driven by loss aversion to switch to green production [50]. In this study, we found that government subsidies have a significant positive impact on the over - use of veterinary drugs by farmers in potential development areas. This is consistent with the research findings of Skevas et al. [51]. This could be because, to a certain extent, subsidies reduce the farmers' breeding costs and enhance their economic security, providing them with more funds to purchase veterinary drugs. From the farmers' perspective, the cost of using veterinary drugs is relatively low, while the losses caused by the death of pigs due to illness or slow growth are relatively high. During the period 2018–2019, the African swine fever outbreak occurred in some provinces included in the key development areas and potential development areas, and, as the hog industry suffered a vast impact, hog farmers still over-applied veterinary antimicrobials in order to stabilize hog production and reduce losses, even with the corresponding government subsidies. Similar to the findings of Yu et al. [52], we found that government propaganda on green production behavior had a negative effect on the non-green production behavior of farmers in all four farming regions. By promoting the advantages of reduced use, the government changed farmers' perceptions, thus promoting their reduced use.

The results of this paper also show the effect of other control variables on the over usage of veterinary antimicrobials by farmers. In the key development areas, constrained development areas and moderate development areas, the sex of the farmers negatively influenced their over usage of veterinary antimicrobials. Male farmers account for more of the four major hog farming regions. Compared to women, men have an advantage in hog farming, with men focusing more on long-term benefits and the science of farming [53]. Consistent with the study of Sharifzadeh and Abdollahzadeh [54], in our study farmers' literacy negatively influenced their overdose use. By understanding the various hazards posed by veterinary antimicrobials overdosing, farmers increase their sense of social responsibility and thus reduce the use of veterinary antimicrobials [55]. Similar to the findings of Zhang et al. [42], we found that having farming as the main household business had a negative effect on farmers' non-green production behavior. When farmers use farming as their main family business, they are more dependent on hog farming, are more concerned about the long-term development of farming, have more time to devote to farming and are more sensitive to the cost of veterinary antimicrobials administration.

Similar to the findings of Lu et al. [56], we found that farm size negatively and significantly influenced farmers' over usage of veterinary antimicrobials in key development areas, constrained development areas and potential development areas. The development of the hog farming scale was higher in the key development area, constrained development area and potential development area than in the moderate development area. Additionally, with the development of the farming scale, farmers are more likely to use the specialized division of labor to apply veterinary antimicrobials in a rational and scientific way to maximize resource utilization, thus effectively reducing the over usage of veterinary antimicrobials. In contrast, in the moderate development area, the farming scale has a positive and significant effect on the over usage of veterinary antimicrobials by farmers, which is similar to the findings of Wang et al. [44]. The foundation of hog breeding in moderately developed areas is weak, the scale of hog breeding is low, the technology of hog breeding is low and there is a lack of large leading enterprises to drive them [57], so some farmers neglect to strengthen management when expanding the scale of breeding, which increases the chance of hogs being infected with epidemics, thus leading to an increase in the use of veterinary antimicrobials. Consistent with the findings of Li et al. [30], participation in farmers' cooperatives had a negative effect on the farmers' over usage of veterinary antimicrobials. On the one hand, farmers' cooperatives can provide farmers with training on standardized disease control, thus enhancing the farmers' awareness of safe production, and on the other hand, farmers' cooperatives supervise farmers through their own disciplinary mechanisms, thus achieving a reduction in the use of veterinary antimicrobials. Consistent with the findings of Luo et al. [58], participation in farming training had a negative effect on farmers' overdosing behavior, which suggests that farming training can be effective in reducing overdosing by informing farmers about the dangers of overdosing so as to raise their awareness.

Main conclusions and policy recommendations

This paper has the following research findings: (1)The phenomenon of excessive drug use among farmers in the four major breeding regions is severe, with the proportions of farmers who use drugs excessively being 47.4%, 66.1%, 67.2% and 54.2% respectively.(2)Government supervision negatively impacts excessive drug use by pig farmers in key and moderately developed regions. Fines have a negative effect in key, restricted, and potential development regions. Subsidies positively affect excessive drug use in potential development regions, though the subsidy - farming scale interaction has a negative impact. Publicity negatively impacts excessive drug use in potential and moderately developed regions. (3)The impacts of factors like farmers' gender, age, education, part - time job status, cooperative participation, and training involvement on their excessive drug use vary by breeding region.

Based on the above conclusions, the corresponding policy recommendations are as follows: (1) For key development regions and moderately - developed regions, the intensity of supervision should be strengthened. (2) For potential development regions, efforts should be made to increase the intensity of fines and publicity. At the same time, the intensity of supervision and subsidies should be reduced. In addition, farmers should be encouraged to join specialized farmers' cooperatives and develop large-scale farming.

(3) For restricted development regions, the intensity of government fines and publicity should be heightened. Moreover, the frequency and scale of training on the standardized use of veterinary drugs should be increased.

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Author contributions

All authors were involved in the conceptualization and design of the study. H.Y. was mainly responsible for writing the paper twe. Y.Y. was responsible for conceptualization and checking. M.W. was responsible for organizing the data and revising. W.K. was responsible for data analysis and obtaining data. All authors read and approved the final manuscript.

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Data availability

The data that support the findings of this study are available from Fixed Observation Sites in Rural China but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Fixed Observation Sites in Rural China. The application database is available at http://zdscxx.moa.gov.cn:8080/nyb/pc/index.jsp.

Declarations

Ethics approval and consent to participate
Not applicable.

Ethical statement
The manuscript has not been previously published, is not currently submitted for review to any other journal and will not be submitted elsewhere before a decision is made by this journal.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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