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How does price insurance alleviate the fluctuation of agricultural product market? A dynamic analysis based on cobweb model

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Abstract: Food security is of great importance to all countries. Correspondingly, agricultural price insurance is an important tool to maintain food security. This study adopts the traditional spider web model to establish a mathematical framework for exploring the internal mechanism of agricultural price insurance, which can ease the volatility of the agricultural market. Then, the influence of agricultural price insurance on the supply of agricultural products is examined. The findings show that the supply elasticity of most agricultural products is greater than the demand elasticity, with agricultural product markets presenting a natural divergence. Agricultural price insurance changes the supply curve of agricultural products by reducing their supply elasticity, subsequently positively affecting the reduction of price fluctuation and the stabilisation of outputs. Agricultural price insurance can even change agricultural product markets under certain conditions, allowing a shift from divergence to convergence. Moreover, by adjusting the insurance parameters of agricultural prices, the equilibrium yield and price can be changed, and the planting area and income of farmers can be maximised. The mathematical basis for agricultural insurance derived in this study can support food security strategies at the national level and further provide a theoretical basis to formulate policies and departmental measures.

Keywords: agricultural product supply elasticity; agricultural risk; crop insurance; food security

Food supply concerns the livelihood, well-being and sustainable development of communities and has always been a concern of many countries. The COVID-19 epidemic outbreak and the Russian-Ukrainian war highlighted the importance and urgency of food security. To stabilise the market for agricultural products in China, the government has successively adopted a series of policies, such as minimum purchase prices, temporary storage and storage and government subsidies, and achieved good results. However, many government interventions are not only expected to distort the market and increase the financial burden but also violate World Trade Organization (WTO) rules and agreements and may even be unsustainable in the long term. Agriculture is generally considered one of the most effective tools to stabilise agricultural product markets, and in line with this notion, agricultural insurance can be used to manage agricultural risks. However, government bodies often find it challenging to directly intervene in agricultural product markets with high management efficiency and low financial burden. Moreover, agricultural insurance belongs

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to the 'green box policy' of the WTO, indicating high implementation support (Glauber 2016).

Scholars have widely investigated the impact of agricultural insurance on the agricultural sector and determined its overall benefit in reducing agricultural production risk. According to the production process, the research can be divided into the influences on crop selection (Du et al. 2017; Yu and Sumner 2018), planting area decisions (Claassen et al. 2017; Burns and Prager 2018), insurance decision (Roll 2019; Yanuarti et al. 2019), input (He et al. 2020), farmer's income (Mote 2017; Sharma and Walters 2020; Agbenyo et al. 2022), and output (Fadhliani et al. 2019; Zou et al. 2022). The study found that agricultural insurance can increase production, stabilize farmers' income, and protect national food security. While scholars have studied the effects of agricultural insurance from all aspects of agricultural product markets, they have not clarified the influence mechanism between them. By performing mathematical deduction and establishing a set of proof, the following four questions can be comprehensively explored: *i*) Does the agricultural product market entail a natural divergence?; *ii*) How does agricultural price insurance affect the supply of agricultural products?; *iii*) Under what conditions will agricultural price insurance lead to the convergence of agricultural product markets?; *iv*) What is the equilibrium state of the agricultural product markets and the maximum income of farmers after the introduction of agricultural price insurance?

The answers to these four questions can help to provide a mathematical basis for many existing studies, further enriching the research on agricultural insurance and agricultural product markets. The findings can also help the government to design and further improve support policies on agricultural price insurance and agricultural product markets.

MATERIAL AND METHODS

The cobweb model describes the law of supply and demand and the fluctuations caused by product supply–demand–price interactions; such concepts were first proposed by the American economist H. Shultz, Italian economist U. Riel, and Dutch economist J. Tabbergen. Then, in 1934, N. Aldor, a British economist, systematically studied the same concepts and coined the name for this theory (Kaldor 1934). The cobweb model centres on three basic assumptions: *i*) the market is a perfectly competitive market; *ii*) the price is determined by the supply, which is influenced by previous market prices; and *iii*) the product is short-lived and cannot be stored until the next instalment.

The cobweb model is often used to analyse dynamic price fluctuations in the market from the perspective of elasticity of supply and demand (Hommes 2022; Poitras 2022), especially for the agricultural market. According to the different expectations and production strategies of producers, the cobweb model can be classified into the following types: traditional, simple expectation, adaptive expectation, and rational expectation. The traditional cobweb model takes the previous price as the expected price and thus is also called naive expectation. The simple expectation cobweb model takes the average value of the historical sample as the expected price (Carlson 1968). The adaptive expectation cobweb model determines the expected price by appropriately adjusting it according to the historical price (Nerlove 1958). The rational expectation cobweb model has perfect predictability for the future price (Muth 1961). Therefore, the evolution of the cobweb model is essentially a description of the expected price.

Which cobweb model is more suitable for agricultural product market research? First, in the presence of information barriers and other reasons, rational expectations are difficult to establish. With the main task of producing and managing agricultural products, in terms of the learning ability of farmers, their level of obtaining and processing information is low. In this case, the actual situation can be better investigated on the premise of biased expectations. Second, some studies have established that simple price expectations can more generally reflect the production decision-making behaviour of farmers. Finally, fluctuations in planting areas and prices of agricultural products under certain assumptions or naive expectations are obviously greater than those under adaptive and rational expectations. On this basis, this research uses the traditional cobweb model as a reference to construct the theoretical framework and model and then explores the internal mechanism of agricultural price insurance affecting agricultural product markets.

Agricultural product markets in the absence of agricultural price insurance

Supply curve. For this type of agricultural product market, the number of producers engaged in agricultural activities is given by n, and they are assumed to grow the same crop. Therefore, the substitution effect between agricultural products can be ignored. Each farmer knows his or her output per unit area q.

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As the production technology and production conditions of individual farmers differ amongst each other but are unchanged in a short time, the output per unit area q_i of farmer i remains constant. Nonetheless, farmers can change the planting area x according to their expectations and experiences during production to maximise their production profits. Furthermore, as agricultural products are difficult to store, those produced in the current period must also be sold in the current period. If the supply exceeds the demand, with the aim of selling all agricultural products, then farmers will likely sell them amongst themselves at a low price. By contrast, if the supply is less than the demand, then consumers will likely set the price, and the price of these agricultural products will rise.

The demand curve of the agricultural product market is given by $D: P = a_1 - b_1Q$, whilst the supply curve is given by $S: P = a_2 + b_2Q$. At this time, a_1, b_1, a_2, and b_2 are constant. b_1 and b_2 are the absolute values of the slopes of D and S, which are opposite to the magnitude of elasticity.

A farmer's profit consists of the income from operating agricultural products and the cost of planting agricultural products. The farmer adjusts the planting area of agricultural products according to the expected profit of agricultural products. The expected profit function of farmer i is given by Equation (1):

$$\pi(x_i) = P^e q_i x_i - cx_i^2 \tag{1}$$

where: π – profit of farmer; P^e – expected price of agricultural products of the farmer; q_i – yield per mu of the i^{th} farmer; x_i – planting area of farmer i; cx_i^2 – cost of planting agricultural products (Alizamir 2019), indicating an increase in the marginal cost when the planting area increases for a given constant c.

According to the principle of profit maximisation, the supply curve S of agricultural products can be obtained as follows [Equation (2)]. Detailed mathematical calculations are provided in Electronic Supplementary Material (ESM, Appendix S4).

$$P^e = \frac{2c}{\sum_{i=1}^{i=n} q_i^2} Q \tag{2}$$

where: Q – output.

Cobweb model. The cobweb model hypothesises that farmers take the previous period's agricultural price as the expectation of the current period's agricultural price. Then, according to the demand and supply curves, the traditional cobweb model can be expressed by the following Equations (3–5):

$$P_t = a_1 - b_1 D_t \tag{3}$$

$$P_{t-1} = \frac{2c}{\sum_{i=1}^{i=n} q_i^2} S_t \tag{4}$$

$$D_t = S_t \tag{5}$$

where: D_t and S_t – quantity demanded and supplied in period t, respectively; P_t – price in period t; P_{t-1} – price in period t–1.

Equation (3) indicates that the price in period t determines demand in period t; Equation (4) indicates that the price in period t–1 determines the supply in period t; and Equation (5) indicates that the supply and demand are equal in period t. The logical sequence of the cobweb model implies that the producer erroneously determines the supplied quantity based on the price of the previous period, the consumer passively consumes the entire quantity of production provided by the producer, and the price is determined by the quantity that has been erroneously produced.

Proof of divergence. When the divergent agricultural product market deviates from the original equilibrium state due to external shocks, the actual price and actual output fluctuate around the equilibrium level. However, the fluctuations increasingly widen and finally deviate from the original equilibrium point in the long term. Figure 1 illustrates whether agricultural product markets naturally diverge. The supply elasticity of most agricultural products is greater than the demand elasticity, which is expressed as Equation (6):

$$b_1 > b_2 = \frac{2c}{\sum_{i=1}^{i=n} q_i^2} \tag{6}$$

This scenario proves that when $b_1 > b_2$, the market of agricultural products must diverge.

This study assumes that in period t, the agricultural product market is subject to a positive shock (e.g. good weather), indicating a greater output Q_t in period t compared with the equilibrium output Q_0. At this time, the output is higher than the equilibrium level, and the market experiences a phenomenon of oversupply. Furthermore, P_t is less than the equilibrium

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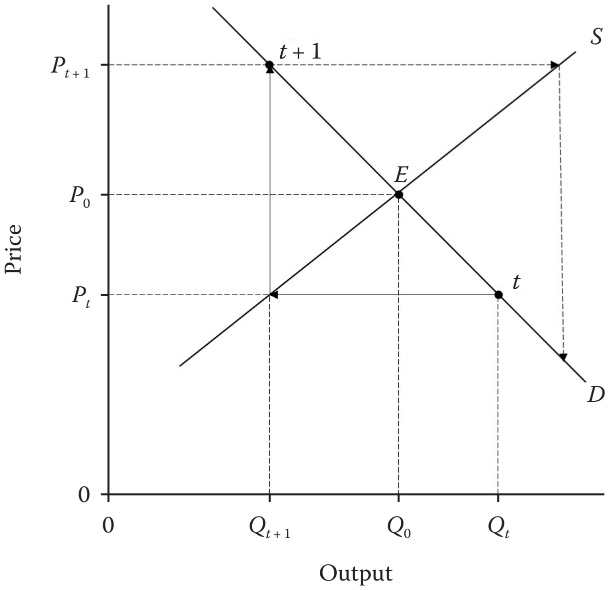

Figure 1. Proof of divergence of agricultural product markets

P_t – price in period t; P_0 – equilibrium price; Q_t – output in period t; Q_0 – equilibrium output; E – equilibrium point; S – supply elasticity; D – demand elasticity

Source: Authors' own calculations

level P_0. According to Equation (3), the price in period t can be obtained as follows [Equation (7)]:

$$P_t = a_1 - b_1 Q_t \tag{7}$$

In period $t + 1$, farmers determine the planting area and output according to P_t. The supply in period $t + 1$ can be obtained according to Equation (4) as follows [Equation (8)]:

$$S_{t+1} = \frac{P_t}{\frac{2c}{\sum_{i=1}^{i=n} q_i^2}} \tag{8}$$

Equation (7) indicates equal demand and supply. Subsequently, according to Equation (8), the price in period $t + 1$ can be obtained as follows [Equation (9)]:

$$P_{t+1} = a_1 - b_1 \frac{P_t}{\frac{2c}{\sum_{i=1}^{i=n} q_i^2}} \tag{9}$$

Equation (9) illustrates the relationship between the price of each period and the price of the previous period in the agricultural product market. In divergent agricultural product markets, the price gradually deviates from the equilibrium point when the agricultural product market is subjected to external shocks. Therefore, to prove that the price of the agricultural product markets diverges under the condition of Equation (6)

$$b_1 > \frac{2c}{\sum_{i=1}^{i=n} q_i^2},$$

the continuously increasing gap between the price and the equilibrium price must also be proven. The change in the gap between the price and the equilibrium price can be expressed as follows [Equations (10) and (11)]:

$$d = \left|P_{t+1} - P_0\right| - \left|P_t - P_0\right| \tag{10}$$

By calculation, Equation (10) is greater than 0 [Equation (11)]. Detailed mathematical calculations are provided in ESM, Appendix S4.

$$\left|P_{t+1} - P_0\right| - \left|P_t - P_0\right| > 0 \tag{11}$$

According to Equation (11), when the slope of the demand function is greater than the slope of the supply function, the price in each period deviates more prominently from the equilibrium price compared with the price in the previous period. This scenario proves the divergence of agricultural product markets.

Agricultural product markets in the presence of agricultural price insurance

After the presence of agricultural price insurance, farmers need to decide whether to participate in the insurance before deciding on planting areas. Insurance decision is related to the positive and negative of expected insurance income. The planting area decision is based on the theory of expected profit maximization. The planting area decision of the farmer determines the supply, whose change will also likely alter the market price of agricultural products. The subsequent section describes the change in the supply curve when agricultural price insurance is introduced with respect to insurance and planting area decision making.

Supply curve. *i*) Insurance decision: The income to be obtained from insurance represents the difference between insurance compensation and insurance premiums. The expected insurance income S of farmer i is given by Equation (12):

$$S = -r\, p_m\, q_i\, x_i + \max\left\{\rho\, q_i\, x_i \left(p_m - P^e\right), 0\right\} \tag{12}$$

where: P^e – expected price of agricultural products of farmers; $r\, p_m\, q_i x_i$ – premium in which farmers are

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insured for all planted agricultural products; the cost is proportional to yield $q_i x_i$ and target price p_m; $\max\left\{\rho\, q_i x_i \left(p_m - P^e\right), 0\right\}$ – insurance compensation expected by farmers, which can be either paid or unpaid; the guarantee level ρ – proportion of guaranteed farmers' income, which is proportional to the output $q_i x_i$ and proportional to the guarantee level ρ.

If the price of agricultural product P^e is less than the target price p_m, then the farmer will receive insurance compensation $\rho\, q_i x_i (p_m - P^e)$. If the price of agricultural product P^e is greater than the target price p_m, then the farmer cannot be compensated.

Farmer i only chooses to insure when the insurance income is positive. The condition for farmer i to participate in the insurance is given by Equation (13):

$$S > 0 \tag{13}$$

The abovementioned equation can be solved as Equation (14):

$$P^e < \frac{\rho - r}{\rho} p_m \tag{14}$$

This study sets the critical point p_z

$$p_z = \frac{\rho - r}{\rho} p_m$$

of farmer i participating in agricultural price insurance. If $P^e \geq p_z$, then farmer i will likely forgo agricultural price insurance. If $P^e < p_z$, then farmer i will likely choose to participate in agricultural price insurance.

ii) Planting area decision: The expected profit functions of farmers vary in line with different insurance participation situations. A farmer eventually deciding to participate in the insurance will have a profit consisting of the income from operating agricultural products, insurance compensation, the cost of planting agricultural products and the insurance premium. By contrast, if the farmer decides to forego the insurance, then his or her profit will consist of the income from operating the farm products and the cost of growing the farm products.

When farmer i decides to forgo the insurance, at this time ($P^e \geq p_z$), his or her expected profit function is given by Equation (15):

$$\pi\left(x_i\right) = P^e q_i x_i - c x_i^2 \tag{15}$$

When farmer i decides to participate in the insurance, at this time ($P^e < p_z$), his or her expected profit function is expressed as Equation (16):

$$\pi\left(x_i\right) = P^e q_i x_i - c x_i^2 - r p_m q_i x_i + \rho\, q_i x_i \left(p_m - P^e\right) \tag{16}$$

According to the principle of profit maximisation, the decision function of farmers can be obtained as follows [Equation (17)]. Detailed mathematical calculations are provided in ESM, Appendix S4.

$$x_i = \begin{cases} \dfrac{P^e q_i}{2c}, \ P^e \geq p_z \\ \left[\dfrac{P^e}{2c} + \dfrac{p_m\left(\rho - r\right)}{2c} - \dfrac{\rho\, P^e}{2c}\right] q_i, \ P^e < p_z \end{cases} \tag{17}$$

iii) Bent supply curve: According to Equation (17), the supply curve of agricultural products can be obtained as Equation (18). Detailed mathematical calculations are provided in ESM, Appendix S4.

$$P = \begin{cases} \dfrac{2c}{\sum_{i=1}^{i=n} q_i^2} Q, \ P \geq p_z \\ \dfrac{2c}{\left(1 - \rho\right)\sum_{i=1}^{i=n} q_i^2} Q - \dfrac{p_m\left(\rho - r\right)}{1 - \rho}, \ P < p_z \end{cases} \tag{18}$$

The supply curve is shown in Figure 2. When $P \geq p_z$, farmers will likely forgo the insurance. At this time, in the

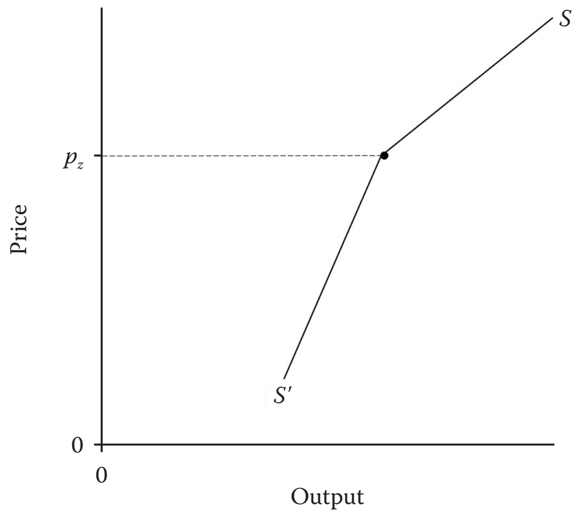

Figure 2. Supply curve in the presence of agricultural price insurance

p_z – critical point; S, S' – supply elasticity
Source: Authors' own calculations

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absence of agricultural insurance, the supply curve coincides with the original supply curve, which is represented by S. When $P < p_z$, the supply curve slope denoted by

$$\frac{2c}{\sum_{i=1}^{i=n} q_i^2} \text{ reaches } \frac{2c}{(1-\rho)\sum_{i=1}^{i=n} q_i^2}.$$

This scenario suggests a decreasing supply elasticity, and the supply curve is represented by S'. Therefore, after the introduction of agricultural price insurance, the supply curve changes from a straight line to a broken line at p_z, which is called a bent supply curve in this study. The bent supply curve consists of two features, namely, the point of bending and the degree of bending, which are determined by the critical point p_z and the slope

$$\frac{2c}{(1-\rho)\sum_{i=1}^{i=n} q_i^2}.$$

According to the critical point p_z

$$p_z = \frac{\rho - r}{\rho}\, p_m$$

and slope

$$\frac{2c}{(1-\rho)\sum_{i=1}^{i=n} q_i^2},$$

the change in agricultural insurance price also alters the shape of the supply curve of bending.

Cobweb model. On the basis of the demand and supply curves, the cobweb model of the agricultural market in the presence of agricultural price insurance can be expressed as follows [Equations (19–22)]:

$$P_t = a_1 - b_1 D_t \tag{19}$$

$$P_{t-1} = \frac{2c}{\sum_{i=1}^{i=n} q_i^2} S_t,\ (P \geq p_z) \tag{20}$$

$$P_{t-1} = -\frac{p_m(\rho - r)}{1-\rho} + \frac{2c}{(1-\rho)\sum_{i=1}^{i=n} q_i^2} S_t,\ (P < p_z) \tag{21}$$

$$D_t = S_t \tag{22}$$

In contrast to markets lacking agricultural price insurance, the supply curve in this case transforms into a curve that bends at p_z. Consequently, Equation (4) can be expressed as Equations (20) and (21).

RESULTS AND DISCUSSION

Proof of convergence. This study has proven that the divergence condition of agricultural product markets requires the supply elasticity to be greater than the demand elasticity. The introduction of agricultural price insurance causes the shape of the agricultural product supply curve to change and the elasticity of the bent part to become less apparent. What impact will the elasticity of the agricultural product supply curve have on the agricultural product market? What conditions will lead to the convergence of the agricultural product markets? This section focuses on these problems. In addition, the impact of agricultural price insurance on the convergent market is presented in ESM, Appendix S1.

Three functions in the model can be established on the basis of the change in the supply curve: the demand curve denoted by $D{:}P = a_1 - b_1 Q$ and the supply curve denoted by $S{:}P = a_2 + b_2 Q(P \geq p_z)$, $S'{:}P = a_2' + b_2' Q(P < p_z)$. $(b_1, b_2, b_3 > 0)$,

where: S' – part of the supply curve that changed after agricultural price insurance was introduced.

At this time:

$$a_2' = -\frac{p_m(\rho - r)}{1-\rho},\ b_2' = \frac{2c}{(1-\rho)\sum_{i=1}^{i=n} q_i^2},\ a_2 = 0, \text{ and}$$

$$b_2 = \frac{2c}{\sum_{i=1}^{i=n} q_i^2}.$$

The impact of agricultural price insurance on the agricultural market can be further classified into three cases: p_z is equal to the equilibrium price; p_z is greater than the equilibrium price; and p_z is less than the equilibrium price. The case of p_z being equal to the equilibrium price is discussed below, whereas the other cases are presented in ESM, Appendix S2.

In Figure 3, the agricultural product market is assumed to be positively affected in period t, and the output Q_t in this period is assumed to be greater than the equilibrium output Q_0. The supply exceeds the demand in the market, and farmers bid with each other, resulting in price reduction. In this case, P_t is less than p_z.

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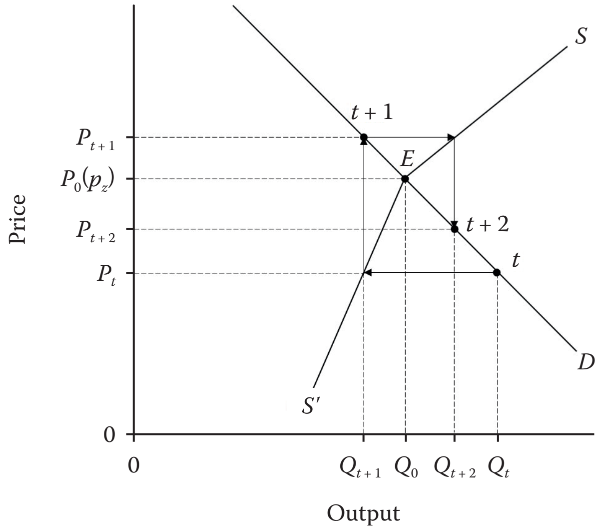

Figure 3. Proof of agricultural product market convergence (p_z equals P_0)

p_z – critical point; P_0 – equilibrium price; P_t – price in period t; Q_t – output in period t; Q_0 – equilibrium output; E – equilibrium point; S, S' – supply elasticity; D – demand elasticity

Source: Authors' own calculations

According to Equation (19), the price in period t can be obtained as Equation (23):

$$P_t = a_1 - b_1 Q_t \tag{23}$$

In period $t + 1$, farmers decide the planting area and the supply based on P_t. As P_t is less than the equilibrium level P_0 and p_z is equal to the equilibrium price, P_t is less than p_z. According to Equation (21), the supply in period $t + 1$ can be obtained as Equation (24):

$$S_{t+1} = \frac{P_t + \dfrac{p_m\left(\rho - r\right)}{1 - \rho}}{\dfrac{2c}{\left(1 - \rho\right)\sum_{i=1}^{i=n} q_i^2}} \tag{24}$$

In Equation (22), the quantity demanded and supplied are equal to each other. Therefore, according to Equation (19), the price of period $t + 1$ can be obtained as Equation (25):

$$P_{t+1} = a_1 - b_1 \frac{P_t + \dfrac{p_m\left(\rho - r\right)}{1 - \rho}}{\dfrac{2c}{\left(1 - \rho\right)\sum_{i=1}^{i=n} q_i^2}}, \left(P_t < p_z\right) \tag{25}$$

In period $t + 2$, farmers decide the planting area and the yield according to P_{t+1}. As P_{t+1} is greater than the equilibrium level P_0 and p_z is equal to the equilibrium price, P_{t+1} is greater than p_z. According to Equation (20), the output of period $t + 2$ can be obtained as Equation (26):

$$S_{t+2} = \frac{P_{t+1}}{\dfrac{2c}{\sum_{i=1}^{i=n} q_i^2}} \tag{26}$$

In Equation (22), the quantity demanded and supplied are equal to each other. Therefore, according to Equation (19), the price of period $t + 2$ can be obtained as Equation (27):

$$P_{t+2} = a_1 - b_1 \frac{P_{t+1}}{\dfrac{2c}{\sum_{i=1}^{i=n} q_i^2}}, \left(P_{t+1} \geq p_z\right) \tag{27}$$

The change in the gap between the price and the equilibrium price in different periods is expressed as follows [Equations (28) and (29)]:

$$d_1 = \left|P_{t+1} - P_0\right| - \left|P_t - P_0\right|, \left(P_t < p_z\right) \tag{28}$$

$$d_2 = \left|P_{t+2} - P_0\right| - \left|P_{t+1} - P_0\right|, \left(P_{t+1} \geq p_z\right) \tag{29}$$

When $d_1 + d_2 < 0$, the agricultural market will converge [Equation (30)]:

$$d_1 + d_2 = \left|P_{t+2} - P_0\right| - \left|P_t - P_0\right| \tag{30}$$

The condition needed for the agricultural product market to converge can be obtained as follows [Equation (31)]:

$$\left(1 - \rho\right)P_t + p_m\left(\rho - r\right) >$$
$$> a_1\left(\frac{\dfrac{2c}{\sum_{i=1}^{i=n} q_i^2}}{b_1}\right) + \left(P_t - a_1\right)\left(\frac{\dfrac{2c}{\sum_{i=1}^{i=n} q_i^2}}{b_1}\right)^2, \tag{31}$$
$$\left(P_t \in c \cap P_t < p_z\right)$$

Equilibrium. As the shape of the supply curve changes on the basis of agricultural price insurance,

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the intersection of the supply and demand curves determines the balance in output and price. Therefore, by adjusting the target price p_m, premium rate r, and guarantee level ρ of agricultural price insurance, the equilibrium state can be changed to achieve the goal of guaranteeing farmers' income. The supply and demand curves after introducing agricultural price insurance can be expressed as follows [Equation (32)]:

$$\begin{cases} D: P = a_1 - b_1 Q \\ S: P = \dfrac{2c}{\sum_{i=1}^{i=n} q_i^2} Q,\ \left(P \geq p_z\right) \\ S': P = -\dfrac{p_m\left(\rho - r\right)}{1-\rho} + \dfrac{2c}{\left(1-\rho\right)\sum_{i=1}^{i=n} q_i^2} Q,\ \left(P < p_z\right) \end{cases} \tag{32}$$

Thus far, three cases of p_z relative to the equilibrium price have been explored. According to Figure 4, when $p_z > P_0$, the supply curve can be expressed as S_1 and S_1'; when $p_z = P_0$, the supply curve can be expressed as S_2 and S_2'; and when $p_z < P_0$, the supply curve can be expressed as S_3 and S_3'. Furthermore, p_z is represented by p_{z1}, p_{z2}, and p_{z3}. Figure 4 also shows that the equilibrium state changes only when p_z is greater than the equilibrium price. At this point, demand curve D and supply curve S' intersect at E'. The equilibrium output is larger, and the equilibrium price is smaller compared with the original equilibrium. Therefore, when p_z is larger than the equilibrium price, the equilibrium price P_0' and the equilibrium output Q_0' can be obtained according to Equation (32) [Equations (33) and (34)]:

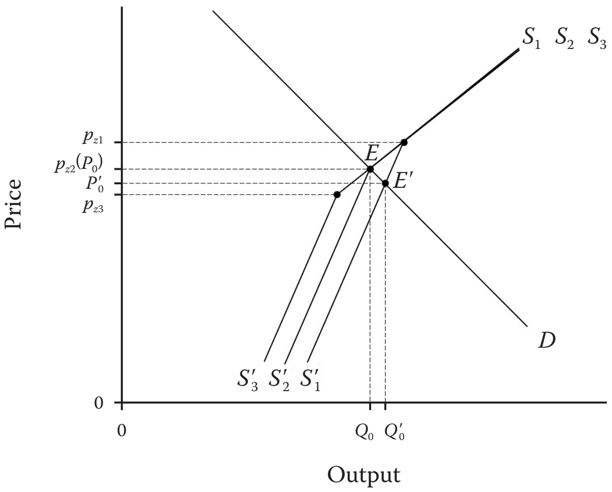

Figure 4. Equilibrium in the presence of agricultural price insurance

p_z – critical point; P_0, P_0' – equilibrium price; Q_0, Q_0' – equilibrium output; E, E' – equilibrium point; S, S' – supply elasticity; D – demand elasticity

Source: Authors' own calculations

$$P_0' = a_1 - b_1 \frac{a_1 + \dfrac{p_m\left(\rho - r\right)}{1-\rho}}{b_1 + \dfrac{2c}{\left(1-\rho\right)\sum_{i=1}^{i=n} q_i^2}} \tag{33}$$

$$Q_0' = \frac{a_1 + \dfrac{p_m\left(\rho - r\right)}{1-\rho}}{b_1 + \dfrac{2c}{\left(1-\rho\right)\sum_{i=1}^{i=n} q_i^2}} \tag{34}$$

A comparison of the values obtained from Equations (33) and (34) with the original equilibrium

$$P_0 = a_1 - b_1 \frac{a_1}{b_1 + \dfrac{2c}{\sum_{i=1}^{i=n} q_i^2}},\ Q_0 = \frac{a_1}{b_1 + \dfrac{2c}{\sum_{i=1}^{i=n} q_i^2}}$$

indicates the role of agricultural price insurance in increasing the equilibrium output and decreasing the equilibrium price. Therefore, the equilibrium state of agricultural product markets can be changed by adjusting the target price p_m, premium rate r, and guarantee level ρ.

Income of farmers. As the income of farmers is related to the equilibrium output and price, agricultural price insurance indirectly determines this income. The total income of farmers is composed of income from agricultural products and insurance compensation. The total income of farmers can be expressed as Equation (35):

$$w = PQ + \rho\left(p_m - P\right)Q \tag{35}$$

Taking the derivative of Q by w leads to Equation (36):

$$\frac{\partial w}{\partial Q} = -b_1 Q + \left(a_1 - b_1 Q\right) + \rho\left(p_m - P\right) \tag{36}$$

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When $\dfrac{\partial w}{\partial Q} = 0$

and the farmer's income reaches the maximum, the output and price can be expressed as Equations (37) and (38):

$$Q = \frac{a_1}{2b_1} + \frac{\rho\, p_m}{2\left(1-\rho\right)b_1} \tag{37}$$

$$P = \frac{a_1}{2} - \frac{\rho\, p_m}{2\left(1-\rho\right)} \tag{38}$$

When the equilibrium price is equal to the price at the maximum income of farmers, the solution obtained by Equations (33) and (38) can be substituted by Equation (39):

$$\frac{a_1 + \dfrac{p_m\left(\rho - r\right)}{1-\rho}}{b_1 + \dfrac{2c}{\left(1-\rho\right)\sum_{i=1}^{i=n} q_i^{\,2}}} + \frac{\rho\, p_m}{2\left(1-\rho\right)} - \frac{a_1}{2} = 0 \tag{39}$$

The condition of

$$\frac{\rho - r}{\rho} p_m \geq a_1 - b_1 \frac{a_1 - a_3}{b_1 + b_3}$$

must be considered to ensure that it can be adjusted with respect to agricultural price insurance.

CONCLUSION

This study explores the influence of agricultural price insurance on the agricultural product market via mathematical derivation. The following conclusions can be drawn from the main discussions: First, the supply elasticity of most agricultural products is greater than the demand elasticity, causing the agricultural product markets to be naturally divergent. Under the background of divergent agricultural product markets, agricultural production deviates from the equilibrium price and equilibrium output, which leads to huge fluctuations in the price and output. For China, this scenario negatively affects the goal of food security at the national level; for individual farmers, it brings huge risks to their production and income and reduces their enthusiasm to produce. Second, agricultural price insurance causes the slope of certain supply curves to be larger when the supply curve of agricultural products is changed. A decreasing supply elasticity of agricultural products is conducive to alleviating the fluctuations in the agricultural product market. Third, when Equation (31) is satisfied, agricultural price insurance can lead to the convergence of divergent agricultural product markets. In convergent agricultural markets, the price and output converge to the equilibrium state, positively affecting food security at the national level and the income stability of individual farmers. Fourth, the equilibrium state of the agricultural product markets and farmers' income both change when the insurance rate, guarantee level, and target price of agricultural price insurance are adjusted. Furthermore, adjusting these three factors to meet Equation (39) can lead to a maximisation of farmers' income.

The following insights can be drawn from the conclusions: First, agricultural insurance products must be continuously optimised. By increasing the protection depth of agricultural price insurance, the stabilising effect of agricultural price insurance on the price of agricultural products can be maximised. Second, the policy support of agricultural price insurance should be strengthened, the premium subsidy ratio of the Ministry of Finance for agricultural price insurance should be increased, and the insurance premium rate paid by farmers should be reduced (ESM, Appendix S3). Finally, on the basis of the difference between the supply elasticity and demand elasticity of agricultural products, differentiated price insurance for agricultural products must be introduced.

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