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Safety assessment of agricultural products and the pesticide regulation trend in China

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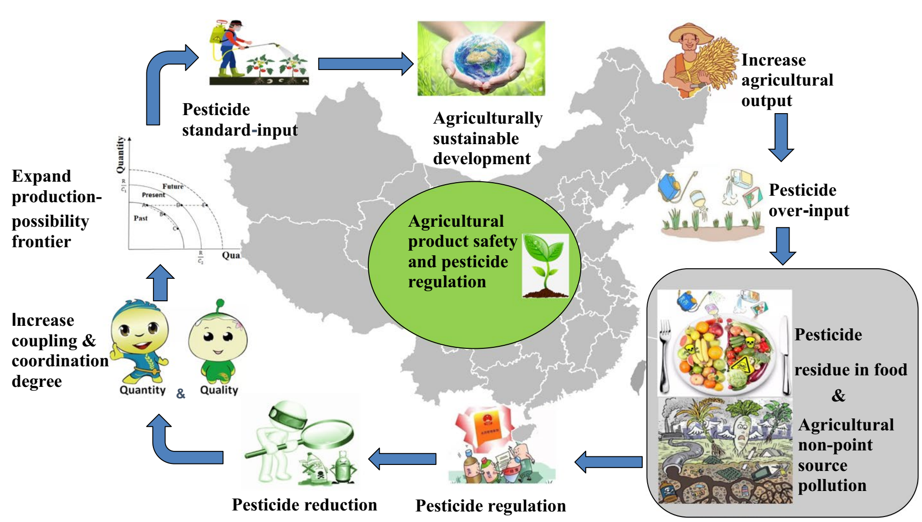
Abstract

The sustainable development of Chinese agriculture needs to coordinate the quality and quantity of agricultural products. To verify whether government regulation can promote agricultural development by controlling pesticides, the indices of government regulation, quantity and quality of agricultural products, and pesticide use per area of cropland were calculated, and a comprehensive evaluation index and the coupling degree and coordination degree of agricultural products were analyzed by coupling function. The results showed that the coupling and coordination degree of the quality and quantity of agricultural products and the comprehensive index are improving. The regulation of pesticide use per area of cropland is a key mechanism in promoting the coordinated development of agricultural product safety. The regulation trend of agricultural development in China is to reduce pesticide usage appropriately and expand the production-possibility frontier of agricultural products.

Keywords: Agricultural product safety, Coupling mechanism, Government regulation, Pesticides

Graphical abstract



Introduction

The Chinese government regards agricultural product safety as a basic guarantee for people's livelihood. China's crop sown area has remained over 120 million hectares, and the annual grain output has remained above 650 million tons in recent years, which has effectively provided food for 1.4 billion Chinese people. As evidenced by the report of *The State of Food Security and Nutrition in the World* (FAO 2020), the most recent estimate for 2019 shows that prior to the COVID-19 pandemic, almost 690 million people around the world went hungry. Therefore, the high and stable output of agricultural products in China has contributed to the improvement of world food security. However, China is facing difficulties and challenges such as insufficient agricultural labor supply, increased agricultural nonpoint source pollution, and potential quality and safety risks of agricultural products. In recent years, China's food safety incidents have shown that the current management model needs to be further improved (Shao et al. 2021a, b; Song et al. 2020). Strengthening government regulation is the common international consensus to ensure the safety of agricultural products (Teng et al. 2021; Khan et al. 2015). However, China's agricultural product safety problems have not disappeared even with strengthened government regulation (Zhong and Kong 2012; Shao et al. 2021a, b). Chinese pesticide regulatory requirements are shown in Table 1.

Table 1 Pesticide regulatory requirements in China's No.1 Central Document

Year	Pesticide regulatory requirements
2023	Establish a collection, utilization and treatment system for pesticide packaging waste
2022	Further reduce agricultural inputs such as pesticides
2021	Continue to reduce chemical pesticides usage and increase pesticides efficiency
2020	Promote and implement of various pesticide reduction campaigns
2019	Implement of pesticide conservation campaign and achieve negative growth in pesticide usage
2018	Achieve the reduction of agricultural chemical inputs and cleaner production
2017	Achieve zero growth of chemical pesticides use
2016	Implement of zero growth of chemical pesticides campaigns; promote high-efficiency and low-toxicity pesticides
2015	Promote low-toxicity and less persistent pesticides
2014	Support less persistent pesticides application
2013	Subsidize low-toxicity and less persistent pesticides application
2012	Encourage low-toxicity and less persistent pesticides application
2009	Resolutely prohibit illegal pesticide application activities
2008	Accelerate the development of highly efficient and safe pesticides
2007	Develop low-toxicity and high-efficiency pesticides; Support R&D of new pesticides
2005	Prohibit the production, sale and application of pesticides with high-toxicity and high-residue

The current safety risks of China's agricultural products are still widespread. For example, pesticide residue problems in vegetables, fruits and other kinds of agricultural products are still conspicuous (Pang 2019). Pesticide standard input is conducive to improving both agricultural production and labor-saving innovation (Kong et al. 2018; Soares and Porto 2009). Studies show that a 1% global increase in agricultural production is associated with a 1.8% increase in pesticide usage (Schreinemachers and Tipraqsa 2012). However, the increased use of pesticides has increased pest resistance to pesticides, and pesticide resistance in turn leads to increased use of pesticides, forming a vicious cycle (Li and Liang 2021; Hawkins et al. 2019). In addition, pollution of the ecological environment and dozens of human diseases are directly related to pesticide residues (Qu et al. 2011; Syed et al. 2014).

Chemical pesticide use has been cited as one of the plausible causes for the drastically declining trends observed in insect biomass (Hallmann et al. 2017). Although it is known that excessive use of pesticides may lead to the destruction of biodiversity and impose a serious negative impact on the environment (Mahmood et al. 2016), China's agricultural product shortage still heavily depends on pesticide technology at the current level of agricultural productivity (Huang et al. 2021). A study shows that the average intensity of pesticide use in China is 2.5–5 times higher than that in developed countries, and more than 67 million hectares of crops in China are contaminated with pesticide residues every year (Wang and Gu 2013). According to FAO statistics, in 2019, the total amount of pesticides used in agricultural production in China exceeded 1.77 million tons, 4.35 times that of the USA and 4.7 times that of Brazil, making China rank first in the world. According to the Ministry of Agriculture of China, the utilization rate of pesticides in China was 36.6% in 2015, 38.8% in 2017 and 40.6% in 2020, meaning that China still lags behind developed countries such as European countries and the USA.

Existing research results have shown that policy support for and implementation of pesticide use-reduction strategies such as integrated pest management has been inadequate across regions (Van den Berg et al. 2020). The regulations on the maximum residue limit (MRL) of pesticides are closely associated with public health (Carrère et al. 2018), and these regulations and pest risk management measures have an impact on the trade of agricultural products (Federica et al. 2021; Drogue and DeMaria 2012). There is broad international consensus on the need to implement strategies to reduce dependence on chemical pesticides. In recent years, China has implemented strict regulatory policies on pesticides, and pesticide usage has gradually decreased. The main regulatory policies are shown in Table 2. The key question is whether government pesticide management can contribute to the sustainable development of agricultural systems, and there is a need to bring balance to pesticide use in agriculture for the quantity and quality of agricultural products. Finding an appropriate agri-environmental policy design represents a typical optimization problem (Nadoveza and Šimurina 2020). This paper attempts to take pesticide use and regulation in China as an example and provide a balanced view and describe the trends of pesticide regulation from the perspective of economics, with the purpose of providing a reliable reference for policy research on reducing the use of chemical pesticides in China and providing theoretical exploration and pioneering methods.

Table 2 Main pesticide regulatory policies in China

Year	Pesticide regulatory policies
2022	Action Plan for pesticide Reduction by 2025
2021	Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution
2020	Administrative Measures for the Recovery and Disposal of Pesticide Packaging Waste
2017	Regulation on Pesticide Administration (2017 Revision)
2017	Measures for the Administration of the Soil Environment of Agricultural Land (for Trial Implementation)
2016	Program on cultivating and developing the main body of rural sewage and garbage treatment market for agricultural nonpoint source pollution treatment
2015	Suggestions on how to combat agricultural nonpoint source pollution
2015	Action Plan for Zero Increase in Pesticide Use by 2020
1998	Regulations of the People's Republic of China on the protection of basic farmland
1997	Regulation on Pesticide Administration
1997	Circular on further strengthening the regulation and management of waste water discharge from pesticide production enterprises
1993	Agriculture Law of the People's Republic of China
1990	Decision of the State Council on further strengthening environmental protection
1989	Using pesticide safety standards
1989	Environmental Protection Law of People's Republic of China
1982	Pesticide registration requirements
1982	Regulations for the safe use of pesticides
1982	Rules for the implementation of the Provisions on pesticide Registration
1979	Decisions of the Central Committee of the Communist Party of China on accelerating agricultural development (for Trial Implementation)
1979	Environmental Protection Law of Peoples Republic of China (for Trial Implementation)
1979	Trial standards for the safe use of pesticides

Data and methodology

Indices selection and source

Quantity evaluation index of agricultural products

Grains, vegetables and fruits are the three basic kinds of food that Chinese people eat and the three kinds of agricultural products with the highest output in China. In addition, average dietary energy supply adequacy and the grain import dependence ratio are the two important indicators reflecting the safety of agricultural products. For example, in 2021, China's grain imports accounted for 24.1% of its total domestic production. Therefore, the quantity evaluation index in this paper includes the following five secondary indices: (1) vegetable output per area of cropland, (2) fruit output per area of cropland, (3) grain output per area of cropland, (4) average dietary energy supply adequacy (percent) (3-year average) and (5) grain import dependence ratio. y_1 represents the quantity evaluation index.

Quality evaluation index of agricultural products

According to the Agricultural Product Quality and Safety Law of the People's Republic of China, the quality and safety of agricultural products means that agricultural products meet the requirements of protecting people's health and safety. In particular, it refers to the technical standards and requirements that the quality and safety level and sanitary conditions of agricultural products meet the requirements to guarantee human health and safety. Therefore, the quality evaluation index in this paper includes the following five secondary indices: (1) the qualified rate of vegetables, (2) the qualified rate of fruits, (3) the qualified rate of pesticides, (4) the ratio of patients with food-borne disease and (5) the consumer complaint ratio of food quality and safety. y_2 represents the quality evaluation index.

Government regulation evaluation index of agricultural product safety

The evaluation index includes the following three secondary indices: (1) investment ratio of biological pesticides and chemical pesticides (affected by national pesticide policy and national economic policy), (2) expenditure on the quality and safety of agricultural products (affected by national agricultural policy and law of China on quality and safety of agricultural products) and (3) per capita crop sown area (affected by national population policy and national land policy). x represents the government regulation evaluation index.

Mediator variable

A mediator variable is intermediate in the causal sequence relating an independent variable to a dependent variable, such that the independent variable affects the mediator variable that causes the dependent variable (Mackinnon 2015). The standard application of pesticides can guarantee the quantity and quality of agricultural products, but the nonstandard application of pesticides will affect the quality and safety of agricultural products. In 2015, the Ministry of Agriculture of the People's Republic of China issued the Zero-Growth Action Plan for Pesticide Use by 2020, taking pesticides as an important means to control the quality and safety of agricultural products. Therefore, this paper takes pesticide use per area of cropland as the mediator variable between government regulation and agricultural product safety.

Main sources of data

The main data involved in this paper are from authoritative statistical institutions, which can avoid the problem of rigor in quantitative research. The main sources of data are listed in Table 3.

Coupling function

The term coupling comes from physics and can be defined as a phenomenon in which the dimensions under investigation influence each other through different links (Li et al. 2012). Coupling theory has gradually been used to measure the high-quality development index system (Jian and Nie 2020), financial development, technological

Table 3 The main sources of data (2005–2019)

Data	Sources
Vegetable and fruit output per area of cropland	National Bureau of Statistics of China
Grain output per area of cropland	China Statistical Yearbook
Average dietary energy supply adequacy (percent) (3-year average); Grain import dependence ratio and pesticide use per area of cropland; Pesticide application intensity in China and the USA	FAO
Qualified rate of vegetable and fruit; Expenditure on the quality and safety of agricultural products	Ministry of Agriculture and Rural Affairs of China
Qualified rate of pesticide	National Bureau of Statistics and Ministry of Agriculture and Rural Affairs of China
The ratio of patients with food-borne disease	China Health Statistics Yearbook
Consumer complaint ratio of food quality and safety	China Administration for Industry and Commerce Statistics Yearbook
Investment ratio of biological pesticides and chemical pesticides	China Fixed Assets Investment Statistical Yearbook
Per capita crop sown area	China Statistical Yearbook and China Rural Statistics Yearbook

innovation and economic growth (Wang and Tan 2021), and the coupling between subsystems requires mediator variables (Yang and Yang 2022). Is there a coupling effect between the quantity and quality of agricultural products? Can government pesticide regulation be used as a mediator variable? To answer the above questions, this paper refers to the research design of Miyazaki and Kinoshita (2006) and Van Heumen et al. (2009) to set up the internal coupling function of agricultural product safety.

$$y_3 = \left[\frac{\prod_{i=1}^{k} E_i}{\left(\sum_{i=1}^{k} E_i/k \right)^k} \right]^{\frac{1}{k}} \tag{1}$$

In Eq. (1), y_3 represents the coupling degree of agricultural products ($0 \leq y_3 \leq 1$). y_3 is determined jointly by the agricultural product quantity and quality evaluation index. A larger y_3 indicates a higher coupling degree among the agricultural subsystems. i represents the agricultural product safety subsystem. This function contains two subsystems, the quantity and quality of agricultural products ($k=2$). E_i represents the evaluation index of the agricultural product safety subsystem.

$$E_i = \sum_{j=1_{ij}}^{n} w_{ij} \left(i = 1, 2;\ j = 1, 2, \ldots, n \right) \tag{2}$$

In Eq. (2), λ_{ij} represents a positive indicator of the jth variable in the ith subsystem.$\lambda_{ij} = \left(x_{ij} - \min x_{ij} \right) / \left(\max x_{ij} - \min x_{ij} \right)$. w_{ij} represent the weight of the jth variable in the ith subsystem.

However, the coupling degree does not indicate whether the dimensions are developing in harmony but only the strength of the subsystem interaction, leading to an erroneous conclusion when relying solely on values calculated from Eq. (2) (Tomal

2021). Therefore, a coupling coordination degree is used to assess the degree of synergy between the subsystems, and the coupling coordination degree function is set as follows:

$$y_4 = [y_3 \times (\alpha E_1 + E_2)]^{\frac{1}{2}} \tag{3}$$

In Eq. (3), y_4 represents the coupling coordination degree of agricultural products ($0 \le y_4 \le 1$). A higher y_4 indicates a more harmonious relationship between the quantity and quality of agricultural products. $y_5 = \alpha E_1 + \beta E_2$; y_5 represents the comprehensive index of agricultural products, and α and β are undetermined coefficients, $\alpha = 1 - \beta$. α and β will be determined using Granger's causal test.

Transmission mechanism functions

The manner in which exogenous variables affect the variables of interest is referred to as the transmission mechanism (Koop et al. 2009). In this paper, we divide the transmission mechanism into direct and indirect forms according to the influence of government regulatory policies on the safety index of agricultural products.

The basic equation of direct transmission mechanism functions is as follows:

$$y = \alpha_0 + \alpha_1 x + \varepsilon \tag{4}$$

In Eq. (4),y represents the evaluation index of agricultural products, including y_1 to y_5, x represents the government regulation evaluation index, ε represents the stochastic disturbance team, α_0 is a constant, and α_1 is the regression coefficient.

Generally, the independent variable has an effect on the dependent variable through the mediator, and this process is called the mediating effect (Baron and Kenny 1986). Mediation theory can help us analyze the various shapes these relations can take, the points of application between a technology and its user, and the specific types of mediation at play (Verbeek 2015). According to the mediation theory of the coupling function (Zhao et al. 2020), the basic equation of indirect transmission mechanism functions is as follows:

$$p = \beta_0 + \beta_1 x + \varepsilon \tag{5}$$

$$y = \gamma_0 + \gamma_1 x + \gamma_2 p + \varepsilon \tag{6}$$

In Eqs. (5) and (6), p represents pesticide use per area of cropland, and x represents the government regulation evaluation index. β_0 and γ_0 are constants, β_1 and γ_1 are the regression coefficients, and ε represents the stochastic disturbance team.

Production-possibility frontier of agricultural products

In economics, a production possibilities frontier (PPF) or "transformation curve" is a graph that shows the different quantities of two goods that an economy could efficiently produce with limited productive resources. The curve illustrates that increasing the production of one good reduces the maximum production of the other good as resources are transferred away from the other good. Referring to similar research designs (Devadoss and Song 2003; Wu et al. 2021), the basic equation of the PPF of agricultural product functions is as follows:

$$N = \frac{R}{C_1} - \frac{C_2}{C_1}Q \tag{7}$$

In Eq. (7), N represents a quantitative index of the quantity of agricultural products, Q represents a quantitative index of the quality of agricultural products, R represents maximizing agricultural means of production at the level of existing agricultural natural resources and production technology, C_1 represents the cost of increasing the quantity of agricultural product per unit, and C_2 represents the cost of increasing the quality of agricultural product per unit. The marginal rate of transformation (MRT) is the number of units or amount of a good that must be forgone to create or attain one unit of another good. It is the number of units of N that will be foregone to produce an extra unit of Q while keeping the factors of production and technology constant. Therefore, the PPF of agricultural products is concave toward the origin.

Pesticide residue function of agricultural products

After a period of application, the pesticide will degrade to a safe level naturally due to its own characteristics and external environment. Referring to the characteristics of the elimination half-life of drugs (Greenblatt 1985) and the atomic nuclei decay modes (Poenaru et al. 1985), the basic equation of the pesticide residue function of agricultural products is created as follows:

$$Q = Q_0\left(\frac{1}{z}\right)^{\frac{t}{T}}\frac{\lambda}{\theta} \tag{8}$$

In Eq. (8), Q represents the pesticide residue, Q_0 represents pesticide use per area of cropland, T represents the pesticide safety interval, t represents the actual pesticide interval, z represents the dilution ratio of pesticide use per area of cropland to the pesticide maximum residual limit (MRL), λ represents the degradation coefficient of pesticides in the agricultural production environment, and θ represents the uniformity coefficient of pesticide spraying ($\theta \leq 1$).

Results

Descriptive analysis of the evaluation index of agricultural products

Quantity evaluation index of agricultural products

The quantity evaluation index of agricultural products from 2005 to 2019 is shown in Fig. 1. The vegetable, fruit and grain output per area of cropland in China has maintained a steady growing trend. The average dietary energy supply adequacy and grain import dependence ratio have increased slightly. As shown in Fig. 1, the quantity of agricultural products in China is relatively steady and safe.

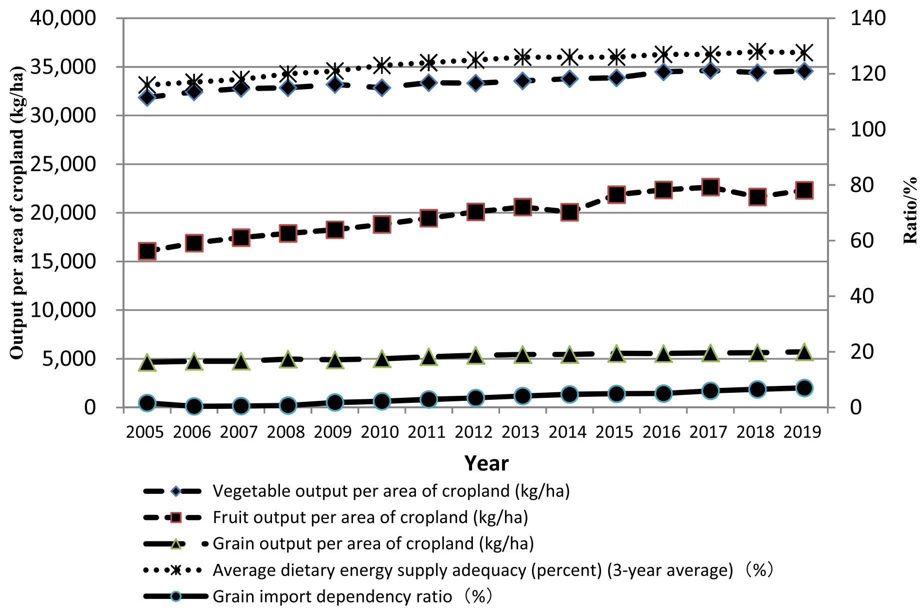


Fig. 1 Quantity evaluation index of agricultural products

Quality evaluation index of agricultural products

The quality evaluation index of agricultural products from 2005 to 2019 is shown in Fig. 2. The qualified rate of vegetables and fruits is maintained at a high level (average above 0.96), the overall qualified rate of pesticides is maintained above 0.85, and the ratio of patients with food-borne disease has grown continuously in the past decade. As shown in Fig. 2, although the quality of agricultural products in China possesses relatively slight fluctuating asymmetries, changes are needed for further improvement of quality and safety.

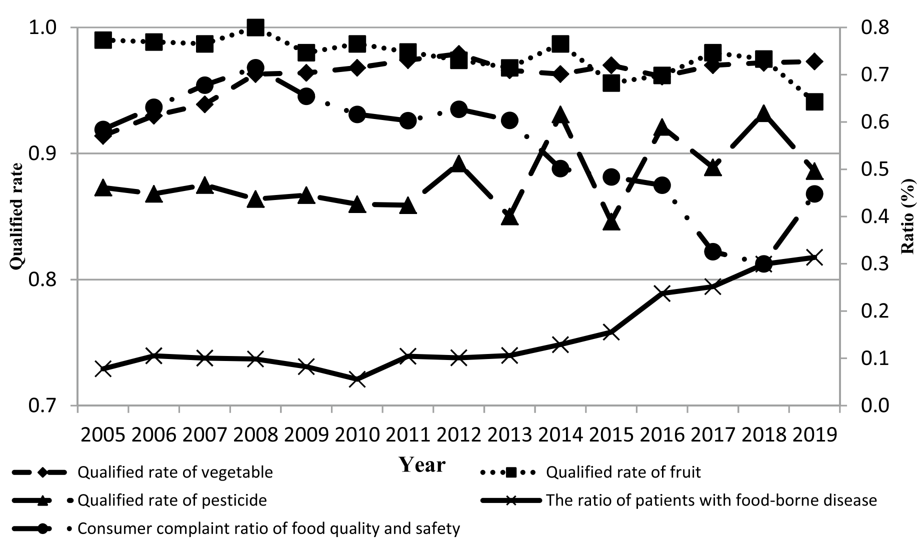


Fig. 2 Quality evaluation index of agricultural products

Descriptive statistics of the main indices

The descriptive statistics of the main indices are shown in Table 4. The following indices obviously fluctuated: the indices of fruit and grain output per area of cropland, grain import dependence ratio, ratio of patients with food-borne disease, consumer complaint ratio of food quality and safety, investment ratio of biological pesticides and chemical pesticides, and expenditure on the quality and safety of agricultural products. The above indices could be influenced by the external environment or internal factors in the past 15 years. These variable indices could also become a key element of government regulation. Other indices, such as the qualified rate of vegetables, qualified rate of fruits and per capita crop sown area, remain relatively unchanged.

Table 4 Descriptive statistical results of evaluation index

Evaluation index	Mean value	Variance	SD	Maximum	Minimum
Vegetable output per area of cropland (kg/ha)	33,462.328	699,161.289	836.159	34,629.110	31,856.230
Fruit output per area of cropland (kg/ha)	19,761.197	4,602,352.372	2145.309	22,641.278	16,064.187
Grain output per area of cropland (kg/ha)	5233.152	134,257.071	366.411	5719.700	4641.630
Average dietary energy supply adequacy (%)	123.440	16.447	4.056	128.000	116.000
Grain import dependence ratio (%)	3.446	4.893	2.212	7.029	0.400
Qualified rate of vegetable	0.960	0.0003	0.018	0.979	0.914
Qualified rate of fruit	0.977	0.0002	0.015	1.000	0.941
Qualified rate of pesticide	0.881	0.0008	0.028	0.932	0.846
The ratio of patients with food-borne disease (%)	0.148	0.007	0.084	0.314	0.056
Consumer complaint ratio of food quality and safety (%)	0.549	0.015	0.124	0.715	0.300
Pesticide use per area of cropland (kg/ha)	12.707	0.499	0.706	13.360	10.980
Investment ratio of biological pesticides and chemical pesticides (%)	48.761	199.088	14.110	82.379	31.499
Expenditure on the quality and safety of agricultural products (100 million RMB)	5.113	2.388	1.545	7.032	1.500
Per capita crop sown area (ha)	0.119	0.000	0.002	0.121	0.114

Coupling and coordination degree of agricultural product safety

Evaluation index of agricultural product safety

First, the range of the evaluation index is standardized, and positive indices are used in this paper. The values range from 0 to 1. Second, the statistical product and service solutions (SPSS) software entropy method is used to calculate the weight coefficient of each index, and the results are shown in Table 5. Finally, Eq. (2) is used to calculate the evaluation index of the quantity and quality subsystem, and the results are shown in Fig. 3.

Table 5 Evaluation index of agricultural products safety

First-level index	Second-level index	Information entropy value	Information utility value	Weighting coefficient (%)
Quantity	Vegetable output per area of cropland (kg/ha)	0.9453	0.0547	14.66
	Fruit output per area of cropland (kg/ha)	0.9321	0.0679	18.20
	Grain output per area of cropland (kg/ha)	0.9205	0.0795	21.31
	Average dietary energy supply adequacy (%)	0.9338	0.0662	17.74
	Grain import dependence ratio (%)	0.8952	0.1048	28.09
Quality	Qualified rate of vegetable	0.9615	0.0385	11.35
	Qualified rate of fruit	0.9596	0.0404	11.93
	Qualified rate of pesticide	0.8947	0.1053	31.05
	The ratio of patients with food-borne disease (%)	0.9386	0.0614	18.11
	Consumer complaint ratio of food quality and safety (%)	0.9066	0.0934	27.56

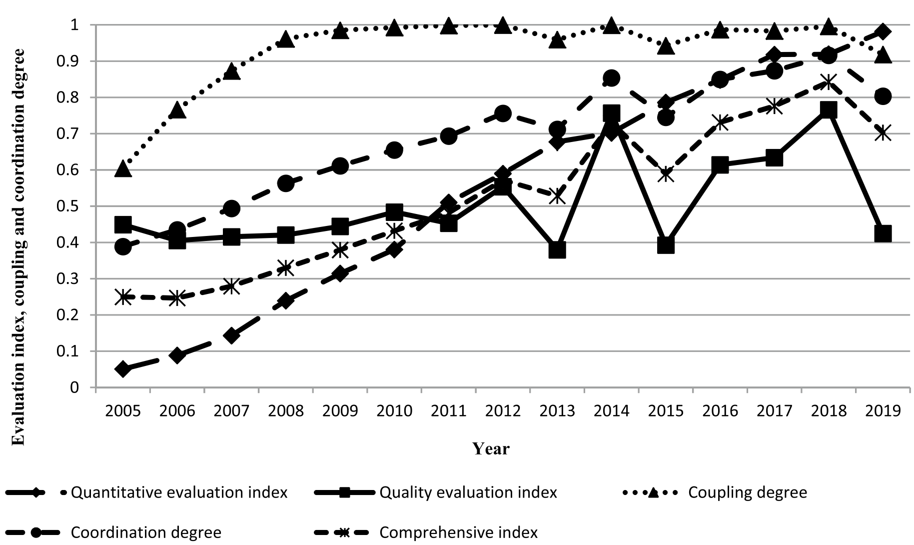


Fig. 3 Evaluation index, coupling and coordination degree of agricultural products

Calculation of coupling and coordination degree of subsystem

The coupling degree of the quantity and quality of agricultural products can be calculated by substituting the subsystem evaluation index into Eq. (1), and the results are shown in Fig. 3. The undetermined coefficients of quantitative and quality evaluation indices should be determined when calculating the degree of coordination. In this paper, the Granger causality test is used to determine the value of the undetermined coefficient, and the results are shown in Table 6. The optimum lag in the internal disturbance is a phase lag. Therefore, the undetermined coefficients of both subsystems can be approximately set to 0.5. According to the undetermined coefficient and subsystem evaluation index, the comprehensive index of agricultural products y_3 can be calculated, and the results are shown in Fig. 3.

By substituting the undetermined coefficients and coupling degrees of the two subsystems into Eq. (3), the coordination degree can be calculated, and the results are shown in Fig. 3. According to the coupling degree (CD) and calculated values (Wang and Tang 2018), the coupling types are divided into a run-in period ($0.5 \leq CD < 0.8$) and a coordinated coupling period ($0.8 \leq CD < 1.0$). According to the coupling coordination degree (CCD) and calculated values (Wang and Tang 2018),

Table 6 Internal disturbances in the quantity and quality of agricultural products

Internal disturbances	Evaluation index	Optimum lag	*F*-value	*P* value	AIC	BIC
The disturbance of quantity index system to quality index	Vegetable output per area of cropland	A phase lag	12.8	0.0013	− 28.6885	− 26.7714
	Fruit output per area of cropland	A phase lag	11.93	0.0018	− 28.0116	− 26.0944
	Grain output per area of cropland	A phase lag	7.81	0.0077	− 24.231	− 22.3138
	Average dietary energy supply adequacy	A phase lag	6.38	0.0145	− 22.6353	− 20.7182
	Grain import dependence ratio	A phase lag	10.36	0.003	− 26.6859	− 24.7687
	Quantity	A phase lag	11.3	0.0022	− 27.4914	− 25.5742
The disturbance of quality index system to quantity index	Qualified rate of vegetable	A phase lag	750.45	0	− 57.6723	− 55.7551
	Qualified rate of fruit	A phase lag	540.38	0	− 53.1144	− 51.1972
	Qualified rate of pesticide	A phase lag	559.21	0	− 53.5891	− 51.672
	The ratio of patients with food-borne disease	A phase lag	609.88	0	− 54.792	− 52.8749
	Consumer complaint ratio of food quality and safety	A phase lag	636.22	0	− 55.379	− 53.4618
	Quality	A phase lag	564.39	0	− 53.7168	− 51.7997

the coordination types can be divided into four categories, including moderate disorder ($0.2 \leq CCD < 0.4$), basic coordination ($0.4 \leq CCD < 0.5$), moderate coordination ($0.5 \leq CCD < 0.8$) and high coordination ($0.8 \leq CCD < 1.0$). Figure 3 shows that 2005–2006 is the run-in period and 2007–2019 is the coordinated coupling period. The coupling degree can reflect that the quantity and quality of agricultural products in China are in a highly coupled state and in a developing tendency. The coordination degree showed that the quantity and quality of agricultural products in China were moderately disordered in 2005, basically coordinated from 2006 to 2007, moderately coordinated from 2008 to 2013 and 2015, and highly coordinated in 2014 and 2016–2019. The indices show that the coordination degree of the quantity and quality of agricultural products is increasing gradually and reflects the healthy development trend of China's agricultural products market. However, according to various indices in 2019, the comprehensive index, coupling degree and coordination degree of China's agricultural products all declined. The results show that China's agricultural products market needs constantly strengthened government regulation, and agricultural product safety also has room to improve.

Transmission mechanisms of government regulation

First, the direct transmission mechanism is tested according to Eq. (4), and the results are shown in Table 7. Except for the quality evaluation index, the other indices have a significant relationship with the government regulation evaluation index.

Second, according to the mediation theory of the coupling function, the effects of pesticide use per area of cropland on the comprehensive index, coupling degree and coordination degree of agricultural products are discussed. According to Eq. (5), the significance of the government regulation index on mediating variables is tested, and the results are shown in Table 8. After the addition of the mediator variable, the coupling degree, coordination degree and composite index have no significant relationship with the government regulation index. Therefore, the Chinese government can regulate agricultural products by controlling pesticide use per area of cropland. This implies that pesticide use per area of cropland can be used as a mediator variable to achieve effective government regulation of agricultural products.

Table 7 Test results of the direct transmission mechanism

Variables	Quantity evaluation index y_1 (1)	Quality evaluation index y_2 (2)	Coupling degree y_3 (3)	Coordination degree y_4 (4)	Comprehensive index y_5 (5)
Government regulation evaluation index (x)	0.218128** (0.0823995)	0.0372947 (0.0395599)	0.0980318*** (0.0219264)	0.1270508*** (0.0382079)	0.1277114** (0.0533047)
R^2	0.3502	0.064	0.6059	0.4596	0.3063

The robust standard error is reported in brackets in the table. **Significant at 5%. ***Significant at 1%

Table 8 Test results of the indirect transmission mechanism

Variables	Pesticide use per area of cropland z (1)	Coupling degree y_3 (2)	Coupling degree y_3 (3)	Coordination degree y_4 (4)	Coordination degree y_4 (5)	Comprehensive index y_5 (6)	Comprehensive index y_5 (7)
Government regulation evaluation index (x)	0.3015189*** (0.0432442)	0.0980318*** (0.0219264)	−0.0261076 (0.0289986)	0.1270508*** (0.0382079)	−0.0606052 (0.0614527)	0.1277114** (0.0533047)	−0.0934202 (0.0970815)
Pesticide use per area of cropland (p)			0.4117134*** (0.085429)		0.622369*** (0.1810375)		0.733392** (0.2859988)
Number of years	15	15	15	15	15	15	15
R^2	0.789	0.6059	0.8658	0.4596	0.7278	0.3063	0.5519

The robust standard error is reported in brackets in the table. **Significant at 5%. ***Significant at 1%

Production-possibility frontier of agricultural products

According to Eq. (7), the production-possibility frontier of agricultural products is shown in Fig. 4. There are two ways to improve the quality of agricultural products. One transition is from A to B to C, and the whole transition is moving along the same production possibilities frontier. The quality of agricultural products is improved at the expense of quantity reduction. The other transition is from A to D to E, which requires that the agricultural production technology level be improved to expand the production-possibility frontier while the existing agricultural resources remain unchanged. This transition not only guarantees the stability of the quantity of agricultural products but also improves the quality of agricultural products. Comparing the two ways of agricultural product quality improvement has obvious advantages in expanding the production-possibility frontier of agricultural products.

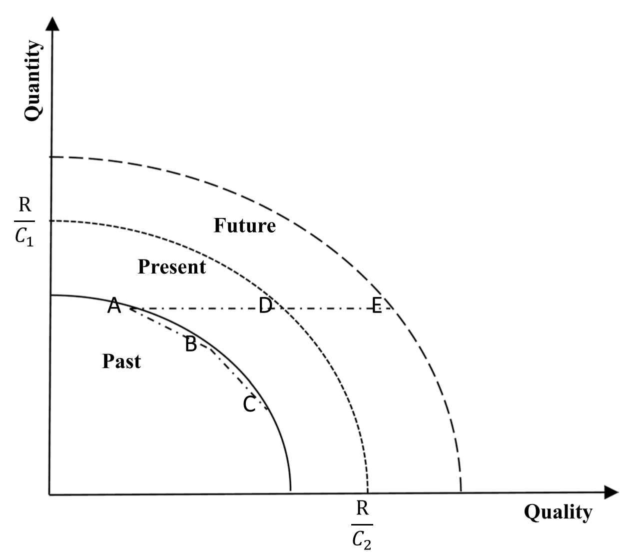


Fig. 4 Production-possibility frontier of agricultural products

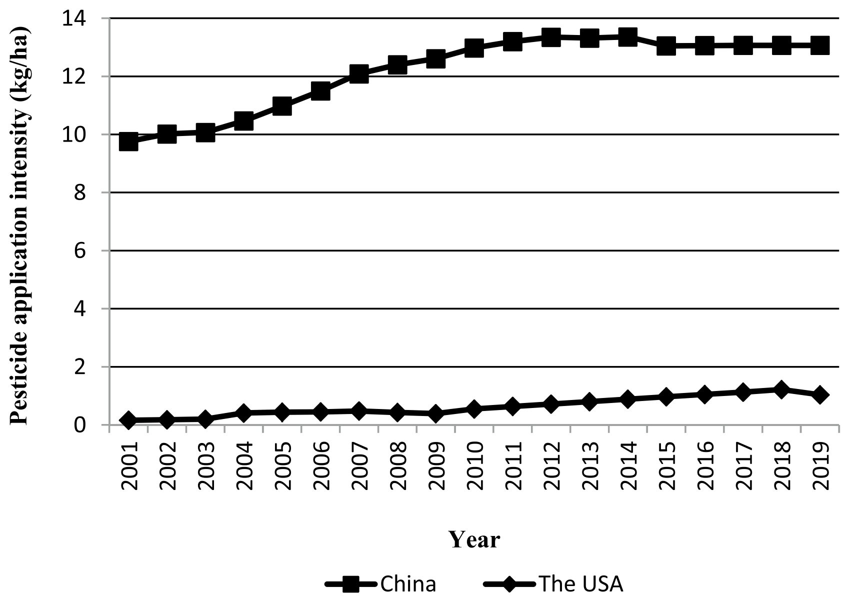


Fig. 5 A comparison of pesticide application intensity between China and the USA

The comparison of pesticide application intensity between China and the USA is shown in Fig. 5. Although the intensity of pesticide application is affected by the regional agricultural environment and other factors, there is huge potential for pesticide reduction in China. Therefore, China urgently needs to strengthen the regulation of pesticide application and implement a policy of pesticide reduction.

Trends in pesticide regulation based on agricultural product safety

The trend chart of pesticide usage and grain output in China is shown in Fig. 6. The use of pesticides in China has decreased significantly since 2015, but grain production has not decreased accordingly. Figure 6 shows that it is a feasible method to

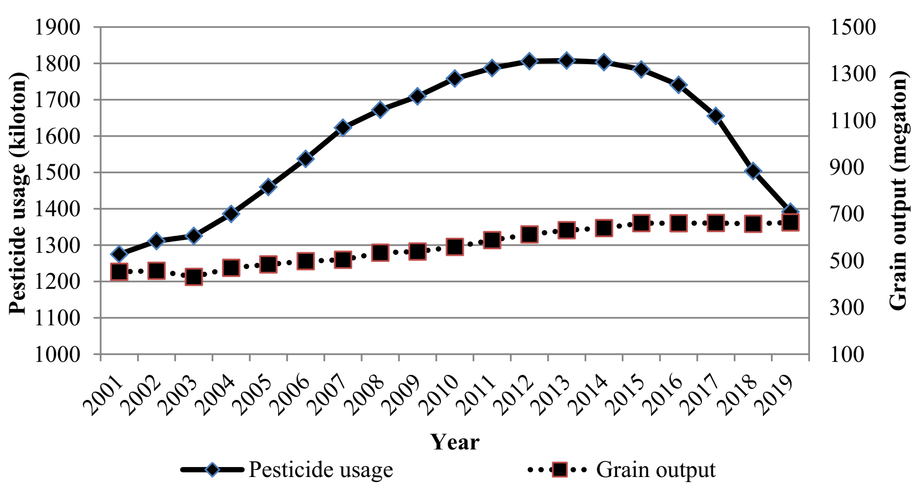


Fig. 6 Trends of pesticide usage and grain output from 2001 to 2019

expand the production-possibility frontier of agriculture to improve the quality and safety of agricultural products by reducing pesticide use on the premise of ensuring the stability of grain production.

It is the traditional driving force of agricultural development to realize the high yield and increase of agricultural products by the input of modern factors such as pesticides. However, the natural weakness of agricultural production means that it needs the support and protection of the government. Regulating pesticide usage is an important measure of government agricultural product safety regulation. Therefore, the government should first continue to implement the regulation policy of pesticide reduction and formulate the development plan of green agriculture to both stabilize the quantity and improve the quality of grain. Second, the production, sale and use of pesticides should be strictly regulated, biological pesticides should be encouraged to replace chemical pesticides, and the use of highly toxic and high-residue pesticides should be reduced. Third, governments should allocate financial funds for the research and development of new pesticides and encourage the use of new agricultural techniques to reduce pesticide use and increase grain production.

Discussion, conclusions and policy implications

Discussion

In the face of natural disasters, diseases, food trade and other uncertain factors, ensuring the safety of agricultural products is a common problem faced by many countries. The key to the safety of agricultural products is to improve the quality and safety on the basis of ensuring the quantity of agricultural products. In modern agricultural science and technology, pesticides are widely used in agricultural production. Pesticides are one of the most important factors affecting the safety of agricultural products. Studies have shown that many ecological and environmental problems and human diseases are closely related to pesticide use. Therefore, how to regulate the application of pesticides has become the focus of many countries.

To feed 1.4 billion people, China has vigorously developed the pesticide industry, which has effectively increased the quantity of agricultural products but also highlighted the problem of pesticide residues. Therefore, China has introduced a series of pesticide regulatory policies aimed at reducing the use of pesticides, thereby reducing pesticide residues and ensuring the quality and safety of agricultural products. In the past 30 years, China has experienced a great transformation from extensive pesticide development to pesticide safety management and has achieved remarkable results. China's experience in pesticide regulation can provide a practical reference for other countries.

According to the indices of agricultural product safety evaluation in this paper, the safety degree of agricultural products in China has gradually improved, which also indicates that the current pesticide regulation policy meets the requirements of agricultural development. However, in the face of new problems and challenges, can China continue to improve the safety level of agricultural products? Where is the room for improvement in China's pesticide regulatory policy? All these problems are worthy of further study and discussion.

Conclusions

In this paper, the coupling function is used to calculate the comprehensive evaluation index, coupling degree and coordination degree of agricultural products in China from 2005 to 2019. The influence of government regulation on the agricultural product evaluation index, coupling degree and coordination degree is empirically analyzed, and the trend of government pesticide regulation is proposed based on the production-possibility frontier theory of agricultural product production. This paper has the following conclusions: (1) From 2005 to 2019, the comprehensive index of quantity and quality, coupling degree and coordination degree of China's agricultural products show a steady trend, but there is still room for improvement. The results show that the policy of pesticide regulation in China is effective. (2) As a mediator variable, pesticide use per area of cropland is a key method for the government to realize the coordinated development of the quantity and quality of agricultural products. Therefore, the formulation of an appropriate pesticide application plan is a significant part of the government to promote sustainable agricultural development. (3) Appropriate reduction of pesticide usage is a feasible method to optimize the quality and quantity structure of agricultural products in China. A critical factor for the government to achieve pesticide reduction is to expand the production-possibility frontier of agricultural products.

Policy implications

Based on the conclusions, the following policy implications can be drawn. First, coordinating the quantity and quality of agricultural products is an important part of China's sustainable agricultural development and national food security strategy. Agricultural policies must balance the quantity and quality of agricultural products. Second, government pesticide regulation is an effective means to ensure the safety of agricultural products. Pesticide reduction is currently a crucial part of the Chinese government's agricultural development. Third, the government should encourage technological innovation and the development of new green pesticides and reform the method of government regulation. Expanding the production-possibility frontier of agricultural products through technological innovation is a significant method to promote pesticide reduction and agricultural technical efficiency.

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Author contributions
Yitian Shao was involved in conceptualization, methodology, software, writing—original draft preparation. Jianwei Ni helped in comments, suggestions, manuscript revision. Shengjia Zhou contributed to software, data curation. Yiping Wang was responsible for data curation, visualization. Xuanxuan Jin helped in writing—reviewing and editing, validation.

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Declarations

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Consent for publication
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The authors declare no competing interests.

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References

Baron RM, Kenny DA (1986) The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. J Pers Soc Psychol 51(6):1173–1182. https://doi.org/10.1037/0022-3514.51.6.1173

Carrère M, DeMaria F, Drogue S (2018) Maximum residual levels of pesticides and public health: best friends or faux amis? Agric Econ 49(1):111–118. https://doi.org/10.1111/agec.12399

Devadoss S, Song W (2003) Factor market oligopsony and the production possibility frontier. Rev Int Econ 11(4):729–744. https://doi.org/10.1111/1467-9396.00414

Drogue S, DeMaria F (2012) Pesticide residues and trade, the apple of discord? Food Policy 37(6):641–649. https://doi.org/10.1016/j.foodpol.2012.06.007

FAO, Ifad, UNICEF, WFP, WHO (2020) The State of Food Security and Nutrition in the World 2020: transforming food systems for affordable healthy diets. Rome FAO. https://doi.org/10.4060/ca9692en

Federica D, Sophie D, Pasquale L (2021) The impact of pest risk management measures on trade: the case of apples from France and Chile. Agric Food Econ 9(1):21. https://doi.org/10.1186/s40100-021-00193-5

Greenblatt DJ (1985) Elimination half-life of drugs: value and limitations. Annu Rev Med 36(1):421–427. https://doi.org/10.1146/annurev.me.36.020185.002225

Hallmann CA, Sorg M, Jongejans E et al (2017) More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS ONE 12:e0185809. https://doi.org/10.1371/journal.pone.0185809

Hawkins NJ, Bass C, Dixon A, Neve P (2019) The evolutionary origins of pesticide resistance. Biol Rev 94(1):135–155. https://doi.org/10.1111/brv.12440

Huang Y, Luo X, Liu D, Du S, Yan A, Tang L (2021) Pest control ability, technical guidance, and pesticide overuse: evidence from rice farmers in rural China. Environ Sci Pollut Res 28:39587–39597. https://doi.org/10.1007/s11356-021-13607-0

Jian XH, Nie CF (2020) Measurement of china's high-quality development: 1978–2018. Economist 6:49–58. https://doi.org/10.16158/j.cnki.51-1312/f.2020.06.006. (**in Chinese**)

Khan M, Mahmood HZ, Damalas CA (2015) Pesticide use and risk perceptions among farmers in the cotton belt of Punjab, Pakistan. Crop Prot 67:184–190. https://doi.org/10.1016/j.cropro.2014.10.013

Kong XZ, Zhang C, Zhang XR (2018) Factor endowment change and organic composition of agricultural capital increase. J Manag World 34(10):147–160. https://doi.org/10.19744/j.cnki.11-1235/f.2018.10.013. (**in Chinese**)

Koop G, Leon-Gonzalez R, Strachan RW (2009) On the evolution of the monetary policy transmission mechanism. J Econ Dyn Control 33(4):997–1017. https://doi.org/10.1016/j.jedc.2008.11.003

Li Y, Liang J (2021) Models for determining the optimal switching time in chemical control of pest with pesticide resistance. Math Biosci Eng: MBE 18(1):471–494. https://doi.org/10.3934/mbe.2021026

Li Y, Li Y, Zhou Y, Shi Y, Zhu X (2012) Investigation of a coupling model of coordination between urbanization and the environment. J Environ Manag 98:127–133. https://doi.org/10.1016/j.jenvman.2011.12.025

Mackinnon D (2015) Mediating variable. In: International encyclopedia of the social & behavioral sciences, 2nd edn. Elsevier, Amsterdam, pp 64–69. https://doi.org/10.1016/B978-0-08-097086-8.44037-7

Mahmood I, Imadi SR, Shazadi K et al (2016) Effects of pesticides on environment. In: Plant, soil and microbes: volume 1: implications in crop science, pp 253–269. https://doi.org/10.1007/978-3-319-27455-3_13

Miyazaki J, Kinoshita S (2006) Determination of a coupling function in multicoupled oscillators. Phys Rev Lett 96(19):194101. https://doi.org/10.1103/PhysRevLett.96.194101

Nadoveza Jelić O, Šimurina J (2020) Evaluating sectoral effects of agricultural nitrogen pollution reduction policy in Croatia within a CGE framework. Agric Food Econ 8(1):1–35. https://doi.org/10.1186/s40100-020-0152-6

Pang GF (2019) Report on pesticide residues in fruits and vegetables sold in china (2015–2019). Science Press, Beijing (**in Chinese**)

Poenaru DN, Ivaşcu M, Sndulescu A, Greiner W (1985) Atomic nuclei decay modes by spontaneous emission of heavy ions. Phys Rev C 32(2):572. https://doi.org/10.1103/PhysRevC.32.572

Qu CS, Chen W, Bi J et al (2011) Ecological risk assessment of pesticide residues in Taihu Lake wetland, China. Ecol Model 222(2):287–292. https://doi.org/10.1016/j.ecolmodel.2010.07.014

Schreinemachers P, Tipraqsa P (2012) Agricultural pesticides and land use intensification in high, middle and low income countries. Food Policy 37(6):616–626. https://doi.org/10.1016/j.foodpol.2012.06.003

Shao Y, Wang Y, Yuan Y, Xie Y (2021a) A systematic review on antibiotics misuse in livestock and aquaculture and regulation implications in China. Sci Total Environ 798:149205. https://doi.org/10.1016/j.scitotenv.2021.149205

Shao YT, Wang YP, Yuan YW (2021b) Food safety and government regulation in rural China. J Agric Food Res 5:100170. https://doi.org/10.1016/j.jafr.2021.100170

Soares WL, Porto M (2009) Estimating the social cost of pesticide use: an assessment from acute poisoning in Brazil. Ecol Econ 68(10):2721–2728. https://doi.org/10.1016/j.ecolecon.2009.05.008

Song YH, Yu HQ, Tan YC, Lv W, Fang DH, Liu D (2020) Similarity matching of food safety incidents in China: aspects of rapid emergency response and food safety. Food Control 115:107275. https://doi.org/10.1016/j.foodcont.2020.107275

Syed JH, Alamdar A, Mohammad A et al (2014) Pesticide residues in fruits and vegetables from Pakistan: a review of the occurrence and associated human health risks. Environ Sci Pollut Res 21:13367–13393. https://doi.org/10.1007/s11356-014-3117-z

Teng Y, Chen X, Yu Z, Wei J (2021) Research on the evolutionary decision-making behavior among the government, farmers, and consumers: based on the quality and safety of agricultural products. IEEE Access 9:73747–73756. https://doi.org/10.1109/ACCESS.2021.3078561

Tomal M (2021) Evaluation of coupling coordination degree and convergence behaviour of local development: a spatiotemporal analysis of all Polish municipalities over the period 2003–2019. Sustain Cities Soc 71:102992. https://doi.org/10.1016/j.scs.2021.102992

Van den Berg H, Gu B, Grenier B et al (2020) Pesticide lifecycle management in agriculture and public health: Where are the gaps? Sci Total Environ 742:140598. https://doi.org/10.1016/j.scitotenv.2020.140598

Van Heumen E, Muhlethaler E, Kuzmenko AB et al (2009) Optical determination of the relation between the electron-boson coupling function and the critical temperature in high-T c cuprates. Phys Rev B 79(18):184512. https://doi.org/10.1103/PhysRevB.79.184512

Verbeek PP (2015) COVER STORY beyond interaction: a short introduction to mediation theory. Interactions 22(3):26–31. https://doi.org/10.1145/2751314

Wang CW, Gu HY (2013) Market VS government: what forces influence the choice of pesticide dosage of Chinese vegetable farmers? J Manag World 11:50. https://doi.org/10.19744/j.cnki.11-1235/f.2013.11.006. (**in Chinese**)

Wang R, Tan J (2021) Exploring the coupling and forecasting of financial development, technological innovation, and economic growth. Technol Forecast Soc Change 163:120466. https://doi.org/10.1016/j.techfore.2020.120466

Wang C, Tang N (2018) Spatio-temporal characteristics and evolution of rural production-living-ecological space function coupling coordination in Chongqing Municipality. Geogr Res 37(6):1100–1114. https://doi.org/10.11821/dlyj201806004. (**in Chinese**)

Wu J, Jin X, Feng Z et al (2021) Relationship of ecosystem services in the Beijing–Tianjin–Hebei region based on the production possibility frontier. Land 10(8):881. https://doi.org/10.3390/land10080881

Yang JH, Yang L (2022) Influence of agricultural factor input regulation on internal disturbance and coupling of agro-product quality and safety. J Nat Resour 37(2):494–507. https://doi.org/10.31497/zrzyxb.20220215

Zhao T, Zhang Z, Liang SK (2020) Digital economy, entrepreneurship, and high-quality economic development: empirical evidence from Urban China. J Manag World 10:65–76. https://doi.org/10.19744/j.cnki.11-1235/f.2020.0154. (**in Chinese**)

Zhong Z, Kong XZ (2012) The impact of industrial organization patterns on the quality and safety of agricultural products: evidence from the dairy industry. J Manag World 1:79–92. https://doi.org/10.19744/j.cnki.11-1235/f.2012.01.009. (**in Chinese**)

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