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

Jianru Fu, Ruiyuan Shen, Chao Huang*

School of Finance, Jiangxi Normal University, Jiangxi Province, Nanchang, China

**Corresponding author: sharaen@jxnu.edu.cn*

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Electronic supplementary material

Supplementary Appendices S1–S4

Appendix S1. Extensions

This study explores the impact of agricultural price insurance on the supply curve, convergence, equilibrium, and farmers' income under the premise that the supply elasticity is greater than the demand elasticity. Although most studies have shown that the supply elasticity of agricultural product markets is greater than the demand elasticity, certain high-quality agricultural product markets exist in which the demand elasticity is greater than the supply elasticity (i.e. a convergent agricultural product market). Thus, whether agricultural price insurance has a similar positive impact in convergent markets needs to be explored.

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In convergent markets, the three equations of the model are the demand curve $D: P = a_1 - b_1 Q$, supply curve $S: P = a_2 + b_2 Q\left(P \geq p_z\right)$, and $S': P = a_2' + b_2' Q \left(P < p_z\right)$. S' is the part of the supply curve that changed when agricultural price insurance was introduced. At this time:

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

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

In such a case (i.e. a convergent market), the difference is that the supply elasticity is less than the demand elasticity, and $b_1 < b_2$. No other assumptions leading to change are considered.

Convergence speed. Given that the supply elasticity is less than the demand elasticity in convergent markets, the price of agricultural products will gradually approach the equilibrium price when external shocks occur. Therefore, when agricultural price insurance makes the partial elasticity of the supply curve smaller, the supply in the agricultural market will be more stable. In particular, as the slope of part of the supply curve increases, the output and price will more quickly converge to the equilibrium point when subjected to external shocks. The speed of convergence can be measured by the distance between the price and the equilibrium price in different periods. The succeeding discussions compare the distance between the price and the equilibrium price in different periods before and after the introduction of agricultural price insurance.

By implementing the same analytic method as the divergent market, the relationship between the price of agricultural products in the current period and the price of agricultural products in the previous period before the introduction of agricultural price insurance can be obtained from Equation (9) as follows [Equation (S1)]:

$$P_{t+1} = a_1 - b_1 \frac{P_t}{\frac{2c}{\sum_{i=1}^{i=n} q_i^2}} \tag{S1}$$

According to Equations (25) and (27), the relationship between the current period's agricultural product price and the previous period's agricultural product price after the introduction of agricultural price insurance can be expressed as Equation (S2):

$$P_{t+1}' = \begin{cases} a_1 - b_1 \dfrac{P_t + \dfrac{p_m\left(\rho - r\right)}{1-\rho}}{\dfrac{2c}{\left(1-\rho\right)\sum_{i=1}^{i=n} q_i^2}}, & P_t < p_z \\ a_1 - b_1 \dfrac{P_t}{\dfrac{2c}{\sum_{i=1}^{i=n} q_i^2}}, & P_t \geq p_z \end{cases} \tag{S2}$$

A comparison of the price relationship before and after the introduction of agricultural price insurance indicates a changing price relationship when the price in the previous period is less than p_z. However, when the price in the previous period is greater than or equal to p_z, the price relationship is the same. Therefore, the change in distance between the current period price and the equilibrium price when the previous period price is less than p_z only needs to be compared. As changes occur in the equilibrium price after introducing agricultural price insurance, the convergence speeds at this time are difficult to compare. Consequently, the equilibrium price is assumed to be constant (P_0). When $P_t < p_z$, the scenarios before and after introducing the agricultural insurance price to the current price and the equilibrium price of the difference in the distance of d_3 can be expressed as follows [Equations (S3) and (S4)]:

$$d_3 = \left|P_{t+1} - P_0\right| - \left|P_{t+1}' - P_0\right| \tag{S3}$$

Combined with Equations (S2) and (S3), the following formula can be obtained:

$$d_3 = b_1 \frac{-\rho P_t + p_m\left(\rho - r\right)}{\frac{2c}{\sum_{i=1}^{i=n} q_i^2}} > 0 \tag{S4}$$

On this basis of Equation (S4), Equation (S3) can also be expressed as $|P_{t+1} - P_0| > |P_{t+1}' - P_0|$. This formulation implies that during price fluctuation, the price of agricultural products after introducing agricultural price insurance will move closer to the equilibrium price. Therefore, agricultural price insurance can further accelerate the convergence of agricultural markets.

Equilibrium. Similar to the case of diverging markets, a change in equilibrium requires the supply curve S_1 and the demand curve D to intersect at a new equilibrium point. Therefore, when changing the equilibrium state by adjusting the agricultural price insur-

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ance, it only needs to satisfy p_z being greater than the original equilibrium point price or

$$\frac{\rho - r}{\rho} p_m > a_1 - b_1 \frac{a_1}{b_1 + \frac{2c}{\sum_{i=1}^{i=n} q_i^2}}.$$

The equilibrium price is given by

$$P = a_1 - b_1 \frac{a_1 + \frac{p_m(\rho - r)}{1 - \rho}}{b_1 + \frac{2c}{(1 - \rho)\sum_{i=1}^{i=n} q_i^2}},$$

and the equilibrium output is given by

$$Q = \frac{a_1 + \frac{p_m(\rho - r)}{1 - \rho}}{b_1 + \frac{2c}{(1 - \rho)\sum_{i=1}^{i=n} q_i^2}}.$$

Income of farmers. Additionally, similar to the case of divergent markets, the equation can be constructed according to the coincidence of the equilibrium point and the maximum revenue point when the equilibrium point can be adjusted. Therefore, two conditions, namely

$$\frac{\rho - r}{\rho} p_m > a_1 - b_1 \frac{a_1}{b_1 + \frac{2c}{\sum_{i=1}^{i=n} q_i^2}} \text{ and}$$

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

enable the market to spontaneously converge to the maximum income point of farmers.

In summary, agricultural price insurance plays a role in stabilising the output of agricultural products and the income of farmers in convergent markets. In particular, implementing agricultural price insurance adjustment accelerates the convergence speed, updates the equilibrium state, and maximises the income of farmers. In addition, compared with the condition in which agricultural price insurance maximises farmers' income in divergent agricultural markets, agricultural price insurance can play its role more easily in convergent agricultural markets. In general, the introduction of agricultural price insurance can achieve the policy objectives of guaranteeing the income of farmers and stabilising the output and price of agricultural products, which is relevant in ensuring food security at the national level.

Appendix S2. Proof of convergence

p_z is greater than the equilibrium price. When p_z is larger than the equilibrium price, the price fluctuation under external shocks is partially similar to that when p_z is equal to the equilibrium price. According to the changing law of price fluctuation, the price will fluctuate up and down at the equilibrium point. When p_z is equal to the equilibrium price, the price will fluctuate up and down at p_z. In other words, the relationship between the quantity supplied and the price in the previous period changes continuously between Equations (20) and (21). Therefore, the relationship between the price in each period and the price in the previous period can be determined alternately according to Equations (25) and (26). However, as p_z is larger than the equilibrium price, when the price converges to less than p_z, the relationship between the supply quantity and the price of the last period will always be Equation (21). At this time, the relationship between the price of each period and the price of the previous period can be determined according to Equation (25). The solid line (first case) and the dashed line (second case) in Figure S1 distinguish these two cases. In the first case, similar to the case when the price fluctuates and p_z equals the equilibrium price, the supplied quantity is determined alternately by Equations (20) and (21). In this case, the relationship between the price in each period and the price in the previous period can be determined alternately by Equations (25) and (26). In the second case, the supplied quantity is determined by Equation (21). At this time, the relationship between the price of each period and the price of the previous period can be determined by Equation (25).

Additionally, assume that the agricultural market in period t is subjected to a positive shock. Therefore, the yield Q_t in period t is greater than the equilibrium yield Q_0. At this time, the supply will exceed the demand in the market. In this case, P_t is less than p_z. Then, the trend of the difference between the price and the equilibrium price in different periods can be used to judge the convergence conditions of agricultural product markets.

The first case is the same as the case when p_z is equal to the equilibrium price, as represented by periods t,

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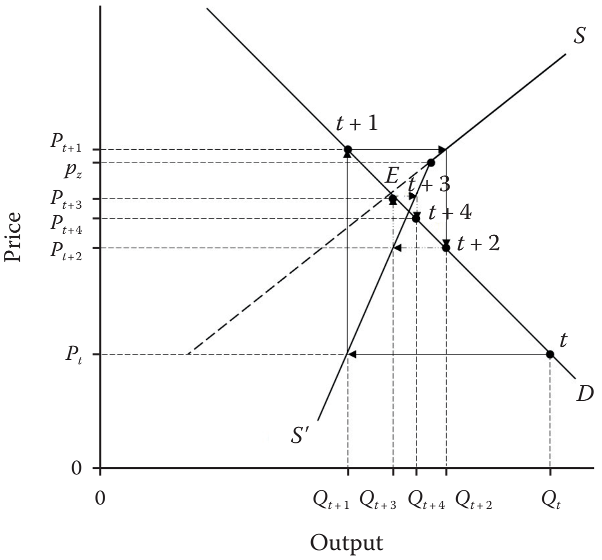

Figure S1. Proof of convergence of agricultural product markets (p_z is greater than P_0)

p_z – critical point; P_0 – equilibrium price; P_t – price in period t; Q_t – output in period t; E – equilibrium point; S, S' – supply elasticity; D – demand elasticity
Source: Authors' own calculations

$t + 1$, and $t + 2$ in Figure S1. The difference between the price and the equilibrium price is represented by d_1, d_2. According to Equation (31), when Equation (31) is met, the agricultural product market will converge. The second case is represented by periods $t + 2$, $t + 3$, and $t + 4$ in Figure S1. The difference between the price and the equilibrium price is represented by d_1. As mentioned previously, when Equation (31) is satisfied, d_1 is at least less than 0. This situation indicates a decreasing gap between the price and the equilibrium price, allowing the agricultural market to converge.

Therefore, when p_z is greater than the equilibrium price, the condition for convergence of the agricultural market can also be represented by Equation (31).

p_z is less than the equilibrium price. When p_z is smaller than the equilibrium price, the price fluctuation under external shocks is similar to that when p_z is greater than the equilibrium price. In the first case, the price fluctuation is the same as when p_z is equal to the equilibrium price. The supplied quantity is determined alternately by Equations (20) and (21). Therefore, the relationship between the price of each period and the price of the previous period can be determined alternately by Equations (25) and (27). The difference is that the supplied quantity in the second case is determined by Equation (20). Thus, the relationship between the price of each period and the price of the previous period can be determined by Equation (27).

Figure S2 presents an assumption in which the agricultural market in period t is also subjected to a positive shock (the solid line is for the first case, whereas the dashed line is for the second case). Therefore, the yield Q_t in period t is greater than the equilibrium yield Q_0. At this time, supply will exceed demand in the market. In this case, P_t is less than p_z. On this basis, the trend of the difference between the price and the equilibrium price in different periods can be used to judge the convergence conditions of agricultural product markets.

The first case is the same as when p_z equals the equilibrium price, as represented by periods t, $t + 1$, and $t + 2$ in Figure S2. The difference between the price and the equilibrium price is denoted by d_1, d_2. According to Equation (31), when Equation (31) is met, the agricultural product market will converge. The second case is represented by periods $t + x$, $t + x + 1$, and $t + x + 2$ in Figure S2. The difference between price and equilibrium price is denoted by d_2. According to Equations (S19) and (29), $d_2 > 0$. This situation implies a continuously widening gap between the price and the equilibrium price, causing the agricultural market to diverge. However, when the deviation of the agricultural product price from the equilibrium price further widens until the value is less than p_z, the

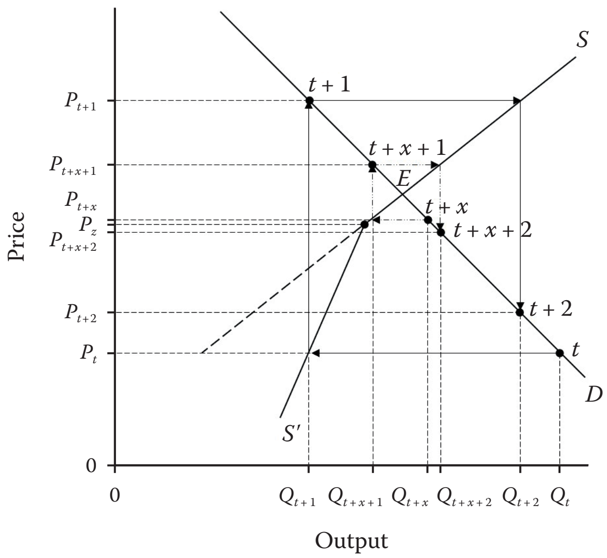

Figure S2. Proof of convergence of agricultural product markets (p_z is less than P_0)

p_z – critical point; P_0 – equilibrium price; P_t – price in period t; Q_t – output in period t; E – equilibrium point; S, S' – supply elasticity; D – demand elasticity
Source: Authors' own calculations

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convergence process of the first case will be repeated. Eventually, the agricultural market will continuously undergo the first and second cases, repeating the process of convergence and divergence. Although agricultural markets cannot converge, prices will always fluctuate around p_z.

Therefore, when Equation (31) is satisfied, although the agricultural market cannot converge, the uncertainty of the agricultural market will be reduced. Compared with the situation in the absence of agricultural price insurance, the agricultural price will continuously diverge. After introducing agricultural price insurance, the agricultural price will continue to fluctuate around p_z. Thus, p_z is similar to a new equilibrium point.

Appendix S3. Analysis

In Equation (31), the left side of the inequality is the variable, whilst the right side is the constant. When agricultural price insurance meets the aforementioned conditions, it can achieve the goal of turning the divergent agricultural product market into a convergent agricultural product market. At the same time, the agricultural product market becomes more stable. The role of agricultural price insurance in stabilising agricultural product markets can be further explored by analysing the left side of the inequality. Let the left side of the inequality be equal to Y such that [Equation (S5)]:

$$Y = \left(1 - \rho\right)P_t + p_m\left(\rho - r\right) \tag{S5}$$

By taking the partial derivative of Equation (S5), the following can be obtained [Equations (S6), (S7), and (S8)]:

$$\frac{\partial Y}{\partial \rho} = -P_t + p_m \tag{S6}$$

$$\frac{\partial Y}{\partial p_m} = \rho - r \tag{S7}$$

$$\frac{\partial Y}{\partial r} = -p_m \tag{S8}$$

Y is on the left side of the inequality. Thus, the larger the Y is, the better the situation when the conditions are met. On the basis of the results, adjusting the agricultural price insurance to stabilise the agricultural product market can be described as follows:

in $\frac{\partial Y}{\partial \rho}$, as $P_t > p_z$ and $p_z = \frac{\rho - r}{\rho}p_m, \frac{\partial Y}{\partial \rho} = p_m - P_t > 0$;

in $\frac{\partial Y}{\partial p_m}$, as $\rho > r$, $\frac{\partial Y}{\partial p_m} = \rho - r > 0$;

in $\frac{\partial Y}{\partial r}$, as $p_m > 0$, $\frac{\partial Y}{\partial r} = -p_m < 0$.

Therefore, ρ, p_m, and agricultural market convergence are positively correlated. Meanwhile, r and agricultural market convergence are negatively correlated. Therefore, the higher the security level and the target price are, the more stable the agricultural product market. Furthermore, the lower the insurance premium rate is, the more stable the agricultural product market. In real situations, when the security level and target price are high, farmers can approximate a stable income by participating in agricultural insurance. A small insurance rate indicates an extremely low price in exchange for stable income, which implies that farmers will likely choose to acquire agricultural insurance to exchange a small price for a large profit.

Appendix S4. Sets of proof

Proof of Equation (2). Take the derivative of x_i in Equation (1) as follows [Equation (S9)]:

$$\frac{d\pi}{dx_i} = P^e q_i - 2cx_i \tag{S9}$$

When $\frac{d\pi}{dx_i} = 0$,

the optimal solution for the planting area of farmer i under profit maximisation can be obtained. The planting area decision of farmer i can be expressed as follows [Equation (S10)]:

$$x_i = \frac{P^e q_i}{2c} \tag{S10}$$

The output of farmer i can be calculated according to Equation (S10). The total output in the market is the sum of the output of farmers, which is given by Equation (S11):

$$Q = \sum_{i=1}^{i=n} q_i x_i \tag{S11}$$

The total output can be obtained by combining Equations (S10) and (S11) as follows [Equation (S12)]:

$$Q = \frac{P^e}{2c}\sum_{i=1}^{i=n} {q_i}^2 \tag{S12}$$

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Then, the supply curve S of agricultural products can be obtained from Equation (S12) as follows [Equation (S13)]:

$$P = \frac{2c}{\sum_{i=1}^{i=n} q_i^2} Q \tag{S13}$$

Finally, the supply curve S can be drawn from

$a_2 = 0$ and $b_2 = \frac{2c}{\sum_{i=1}^{i=n} q_i^2}$.

Proof of Equation (11). Equilibrium price P_0 and equilibrium output Q_0 can be obtained based on the demand and supply curves as follows [Equation (S14)]:

$$\begin{cases} D: P = a_1 - b_1 Q \\ S: P = \frac{2c}{\sum_{i=1}^{i=n} q_i^2} Q \end{cases} \tag{S14}$$

The equilibrium price P_0 and equilibrium output Q_0 can be obtained as follows [Equations (S15) and (S16)]:

$$P_0 = a_1 - b_1 \frac{a_1}{b_1 + \frac{2c}{\sum_{i=1}^{i=n} q_i^2}} \tag{S15}$$

$$Q_0 = \frac{a_1}{b_1 + \frac{2c}{\sum_{i=1}^{i=n} q_i^2}} \tag{S16}$$

By combining Equations (4) and (5), the price distances from the equilibrium price in period t and period $t+1$ can be expressed as Equations (S17) and (S18):

$$P_t - P_0 = P_t - a_1 + b_1 \frac{a_1}{b_1 + \frac{2c}{\sum_{i=1}^{i=n} q_i^2}} \tag{S17}$$

$$P_{t+1} - P_0 = b_1 \frac{a_1}{b_1 + \frac{2c}{\sum_{i=1}^{i=n} q_i^2}} - b_1 \frac{P_t}{\frac{2c}{\sum_{i=1}^{i=n} q_i^2}} \tag{S18}$$

According to the assumption, $P_t - P_0 < 0$ and $P_{t+1} - P_0 > 0$ can be obtained from Equations (S15) and (S18). Then, the gap between the price and the equilibrium price can be obtained from Equations (10), (S17), and (S18) as follows [Equation (S19)]:

$$\left|P_{t+1} - P_0\right| - \left|P_t - P_0\right| = P_{t+1} + P_t - 2P_0 =$$
$$= a_1 + \left(1 - \frac{b_1}{\frac{2c}{\sum_{i=1}^{i=n} q_i^2}}\right) P_t - 2P_0 \tag{S19}$$

As $b_1 > \frac{2c}{\sum_{i=1}^{i=n} q_i^2}$, $1 - \frac{b_1}{\frac{2c}{\sum_{i=1}^{i=n} q_i^2}} < 0$.

According to $P_t < P_0$, Equations (S15) and (S19) can be combined to obtain $|P_{t+1} - P_0| - |P_t - P_0| > 0$.

Proof of Equation (17). Take the derivative of x_i in Equation (15) as follows [Equation (S20)]:

$$\frac{d\pi}{dx_i} = P^e q_i - 2cx_i \tag{S20}$$

When $\frac{d\pi}{dx_i} = 0$,

the optimal solution of farmer i's planting area under profit maximisation can be obtained. Farmer i's planting area decision can be expressed as Equation (S21):

$$x_i = \frac{P^e q_i}{2c} \tag{S21}$$

Take the derivative of x_i in Equation (16) as follows [Equation (S22)]:

$$\frac{d\pi}{dx_i} = P^e q_i - 2cx_i - rp_m q_i + \rho q_i \left(p_m - P^e\right) \tag{S22}$$

When $\frac{d\pi}{dx_i} = 0$,

the optimal solution of farmer i's planting area under profit maximisation can be obtained. Farmer i's planting area decision can be expressed as Equation (S23):

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$$x_i = \left[\frac{P^e}{2c} + \frac{p_m\left(\rho - r\right)}{2c} - \frac{\rho P^e}{2c}\right] q_i \tag{S23}$$

Proof of Equation (18). According to the planting area decision of farmer i, his or her output can be calculated as $q_i x_i$. The total output in the market represents the sum of the output of n farmers, which can be expressed as Equation (S24):

$$Q = \sum_{i=1}^{i=n} q_i x_i \tag{S24}$$

By combining Equations (17) and (S24), the total output can be obtained as follows [Equation (S25)]:

$$Q = \begin{cases} \dfrac{P}{2c} \sum_{i=1}^{i=n} {q_i}^2, \; P \geq p_z \\ \left[\dfrac{P}{2c} + \dfrac{p_m\left(\rho - r\right)}{2c} - \dfrac{\rho P}{2c}\right] \sum_{i=1}^{i=n} {q_i}^2, \; P < p_z \end{cases} \tag{S25}$$