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Impact of government subsidy on agricultural production and pollution: A game-theoretic approach

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A B S T R A C T

To deal with serious environmental problems in agriculture, governments around the world have formulated various subsidy policies. This study aims to investigate the effects of three subsidy schemes using game theory in an agricultural supply chain consisting of a low-cost firm and a high-cost firm. Meanwhile, the cost factor, market structure, product differentiation, and competition are all incorporated in the model as a novel contribution. The results show that neither the output quantity subsidy nor the environmental innovation subsidy alone can resolve the conflict between agricultural development and environmental protection. Furthermore, a hybrid subsidy scheme combining these two unilateral subsidies can reduce pollution emissions, increase output, improve firms' profits, and enhance consumer surplus, which is a truly effective and viable solution. The government who adopts the hybrid subsidy scheme should set a not too high subsidy rate to achieve maximal social welfare, which helps achieve a win-win-win situation for the government, consumers, and firms. Besides, market structure has no impact on the effectiveness of subsidy schemes.

1. Introduction

Food production is critical to meeting the food needs of the growing population. It is predicted that by 2030, global food demand will increase by 50% (Allaoui et al., 2018). However, along with the development of agriculture, serious agricultural pollution has also appeared (Lu et al., 2015). According to Vermeulen et al. (2012), emissions from food systems account for 19%–29% of global greenhouse gas emissions. Also, agricultural sector consumes and pollutes about 70% of the world's freshwater resources, exacerbating the global water shortage (Amiri, 2006). In addition, overuse of pesticides (Lake et al., 2012) and fertilizers (Li et al., 2018) as well as over-cultivation of land (Evans et al., 2019) have led to soil erosion (Zhang and Huang, 2015) and eutrophication (Zhang et al., 2019). Especially in developing countries, agricultural pollution is more serious (Emberson et al., 2001). For instance, fertilizer has been overused in China for decades (Liang et al., 2019). In 2006, the consumption of nitrogen fertilizer in China was 31 million tons, accounting for about 32% of global nitrogen fertilizer consumption (Huang et al., 2015). The excessive usage of fertilizers not only is detrimental to the sustainability of the ecosystem but also has a negative impact on the long-term socio-economic development (Singh et al., 2014). Therefore, how to deal with the relationship between food production and agricultural pollution has become a thorny issue for governments (Huang and Yang, 2017).

Many governments have formulated clear policies for sustainable agricultural development to meet the challenges of agricultural production and environmental protection (Chen et al., 2017). For example, the European Union (EU) countries have implemented the Common Agricultural Policy, in which "greening" is aimed at protecting and enhancing biodiversity and making food production more sustainable (Singh et al., 2014). Meanwhile, the subsidy policy has become a common and important incentive strategy for the sustainable development of agriculture (Garnett et al., 2013). For example, American government provided a per capita agricultural subsidy of $6,947 in 2002 (Kirwan, 2009), and the European governments offered agricultural subsidies exceeding 40% of their annual budgets (Schmedtmann and Campagnolo, 2015). The Indian government provides farmers with input subsidies, price subsidies, infrastructure subsidies, and export subsidies to support agricultural development (Fan et al., 2008). China's agricultural policy has undergone a fundamental transformation over the past 40 years (Lopez et al., 2017), and a series of agricultural subsidy policies have

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been introduced (Qian et al., 2015). These agricultural subsidy policies in China have been summarized in Table 1.

Although governments around the world have introduced a series of subsidies to encourage farmers to increase production and adopt sustainable production methods, the effects of various subsidy policies vary widely. Some subsidy policies ensure food security but worsen the environment. For example, South Asian countries heavily subsidize water and energy to ensure food self-sufficiency. These policies have increased food production but accelerated the degradation of critical natural resources (Alauddin and Quiggin, 2008). However, some subsidies are beneficial to the environment but cannot guarantee food production because these policies have led to changes in the patterns of agricultural production (Pingali, 2012). Therefore, understanding the effects of different subsidy policies on agricultural production and environmental pollution is crucial for sustainable agricultural development. But so far, few studies have been involved in comparing the effects of different agricultural subsidies on food production and environmental protection. Thus, to fill this research gap, we intend to address the following questions:

- What are the effects of different types of subsidies (output quantity subsidy, environmental innovation subsidy, output-innovation subsidy) on agricultural production, environmental innovation investment, and pollution emissions?
- What are the differences among the three different subsidy policies from the perspective of firms' profits, consumer surplus, and social welfare?
- Which subsidy scheme should the government adopt to deal with the relationship between agricultural development and environmental protection?
- What is the impact of cost differences between agribusinesses on production and investment? And will the market structure affect the effectiveness of subsidy schemes?

To shed light on these questions, we use the Stackelberg game method to consider an agricultural supply chain, in which a *low-cost* firm competes with a *high-cost* firm, and the government provides three subsidy schemes (output quantity subsidy, environmental innovation subsidy, and output-innovation subsidy) to promote food production and environmental protection. First, the equilibrium solutions, consumer surplus, and social welfare under the three agricultural subsidy schemes are obtained under different market structures. Then, the equilibrium results of the three subsidy schemes are compared, and the results show that neither the single output subsidy nor the single environmental innovation subsidy can solve the dilemma of food production and environmental protection. Only by adopting a hybrid subsidy (i.e., output-innovation subsidy) scheme can the government really solve the problem.

This study has the following three aspects of contributions. First, we incorporate cost factors, market structure, and product differentiation into an agricultural supply chain model with government subsidies, which has extended the research of Chen et al. (2017) and has addressed one of the four research gaps, namely, the neglected market forces identified by Tang and Zhou (2012). Second, our research results differ from previous research results. Previous research generally believed that high output would lead to high pollution. However, we find that although the output under the output-innovation subsidy scheme is higher than that under the output subsidy scheme, the pollution emission of the former is lower than that of the latter, mainly because the innovative subsidy component in the policy has played a role. Third, our research can provide valuable policy insights for government policymakers. Our research results show that the output-innovation subsidy scheme can improve firm profits, enhance consumer surplus, raise production and reduce pollution emissions, and maximize social welfare under the condition that the subsidy rate is not too high. Such output-innovation subsidies are a good choice if governments want to both increase production and control emissions.

The rest of this article is organized as follows. Section 2 reviews the relevant literature. Problem formulation and assumptions are introduced in Section 3. Section 4 carries out the model analysis and gives equilibrium results. The comparison and the main results are presented in Section 5. Section 6 provides managerial insights. Section 7 summarizes the research and proposes the future research direction. All proofs are given in Appendix A.

2. Literature review

This research is closely related to two research directions: *environmental impacts of agriculture* and *government subsidy policy*. Next, we review relevant literature and compare our work with these studies to highlight our contributions.

2.1. Environmental impacts of agriculture

Agricultural development has brought severe environmental pressures, threatening biodiversity (McLaughlin and Mineau, 1995), ecological sustainability (Van der Werf and Petit, 2002), and human health (Sazvar et al., 2018). The impact of agriculture on the environment has become a subject of academic concern (Allaoui et al., 2018). Most relevant research involved studying three main sources of agricultural pollution, namely water (Moss, 2008), soil

Table 1
The summary of agricultural subsidy policies in China.

Date	Subsidy policy	Specific measures
2002	Fine seed subsidy	2002–2010, a total of 70.56 billion yuan of improved seed subsidies were arranged
2004	Grain direct subsidy	2004–2010, a total of 99.4 billion yuan of grain direct subsidies were arranged
2004	Farm-machinery subsidy	2004–2010, a total of 35.46 billion yuan of agricultural machinery purchase subsidies were arranged
2006	Comprehensive subsidy	2006–2010, a total of 254.4 billion yuan was allocated for comprehensive agricultural subsidies
2011	Ecological compensation policy	Comprehensive implementation of grassland ecological protection reward mechanism in eight provinces
2015	Support protection subsidy	The central government merged the comprehensive subsidy for agricultural materials, grain direct subsidy, and improved seed subsidy into 'agricultural support and protection subsidy'
2016	Green and ecologically subsidy	The central government promulgated the "Reform plan for establishing a green-ecology-oriented agricultural subsidy system"
2019	High-standard farmland funds	The central government allocated about 85.9 billion yuan in high-standard farmland construction funds in 2019, including 69.4 billion yuan in subsidies for farmland construction
2019	Farmland protection subsidy	The central government allocated about 120.485 billion yuan in subsidies for farmland protection to support the development of green and ecological agriculture in 2019

Source: official websites of the Ministry of Finance and the Ministry of Agriculture of China.

(Cobuloglu and Büyüktahtakın, 2017), and greenhouse gas pollution (Qiao et al., 2019). For example, Moss (2008) discussed the problem of water pollution in agriculture, and pointed out that agriculture has greatly destroyed the freshwater system from its primitive state, and the pesticides, nitrogen fertilizers and organic agricultural wastes in agriculture have profoundly changed the nature of water areas. Cobuloglu and Büyüktahtakın (2017) constructed a two-stage stochastic mixed integer programming model to maximize the economic and environmental benefits of food and biofuel production, taking into account environmental impacts such as greenhouse gas emissions, soil erosion, and nitrogen leakage to water. Qiao et al. (2019) examined the greenhouse effect of the agriculture-growth-renewable energy relationship in the Group of Twenty (G20) and showed that agriculture contributes to the carbon dioxide emissions of the G20 and its developing economies. These studies have highlighted the negative impacts of agriculture on the environment, but few studies have considered how to address these adverse impacts.

Moreover, a number of studies have specifically focused on the environmental impact of agriculture in specific countries. For instance, Skinner et al. (1997) provided an overview relating to the environmental impact of British agriculture in terms of pesticides, nitrogen compounds, and soil erosion. Tasca et al. (2017) used life cycle assessment to compare the potential environmental impacts of organic and integrated farming methods of endive in Lombardia (northern Italy), and revealed that neither of the two farming techniques has a better overall environmental profile. Despite these studies contribute to our understanding of the relationship between agricultural development and the environment, they are limited to specific countries and regions, lack a generalized perspective to analyze the environmental impacts of agricultural production, and do not consider the regulatory policy tools provided at the national level. To fill these research gaps, our study investigates the impact of agricultural production on pollution emissions, and provides a reasonable and effective solution to agricultural environmental problems from the perspective of government taxation and subsidies.

2.2. Government subsidy policy

There has developed an abundant stream of literature researching government subsidy schemes in various contexts (Alizamir et al., 2019). A summary of some papers on government subsidy policies are presented in Table 2. These papers are based on standards such as government policies, product substitution, market structure, pollution emissions, environmental investment, and game theory. By examining the table, the research gaps can be clearly identified.

Governments have promulgated many subsidy policies to develop sustainable agriculture. Therefore, many researchers focus on subsidy policies in the context of agriculture, especially the impact of agricultural subsidy policies on production. For example, Xu and Pu (2014) built a risk insurance model to examine the impact of crop insurance subsidies on agricultural output, and pointed out that premium subsidies can continuously increase agricultural production. Yu and Sumner (2018) focused on the effect of subsidized crop insurance on crop selection and found that the influence of insurance subsidy on high-risk crop investment is greater than that of input subsidy when farmers have a high degree of risk aversion and high cost of self-insurance. Alizamir et al. (2019) discussed the impact of two subsidy programs provided by the American government to farmers, namely, Price Loss Coverage (PLC) and Agricultural Risk Coverage (ARC), on farmers' production decisions. They suggested that compared with no subsidy, PLC always encourages farmers to plant more acres, and under ARC, farmers' planting area may be reduced, resulting in a decrease in crop supply. In the context of uncertain output, Peng and Pang (2019) considered a three-level contract agricultural supply chain to analyze the impact of government subsidies on the production decisions of risk-averse farmers. They emphasized that with the increase of subsidies, the overall target output of farmers would also increase, and that subsidies had a positive impact on farmers with high risk aversion. Solaymani et al. (2019) examined the short-term effects of two input removal subsidies and one expansion subsidy, and concluded that the removal subsidies without the rice subsidies could increase rice production and food supply, resulting in a smaller increase in poverty compared to the complete removal policy. However, none of these studies have considered the role of cost factors and market structure factors in the impact of government subsidy schemes on agricultural production.

In addition, a few studies have looked at agricultural subsidy policies in terms of environmental impact. For instance, Chen et al. (2017) captured the impacts of two agricultural subsidy schemes (quantity subsidy and emission-reducing innovation subsidy) on agricultural pollution. They indicated that the innovation subsidy is better than the quantity subsidy because it could reduce agricultural pollution and improve output quantity. This study is most relevant to our study, however, our conclusions are different. Our

Table 2
Review of existing and current research.

Authors	Policy		Factor		Decision			Game theory
	Subsidy	Tax	PS	MS	PE	PQ	EI	
Taheripour et al. (2008)	✓	✓	✓		✓	✓		
Xu and Pu (2014)	✓					✓		
Chen et al. (2015)	✓		✓			✓		
Chen et al. (2017)	✓	✓			✓	✓	✓	✓
Slabe-Erker et al. (2017)	✓				✓			
Yu and Sumner (2018)	✓					✓		
Alizamir et al. (2019)	✓		✓			✓		✓
Liang et al. (2019)	✓				✓			
Peng and Pang (2019)	✓					✓		✓
Safarzadeh and Rasti-Barzoki (2019a)	✓	✓		✓		✓	✓	✓
Safarzadeh and Rasti-Barzoki (2019b)	✓	✓	✓			✓	✓	✓
Solaymani et al. (2019)	✓		✓			✓		
Safarzadeh and Rasti-Barzoki (2020)	✓	✓	✓			✓	✓	✓
Safarzadeh et al. (2020b)	✓	✓	✓	✓			✓	✓
Our research	✓	✓	✓	✓	✓	✓	✓	✓

Note: PS is product substitution, MS is market structure, PE is pollution emissions, PQ is production quantity, and EI is environmental investment.

study finds that neither environmental innovation subsidy alone nor production subsidy alone can solve the dilemma of both increasing production and protecting the environment, and only the hybrid subsidy scheme is truly effective. The reason for this difference is that we have considered competition, cost difference, and market structure factors, which they did not take into account. Using life cycle assessment (LCA), Liang et al. (2019) assessed the environmental impact of the winter wheat-summer maize rotation system under government subsidies, and proposed that production and welfare-oriented agricultural subsidies could bring environmental benefits. Our work differs from these papers in that we not only explore the impact of agricultural subsidy policies on production but also analyze the impact of agricultural subsidy policies on pollution emissions and innovation investment. We also focus on the comparative analysis of three subsidy schemes from the perspectives of consumer surplus, corporate profits, and social welfare. More importantly, we have integrated competition, market structure, and cost factors into an agricultural supply chain with government subsidies.

Government subsidy mechanisms also have been studied in the energy context. For example, Safarzadeh and Rasti-Barzoki (2019a) discussed residential energy efficiency plans and related energy consumption of new energy-efficient appliances by using the Bertrand model, and found that the manufacturer subsidy performs best in energy efficiency plans. Safarzadeh and Rasti-Barzoki (2019b) investigated subsidy scheme by establishing an extended utility function of household energy consumers, and concluded that subsidy policy provides better conditions for controlling the energy consumption in the household sector through energy price reform. Safarzadeh et al. (2020a) presented state-of-the-art work in the energy field from the perspective of optimal energy policy instruments. Safarzadeh et al. (2020b) addressed a new pricing model for new energy-efficient products under a tax-subsidy system, and suggested that energy policies applied on producers are more effective in improving energy conservation than consumer-side energy policies. Safarzadeh and Rasti-Barzoki (2020) investigated some direct, indirect, and combined energy intervention policies in energy-efficiency programs, and concluded that the combined intervention is more effective than the unilateral policies in reducing energy intensiveness. These studies have conducted an in-depth study of government subsidy programs and provided valuable references for our research. However, our research field differs from theirs. We focus on three specific subsidy schemes in the context of agriculture in which two agricultural firms with different production costs compete for market share, and then make production and innovation investment decisions according to different subsidy schemes offered by the government.

3. Problem formulation and assumptions

This paper considers a three-stage Stackelberg game model where a *low-cost* firm competes with a *high-cost* firm in the agricultural market, producing the same product but at different levels. To promote the sustainable development of the agriculture and protect the environment, the government provides three kinds of subsidy schemes (output quantity subsidy, environmental innovation subsidy, and output-innovation subsidy) to these two agricultural firms. After receiving government subsidies, two firms decide whether to invest in environmental innovation under two different market structures (i.e., the *low-cost* or the *high-cost* firm dominates), as shown in Fig. 1.

The following assumptions are made to establish the models, and the relevant parameters and decision variables are summarized in Table 3.

Assumption 1. The *low-cost* agricultural firm produces low-grade products (e.g., second-grade rice) at a lower production cost c_1, while the *high-cost* agricultural firm produces high-grade products (e.g., first-grade rice) at a higher production cost c_2. It is assumed that $c_1 < c_2$. These products can substitute for each other in the market, and λ denotes product substitution coefficient (Roberts and Schlenker, 2013).

Assumption 2. Both agricultural products produce by-products, that is pollution emissions, e_1 and e_2, similar to Nie (2012). It is assumed that pollution emissions increase in production (q_i) while decrease in innovation investment (I_i). The pollution emission function is: $e_i = \alpha(q_i - I_i)$, where α is the marginal emission rate. To avoid triviality, we assume that the innovation investment is less than the output quantity, that is, $0 \le I_i \le q_i$.

Assumption 3. Consumers have environmental consciousness (Ciardiello et al., 2019), and they are willing to buy organic agricultural products with low environmental pollution and zero residue (Cicia et al., 2002). The sensitivity of consumers to pollution emissions is denoted as γ (Chen et al., 2017). The higher the value, the more sensitive consumers are to pollution emissions.

Assumption 4. Similar to Chow (2011) and Nie (2012), the linear inverse demand function is: $p_i = M - \gamma e_i - q_i - \lambda q_j, i,j \in \{1,2\}, i \ne j$. The agricultural price (p_i) is negatively correlated to its own output(q_i), pollution emissions(e_i), and the output of its competitor(q_j). M is a constant, representing the maximum tolerable pollution emissions.

Assumption 5. The output quantity subsidy (QS) aims to increase production and ensure food supplies, while the environmental innovation subsidy (ES) aims to encourage firms to invest in environmental innovation and to take more environmentally friendly production processes. The output-innovation subsidy (BS) is a combination of the two previous subsidy schemes, providing both output subsidy and innovation subsidy. For simplicity, we assume that these three subsidy schemes have the same marginal subsidy rate s, similar to Chen et al. (2017). Meanwhile, the government levies a tax rate of τ on pollution emissions.

Assumption 6. Agricultural firms will decide whether to invest in environmental innovation activities after receiving subsidies. When the government provides output subsidies, agricultural firms are reluctant to invest in environmental innovation ($I_i = 0$) because of its high cost. Thus, the profit function is: $\pi_i = p_i q_i - c_i q_i^2 - \tau e_i + s q_i$. When the government provides environmental innovation subsidies, firms will invest in environmental innovation ($I_i > 0$). Thus, the profit function is: $\pi_i = p_i q_i - c_i q_i^2 - c_i' I_i^2 - \tau e_i + s I_i$. Moreover, the environmental innovation cost is higher than the production cost (i.e., $c_1' > c_1$ and $c_2' > c_2$).

4. Equilibrium analysis

In this section, we examine the effects of three subsidies (output quantity subsidy, environmental innovation subsidy, and output-innovation subsidy) on agricultural production, innovation investment and pollution emissions. The subscripts 1 and 2 represent the *low-cost* and *high-cost* firm, respectively. For ease of expression, we define system XY in the superscript where $X \in \{Q, E, B\}$ represents whether the government provides a Quantity subsidy, an Environmental innovation subsidy, or an Output-innovation subsidy (Both-types subsidy), and $Y \in \{H, L\}$ denotes whether the *High-cost* firm or the *Low-cost* firm is a leader in the agricultural market. To illustrate, the system QH represents the situation that the government provides output quantity subsidies in a market dominated by the *high-cost* firm.

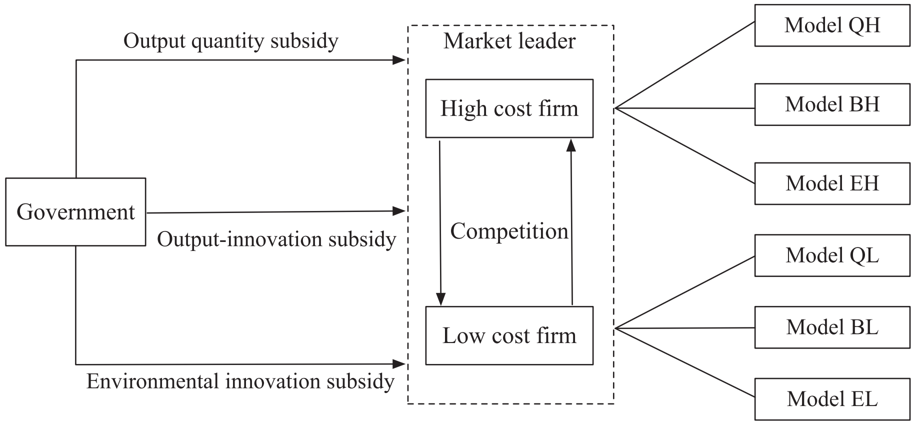


Fig. 1. Framework of the agricultural supply chain.

Table 3
Summary of notations.

Variables	Description
q_i	Production quantity, $i \in \{1, 2\}$
e_i	Pollution emission
I_i	Environmental innovation investment
Parameters	**Description**
λ	Degree of product substitution, $0 \le \lambda \le 1$
α	Marginal pollution emission rate, $0 \le \alpha \le 1$
γ	Sensitivity of consumers to pollution emissions, $0 \le \gamma \le 1$
s	Marginal subsidy rate, $0 \le s \le 1$
τ	Marginal tax rate, $0 \le \tau \le 1$
c_i	Production cost of firm i, $c_i \ge 0$
c_i'	Innovation cost of firm i, $c_i' \ge 0$
π_i	Profit of firm i
M	Maximum tolerable amount of emissions, $M > 0$
CS	Consumer surplus
PS	Producer surplus
GB	Government budget
SW	Social welfare

4.1. Case 1: output quantity subsidy

We consider the impact of output quantity subsidies on agricultural production and pollution emissions in the market dominated by the high- or low-cost firm.

4.1.1. Case 1.1: the high-cost firm is a leader (QH)

In this scenario, the *high-cost* agribusiness is the Stackelberg leader, while the *low-cost* agribusiness is the follower. The government first declares subsidy schemes. Given this subsidy scheme, the *high-cost* agribusiness determines production. Finally, the *low-cost* agricultural firm decides on production. The game sequence is summarized in Fig. 2.

To simplify the expression of the analytical results, the production cost is first assigned. According to Chen et al. (2015) and Chen and Nie (2016), we assume that $c_1 = 1/2$ and $c_2 = 1$. Thus, the profit functions can be rewritten as follows:

$$\max \pi_1^{QH}\left(q_1^{QH}\right) = \left(M - \gamma e_1^{QH} - q_1^{QH} - \lambda q_2^{QH}\right) q_1^{QH} - \frac{1}{2} q_1^{QH^2} - \tau e_1^{QH} + s q_1^{QH}, \tag{1}$$

$$\max \pi_2^{QH}\left(q_2^{QH}\right) = \left(M - \gamma e_2^{QH} - q_2^{QH} - \lambda q_1^{QH}\right) q_2^{QH} - q_2^{QH^2} - \tau e_2^{QH} + s q_2^{QH}. \tag{2}$$

In Eqs. (1) and (2), $e_1^{QH} = \alpha q_1^{QH}$ and $e_2^{QH} = \alpha q_2^{QH}$.

Proposition 1. *Under the output quantity subsidy, if the market is dominated by the high-cost firm, agricultural production and pollution emissions are*

$$q^{QH} = \left\{q_1^{QH}, q_2^{QH}\right\} = \left\{\frac{(\lambda^2 - 2A_1\lambda + \lambda + 2A_3)A_2}{2(2A_1 - 1)A_3}, \frac{(2A_1 - 1 - \lambda)A_2}{2A_3}\right\},$$

$$e^{QH} = \left\{e_1^{QH}, e_2^{QH}\right\} = \left\{\frac{\alpha(\lambda^2 - 2A_1\lambda + \lambda + 2A_3)A_2}{2(2A_1 - 1)A_3}, \frac{\alpha(2A_1 - 1 - \lambda)A_2}{2A_3}\right\}.$$

Note that $A_1 = \alpha\gamma + 2$, $A_2 = M + s - \alpha\tau$, *and* $A_3 = 6 + \alpha\gamma(7 + 2\alpha\gamma) - \lambda^2$.

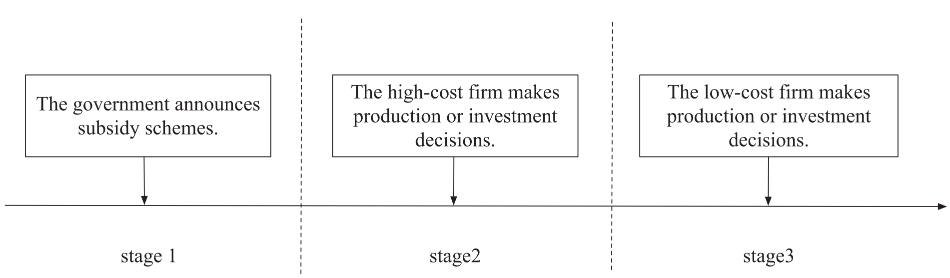


Fig. 2. Sequence of events when the *high-cost* firm is a leader.

4.1.2. Case 1.2: the low-cost firm is a leader (QL)

In this scenario, the *low-cost* agribusiness is a leader, while the *high-cost* firm is a follower. The government first declares subsidy schemes and then the *low-cost* agricultural firm decides on production. Finally, the *high-cost* firm makes production decisions. The game sequence is shown in Fig. 3.

Proposition 2. *Under the output quantity subsidy, if the market is dominated by the low-cost firm, agricultural production and pollution emissions are*

$$q^{QL}=\left\{q_1^{QL},q_2^{QL}\right\}=\left\{\frac{(2A_1-\lambda)A_2}{2A_3},\frac{(\lambda^2-2A_1\lambda+2A_3)A_2}{4A_1A_3}\right\},$$

$$e^{QL}=\left\{e_1^{QL},e_2^{QL}\right\}=\left\{\frac{\alpha(2A_1-\lambda)A_2}{2A_3},\frac{\alpha(\lambda^2-2A_1\lambda+2A_3)A_2}{4A_1A_3}\right\}.$$

4.2. Case 2: environmental innovation subsidy

Under this subsidy scheme, agricultural firms invest in environmental innovation. We also consider the impact of the subsidy on agricultural production, pollution emissions, and environmental innovation investment in the market dominated by the high- or low-cost firm.

4.2.1. Case 2.1: the high-cost firm is the leader (EH)

First, we analyze the situation where the *high-cost* firm dominates the market. The game sequence is the same as that of Case 1.1.

For simplification, we assume that $c_1' = 3/2$ and $c_2' = 2$, which is similar to Chen et al. (2015) and Chen and Nie (2016). The profit functions can be rewritten as:

$$\max\pi_1^{EH}\left(q_1^{EH},I_1^{EH}\right)=\left(M-\gamma e_1^{EH}-q_1^{EH}-\lambda q_2^{EH}\right)q_1^{EH}-\frac{1}{2}q_1^{EH^2}-\frac{3}{2}I_1^{EH^2}-\tau e_1^{EH}+sI_1^{EH}, \tag{3}$$

$$\max\pi_2^{EH}\left(q_2^{EH},I_2^{EH}\right)=\left(M-\gamma e_2^{EH}-q_2^{EH}-\lambda q_1^{EH}\right)q_2^{EH}-q_2^{EH^2}-2I_2^{EH^2}-\tau e_2^{EH}+sI_2^{EH}. \tag{4}$$

In Eqs. (3) and (4), $e_1^{EH}=\alpha(q_1^{EH}-I_1^{EH})$ and $e_2^{EH}=\alpha(q_2^{EH}-I_2^{EH})$.

Proposition 3. *Under the environmental innovation subsidy, if the market is dominated by the high-cost firm, agricultural production, innovation investment, and pollution emissions are*

$$q^{EH}=\left\{q_1^{EH},q_2^{EH}\right\}=\left\{\frac{D_1D_4-3\lambda D_2}{D_1D_5},\frac{D_2}{D_1}\right\},$$

$$I^{EH}=\left\{I_1^{EH},I_2^{EH}\right\}=\left\{\frac{D_1D_6-\alpha\gamma\lambda D_2}{D_1D_5},\frac{D_3}{D_1}\right\},$$

$$e^{EH}=\left\{e_1^{EH},e_2^{EH}\right\}=\left\{\frac{\alpha(D_4-D_6)D_1-\alpha\lambda(3-\alpha\gamma)D_2}{D_1D_5},\frac{\alpha(D_2-D_3)}{D_1}\right\}.$$

Note that $D_1=\alpha\gamma(168+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma)))+24(6-\lambda^2)$, $D_2=4M(9+\alpha\gamma(6-\alpha\gamma)-3\lambda)-\alpha\gamma)+4\lambda))$, $D_3=M\alpha\gamma(9+\alpha\gamma(6-\alpha\gamma)-3\lambda)+s(36+2\alpha\gamma(7-\alpha\gamma)(3+\alpha\gamma)-\alpha^2\gamma^2\lambda-6\lambda^2)$, $D_4=3M+s\alpha\gamma-3\alpha\tau+\alpha^2\gamma\tau$, $D_5=9+\alpha\gamma(6-\alpha\gamma)$, and $D_6=s(3+2\alpha\gamma)+\alpha(M\gamma+3\tau+\alpha\gamma\tau)$.

4.2.2. Case 2.2: the low-cost firm is the leader (EL)

In this scenario, the market is dominated by the *low-cost* agricultural firm. The game sequence is the same as that of Case 1.2.

Proposition 4. *Under the environmental innovation subsidy, if the market is dominated by the low-cost firm, agricultural production, innovation investment, and pollution emissions are*

$$q^{EL}=\left\{q_1^{EL},q_2^{EL}\right\}=\left\{\frac{K_1}{D_1},\frac{D_1K_3-4\lambda K_1}{D_1K_4}\right\},$$

$$I^{EL}=\left\{I_1^{EL},I_2^{EL}\right\}=\left\{\frac{K_2}{D_1},\frac{D_1K_5-\alpha\gamma\lambda K_1}{D_1K_4}\right\},$$

$$e^{EL}=\left\{e_1^{EL},e_2^{EL}\right\}=\left\{\frac{\alpha(K_1-K_2)}{D_1},\frac{\alpha(K_3-K_5)D_1-\alpha\lambda(4-\alpha\gamma)K_1}{D_1K_4}\right\}.$$

Note that $K_1=3M(16+\alpha\gamma(8-\alpha\gamma)-4\lambda)+s\alpha\gamma(16+\alpha\gamma(8-\alpha\gamma)-3\lambda)-\alpha\tau(48+\alpha\gamma(8-\alpha\gamma(11-\alpha\gamma)+3\lambda)-12\lambda)$, $K_2=M\alpha\gamma(16+\alpha\gamma(8-\alpha\gamma)-4\lambda)+s(48+56\alpha\gamma-2\alpha^3\gamma^3+\alpha^2\gamma^2(13-\lambda)-8\lambda^2)+\alpha\tau(48+\alpha\gamma(40+\alpha\gamma(5--\alpha\gamma))+\alpha\gamma(4-\alpha\gamma)\lambda-8\lambda^2)$, $K_3=4M+s\alpha\gamma-4\alpha\tau+\alpha^2\gamma\tau$, $K_4=16+\alpha\gamma(8-\alpha\gamma)$, and $K_5=4s+M\alpha\gamma+2s\alpha\gamma+4\alpha\tau+\alpha^2\gamma\tau$.

4.3. Case 3: output-innovation subsidy

The output-innovation subsidy is the combination of output quantity subsidy scheme and environmental innovation subsidy scheme. Under this subsidy scheme, agricultural firms also invest in environmental innovation.

4.3.1. Case 3.1: the high-cost firm is the leader (BH)

In this scenario, the *high-cost* firm is the Stackelberg leader, while the *low-cost* firm is the follower. The game sequence is the

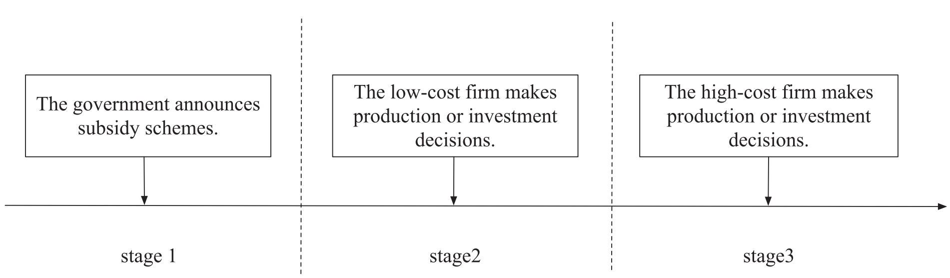


Fig. 3. Sequence of events when the *low-cost* firm is a leader.

same as that of Case 1.1.

The profit functions under the output-innovation subsidy are:

$$\max\pi_1^{BH}\left(q_1^{BH},I_1^{BH}\right)=\left(M-\gamma e_1^{BH}-q_1^{BH}-\lambda q_2^{BH}\right)q_1^{BH}-\frac{1}{2}q_1^{BH^2}-\frac{3}{2}I_1^{BH^2}-\tau e_1^{BH}+s\left(I_1^{BH}+q_1^{BH}\right),\tag{5}$$

$$\max\pi_2^{BH}\left(q_2^{BH},I_2^{BH}\right)=\left(M-\gamma e_2^{BH}-q_2^{BH}-\lambda q_1^{BH}\right)q_2^{BH}-q_2^{BH^2}-2I_2^{BH^2}-\tau e_2^{BH}+s\left(I_2^{BH}+q_2^{BH}\right).\tag{6}$$

In Eqs. (5) and (6), $e_1^{BH}=\alpha(q_1^{BH}-I_1^{BH})$and $e_2^{BH}=\alpha(q_2^{BH}-I_2^{BH})$.

Proposition 5. *Under the output-innovation subsidy, if the market is dominated by the high-cost firm, agricultural production, innovation investment, and pollution emissions are*

$$q^{BH}=\left\{q_1^{BH},q_2^{BH}\right\}=\left\{\frac{D_1D_4+3sD_1-3\lambda L_1}{D_1D_5},\frac{L_1}{D_1}\right\},$$

$$I^{BH}=\left\{I_1^{BH},I_2^{BH}\right\}=\left\{\frac{s\alpha\gamma D_1+D_1D_6-\alpha\gamma\lambda L_1}{D_1D_5},\frac{L_2}{D_1}\right\},$$

$$e^{BH}=\left\{e_1^{BH},e_2^{BH}\right\}=\left\{\frac{\alpha((D_4-D_6)D_1+(sD_1-\lambda L_1)(3-\alpha\gamma))}{D_1D_5},\frac{\alpha(L_1-L_2)}{D_1}\right\}.$$

Note that $L_1=4M(9+\alpha\gamma(6-\alpha\gamma)-3\lambda)+s(\alpha\gamma(33+\alpha\gamma(2-\alpha\gamma)-4\lambda))+12(3-\lambda)$ *and* $L_2=M\alpha\gamma(9+\alpha\gamma(6-\alpha\gamma)-3\lambda)+s(36+\alpha\gamma(51+\alpha\gamma(14-3\alpha\gamma))-$ $-\alpha\gamma(3+\alpha\gamma)\lambda-6\lambda^2)+\alpha\tau(36+\alpha\gamma(33+\alpha\gamma(2-\alpha\gamma))+\alpha\gamma(3-\alpha\gamma)\lambda-6\lambda^2)$.

4.3.2. Case 3.2: the low-cost firm is the leader (BL)

In this scenario, the *low-cost* firm is the Stackelberg leader, while the *high-cost* firm is the follower. The game sequence is the same as that of Case 1.2.

Proposition 6. *Under the output-innovation subsidy, if the market is dominated by the low-cost firm, agricultural production, innovation investment, and pollution emissions are*

$$q^{BL}=\left\{q_1^{BL},q_2^{BL}\right\}=\left\{\frac{F_1}{D_1},\frac{4sD_1+D_1K_3-4\lambda F_1}{D_1K_4}\right\},$$

$$I^{BL}=\left\{I_1^{BL},I_2^{BL}\right\}=\left\{\frac{F_2}{D_1},\frac{D_1K_5+s\alpha\gamma D_1-\alpha\gamma\lambda F_1}{D_1K_4}\right\},$$

$$e^{BL}=\left\{e_1^{BL},e_2^{BL}\right\}=\left\{\frac{\alpha(F_1-F_2)}{D_1},\frac{\alpha((sD_1-\lambda F_1)(4-\alpha\gamma)+(K_3-K_5)D_1)}{D_1K_4}\right\}.$$

Note that $F_1=3M(16+\alpha\gamma(8-\alpha\gamma)-4\lambda))\quad 12(4-\lambda)(s-\alpha\tau)-\alpha^2\gamma(8-\alpha\gamma(11-\alpha\gamma)+3\lambda)\tau$ *and* $F_2=M\alpha\gamma(16+\alpha\gamma(8-\alpha\gamma)-4\lambda))\alpha\gamma(5-\alpha\gamma))+\alpha\gamma(4-\alpha\gamma)\lambda-8\lambda^2)$.

5. Comparative analysis

This section analyzes the effectiveness of each subsidy scheme to provide management insights for the sustainable development of agriculture. The agricultural output, pollution emissions, innovation investment, profits, consumer surplus, and social welfare under the three subsidy schemes are compared, respectively.

5.1. Comparison of agricultural production

To determine which subsidy scheme is more conducive to encouraging agricultural firms to increase production, agricultural output under the three subsidy schemes in two market structures are compared.

Proposition 7. *The relationship between agricultural output under the three subsidy schemes is as follows*:

(i) $q_1^{BH}>q_1^{QH}>q_1^{EH}>q_2^{BH}>q_2^{QH}>q_2^{EH}$;
(ii) $q_1^{BL}>q_1^{QL}>q_1^{EL}>q_2^{BL}>q_2^{QL}>q_2^{EL}$.

Proposition 7 shows that regardless of the market structures (i.e., dominated by the *high-cost* or *low-cost* firm), the agricultural output under the BS scheme is the highest, followed by the QS scheme, and the lowest output is achieved under the ES scheme, as shown in Fig. 4. These results are reasonable and predictable because different subsidy schemes have different development goals. The QS scheme, which is closely related to the output, aims to increase production of agricultural products to ensure adequate food supplies. However, the ES scheme aims to encourage agricultural firms to strengthen the innovation of agricultural technology and to reduce environmental pollution.

Surprisingly, the output under the BS scheme is the highest among the three subsidy schemes, suggesting that this combination of output and environmental innovation has an advantage in increasing output. Therefore, if governments are aiming to increase production, the best scheme is the BS scheme, followed by the QS scheme, and the ES scheme does little to increase production. This is also consistent with the fact that, in most developing countries, governments provide production-related subsidy schemes to ensure food supplies.

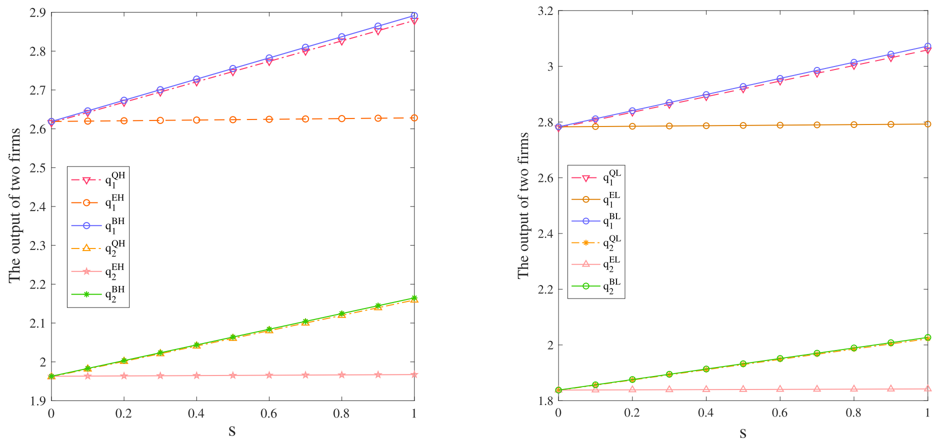
Corollary 1. $q_1^{BH}>q_2^{BH}$, $q_1^{BL}>q_2^{BL}$, $q_1^{QH}>q_2^{QH}$, $q_1^{QL}>q_2^{QL}$, $q_1^{EH}>q_2^{EH}$, *and* $q_1^{EL}>q_2^{EL}$. *The output of the low-cost firm is always higher than that of the high-cost firm under any subsidy scheme.*

Corollary 1 shows that the output of the *low-cost* firm is greater than that of the *high-cost* firm under any subsidy scheme, indicating that cost advantages can drive firms to produce more agricultural products. The *low-cost* firm has an advantage over the *high-cost* firm in production and innovation investment costs before receiving government subsidies. Once after receiving government subsidies, such cost advantages will become more prominent, thus making the *low-cost* firm more motivated to produce more products. As a result, the output of the *low-cost* firm is larger than that of the *high-cost* firm under any subsidy scheme. Therefore, in a competitive market, firms should try to reduce the cost of operation and production to gain a greater competitive advantage.

Lemma 1. *The impact of subsidy rate on agricultural production is*:

(i) $\frac{\partial q_1^{BH}}{\partial s}>0$, $\frac{\partial q_1^{QH}}{\partial s}>0$, $\frac{\partial q_2^{BH}}{\partial s}>0$, $\frac{\partial q_2^{QH}}{\partial s}>0$;
(ii) $\frac{\partial q_1^{BL}}{\partial s}>0$, $\frac{\partial q_1^{QL}}{\partial s}>0$, $\frac{\partial q_2^{BL}}{\partial s}>0$, $\frac{\partial q_2^{QL}}{\partial s}>0$.

Lemma 1 indicates that the agricultural output increases in the subsidy rate under the BS scheme and the QS scheme, regardless of the market structures. This further shows that both the single QS policy and the mixed policy with the QS policy can achieve the purpose of promoting production. It is mainly because these types of subsidies are directly linked to production and thus encourage agricultural firms to increase production. Therefore, production-related subsidies are essential for the government to achieve its



(a) The high-cost firm is a leader. (b) The low-cost firm is a leader.

Fig. 4. Comparison of agricultural output under the three subsidy schemes ($\alpha = 0.2$, $M = 10$, $\lambda = 0.8$, $\gamma = 0.5$, $\tau = 0.3$).

goal of increasing production. The governments' policies in practice have well explained the rationality of this result. To arouse the enthusiasm of agricultural production and stabilize the grain production capacity, governments usually increase the advance allocation of agricultural subsidy funds.

5.2. Comparison of pollution emissions

This section compares the pollution emissions under the three subsidy schemes in two market structures to explore which subsidy scheme is more effective in curbing pollution emissions.

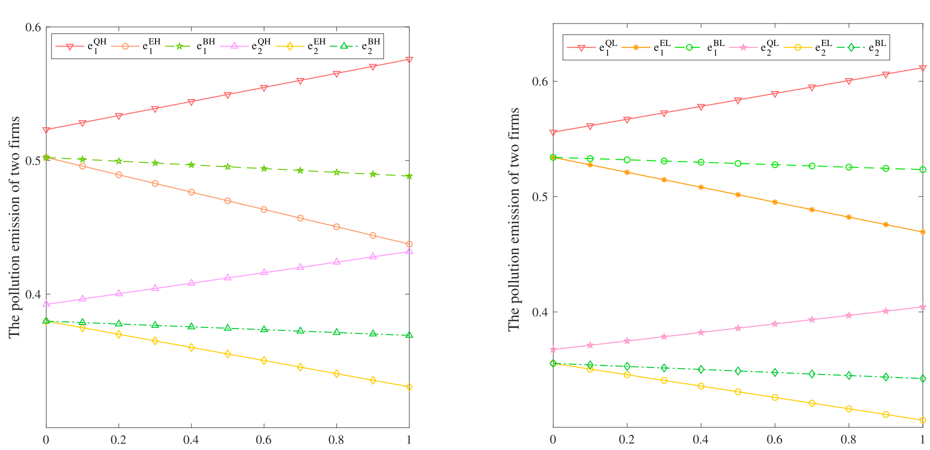
Proposition 8. *The relationship between the pollution emission under the three subsidy schemes is*:

(i) $e_1^{QH} > e_1^{BH} > e_1^{EH} > e_2^{QH} > e_2^{BH} > e_2^{EH}$;
(ii) $e_1^{QL} > e_1^{BL} > e_1^{EL} > e_2^{QL} > e_2^{BL} > e_2^{EL}$.

Proposition 8 shows that regardless of the market structures, the pollution emission under the QS scheme is the highest, followed by the BS scheme, and the pollution emission under the ES scheme is the lowest, as shown in Fig. 5. This is because pollution emissions are by-products of agricultural products. Generally, the higher the output, the more pollution is emitted. According to Proposition 7, the output under both the QS and the BS schemes is higher than that under the ES scheme, thus resulting in the lowest pollution emissions under the ES scheme.

An interesting and counter-intuitive finding is that although the output under the BS scheme is higher than that under the QS scheme, pollution emissions under the BS scheme are lower than those under the QS scheme. It is mainly due to the fact that the ES scheme plays a role in reducing pollution emissions in the BS scheme, which leads to this counterintuitive relationship. This further demonstrates that the BS scheme is superior to the QS scheme in both increasing production and reducing pollution emissions.

Lemma 2. *The impact of subsidy rate on pollution emissions is*:



(a) The high-cost firm as a leader. (b) The low-cost firm as a leader.

Fig. 5. Comparison of pollution emissions under the three subsidy schemes ($\alpha = 0.2$, $M = 10$, $\lambda = 0.8$, $\gamma = 0.5$, $\tau = 0.3$).

(i) $\frac{\partial e_1^{QH}}{\partial s} > 0$, $\frac{\partial e_1^{BH}}{\partial s} < 0$, $\frac{\partial e_1^{EH}}{\partial s} < 0$, $\frac{\partial e_2^{QH}}{\partial s} > 0$, $\frac{\partial e_2^{BH}}{\partial s} < 0$, $\frac{\partial e_2^{EH}}{\partial s} < 0$;
(ii) $\frac{\partial e_1^{QL}}{\partial s} > 0$, $\frac{\partial e_1^{BL}}{\partial s} < 0$, $\frac{\partial e_1^{EL}}{\partial s} < 0$, $\frac{\partial e_2^{QL}}{\partial s} > 0$, $\frac{\partial e_2^{BL}}{\partial s} < 0$, $\frac{\partial e_2^{EL}}{\partial s} < 0$.

Lemma 2 indicates that, regardless of the market structures, with the improvement of the subsidy rate, the QS scheme increases pollution emissions, while both the BS and the ES schemes reduce pollution emissions. It is caused by the different development objectives of different subsidy schemes. The ES scheme aims to improve production processes, develop green production methods, and reduce environmental pollution. As a result, both the ES and the BS schemes can play a role in reducing pollution emissions. Unfortunately, the QS scheme increases production, but at the same time makes the environment worse, thus leading to a dilemma for the government. Therefore, the QS scheme is not a long-term sustainable development program, but is a development policy at the expense of the environment.

5.3. Comparison of environmental innovation investment

Through the above analysis, it can be known that both the BS and the ES schemes can effectively curb pollution emissions, so which of the two subsidy schemes is more conducive to encouraging investment in environmental innovation? Thus, the impact of these two subsidy schemes on environmental innovation investment is compared in this section.

Proposition 9. *The relationship of the environmental innovation investments under the output-innovation subsidy and the environmental innovation subsidy schemes is*:

(i) $I_1^{BH} > I_1^{EH} > I_2^{BH} > I_2^{EH}$, *when the high-cost firm dominates*;
(ii) $I_1^{BL} > I_1^{EL} > I_2^{BL} > I_2^{EL}$, *when the low-cost firm dominates.*

It is clear from Proposition 9 that the environmental innovation investment under the BS scheme is greater than that under the ES scheme, as shown in Fig. 6. There are two possible reasons for this relationship. On the one hand, the pollution emissions under the BS scheme are higher than those under the ES scheme, and high pollution emissions will be subject to high tax penalties. Therefore, to avoid high penalties, firms will increase investment in environmental innovation and further reduce pollution emissions. On the other hand, the output under the BS scheme is higher than that under the ES scheme. The high output enables firms to make abundant profits and thus have more funds to invest in environmental innovation, which reflects the mutual driving relationship between production and investment. This also shows that the BS scheme is more effective than the ES scheme in encouraging agricultural firms to invest in environmental innovation.

Corollary 2. $I_1^{BH} > I_2^{BH}$, $I_1^{BL} > I_2^{BL}$, $I_1^{EH} > I_2^{EH}$, *and* $I_1^{EL} > I_2^{EL}$*The low-cost firm invests more in environmental innovation than the high-cost firm.*

Corollary 2 illustrates that the innovation investment of the *low-cost* firm is always higher than that of the *high-cost* firm under any subsidy schemes, which fully reflects the role of cost advantage. The *low-cost* firm has advantages over the *high-cost* firm not only in production costs but also in innovation investment costs. Therefore, after receiving environmental innovation subsidies from the government, the advantages become more prominent, which prompts the *low-cost* firm to invest in environmental innovation. Moreover, the increased investment in environmental innovation can reduce the pollution emission of agricultural products, which can attract more environmentally aware consumers to buy and thus increase market share. This positive demand incentive also further stimulates the *low-cost* firm to increase investment in environmental innovation.

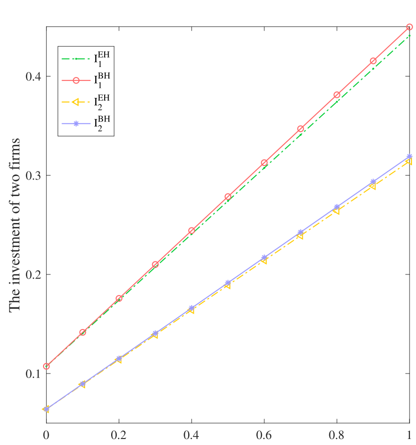
5.4. Comparison of firms' profits under the three subsidy schemes

The previous sections have carried out a comprehensive comparative analysis focusing on production, pollution emissions, and innovation investment. Next, we consider the profits of these two firms under different subsidy schemes.

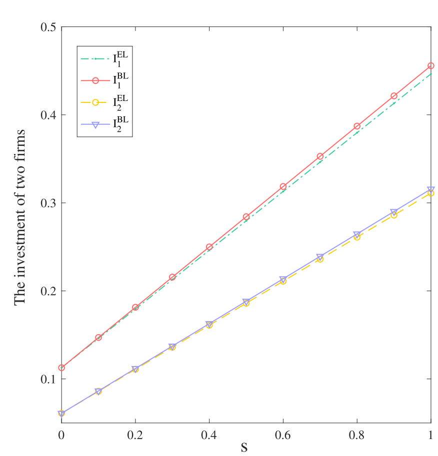
Proposition 10. *The profit relationship of the two agricultural firms under the three subsidy schemes is*:

(i) $\pi_1^{BH} > \pi_1^{QH} > \pi_1^{EH} > \pi_2^{BH} > \pi_2^{QH} > \pi_2^{EH}$;
(ii) $\pi_1^{BL} > \pi_1^{QL} > \pi_1^{EL} > \pi_2^{BL} > \pi_2^{QL} > \pi_2^{EL}$.

Proposition 10 suggests that for both the *high-cost* and *low-cost* agricultural firm, the profit under the BS scheme is the highest, followed by that under the QS scheme, while the profit under the ES scheme is the lowest, as shown in Fig. 7. Interestingly, the relationship between profit and output quantity is consistent, as

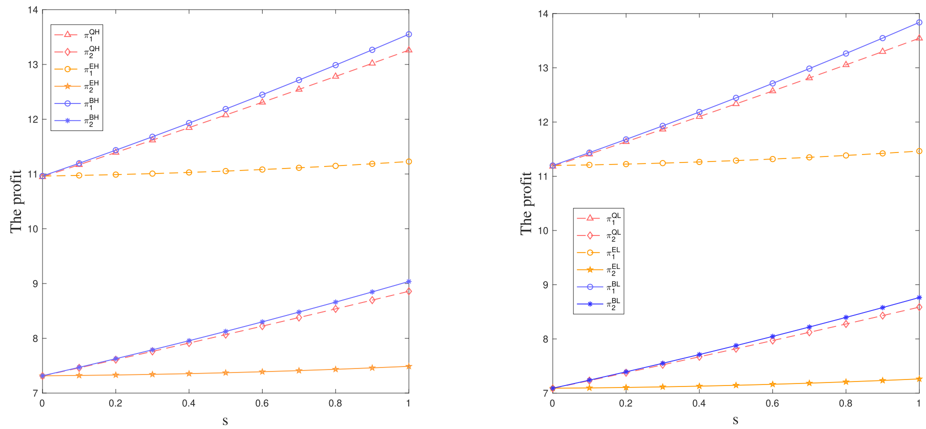


(a) The high-cost firm as a leader.



(b) The low-cost firm as a leader.

Fig. 6. Comparison of innovation investment under the two subsidy schemes ($\alpha = 0.2$, $M = 10$, $\lambda = 0.8$, $\gamma = 0.5$, $\tau = 0.3$).



(a) The high-cost firm as a leader. (b) The low-cost firm as a leader.

Fig. 7. Comparison of profits under the three subsidy schemes ($\alpha = 0.2$, $M = 10$, $\lambda = 0.8$, $\gamma = 0.5$, $\tau = 0.3$).

shown in Proposition 7. The finding is intuitive: higher yields lead to higher profits. Moreover, regardless of the subsidy schemes or the market structures, we find that the profit of the *low-cost* firm is always higher than that of the *high-cost* firm. It is coherent with the general principles of economics that *low-cost* firms always profit more than *high-cost* firms. In addition, according to the previous analysis, the *low-cost* firm tends to have more production and investment than the *high-cost* firm, which is conducive to occupy a larger market share and promote the *low-cost* firm to obtain considerable profits.

5.5. Comparison of consumer surplus under the three subsidy schemes

According to Atasu et al. (2009) and Chen et al. (2019), the consumer surplus is the area below the demand curve and above a given price, defined as $q^2/2$. Considering the substitutability of products, we can derive the consumer surplus function as $(q_1^2 + q_2^2)/2 + \lambda q_1 q_2$. Next, we compare the consumer surplus of the three subsidy schemes to analyze the impact of the subsidy schemes on consumers.

Proposition 11. *The consumer surplus under the three subsidy schemes satisfies the following relationships*:

(i) $CS^{BH} > CS^{QH} > CS^{EH}$, *when the high-cost firm dominates*;
(ii) $CS^{BL} > CS^{QL} > CS^{EL}$, *when the low-cost firm dominates.*

Proposition 11 indicates that the consumer surplus under the BS scheme is the largest, followed by that under the QS scheme, and the consumer surplus under the ES scheme is the smallest, as shown in Fig. 8. The relationship is the same as that between the output under the three subsidy schemes. It is easy to understand the relationship through numerical analysis, because according to the function of consumer surplus, there is a positive correlation between output and consumer surplus. Then, from the logic of economics, consumer surplus mainly depends on the difference between the price consumers are willing to pay and the price they actually pay. Since the output under the BS scheme is the highest, according to the economic principle of large output and low price, the BS scheme owns the advantage of low price, enabling consumers to obtain the maximum consumer surplus. This also suggests that the BS scheme is more favored and supported by consumers.

5.6. Comparison of social welfare under the three subsidy schemes

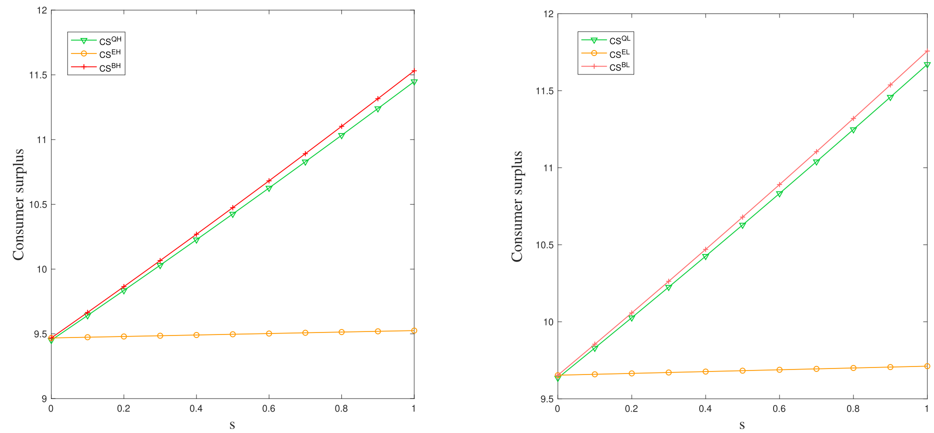
The above analysis has investigated the impact of different subsidy schemes from the perspective of profits and consumer surplus. Next, we consider the differences between the three subsidy schemes from the perspective of overall social welfare, and provide policy insights for promoting the healthy development of agriculture. According to Chen et al. (2017), the social welfare (SW) mainly includes three aspects: consumer surplus (CS), producer surplus (PS), and government budget (GB). GB refers to the difference between the tax revenues and subsidy expenditures. Thus, SW can be expressed as: $SW = CS + PS + GB$.

Proposition 12. *The social welfare under the three subsidy schemes satisfies the following relationships*:

(i) *if* $s \in (0, s_1)$, $SW^{BH} > SW^{EH} > SW^{QH}$ *and* $SW^{BL} > SW^{EL} > SW^{QL}$;
(ii) *if* $s \in (s_1, s_2)$, $SW^{BH} > SW^{QH} > SW^{EH}$ *and* $SW^{BL} > SW^{QL} > SW^{EL}$;
(iii) *if* $s \in (s_2, 1)$, $SW^{QH} > SW^{BH} > SW^{EH}$ *and* $SW^{QL} > SW^{BL} > SW^{EL}$.
(iv) $\frac{\partial SW^{BH}}{\partial s} > 0$, $\frac{\partial SW^{BL}}{\partial s} > 0$, $\frac{\partial SW^{QH}}{\partial s} > 0$, $\frac{\partial SW^{QL}}{\partial s} > 0$, $\frac{\partial SW^{EH}}{\partial s} < 0$, *and* $\frac{\partial SW^{EL}}{\partial s} < 0$.

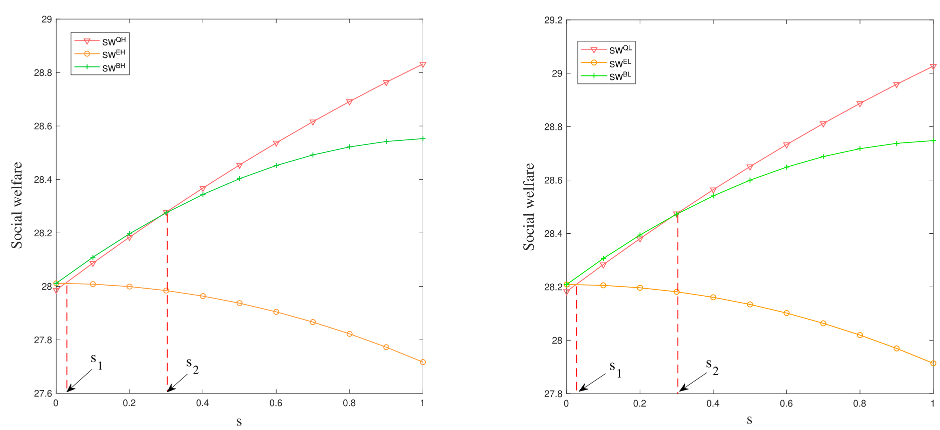
Proposition 12 shows that the relationship between social welfare under the three subsidy schemes depends on the value of the subsidy rate. There are two thresholds for subsidy rate, s_1 and s_2, as shown in Fig. 9. If the subsidy rate is relatively low ($0 < s < s_1$), then the social welfare under the BS scheme is the largest, followed by the ES scheme, and the social welfare under the QS scheme is the smallest. If the subsidy rate is the median ($s_1 < s < s_2$), the relationship between social welfare is, in descending order, as follows: BS, QS, and ES. If the subsidy rate is high ($s_2 < s < 1$), the social welfare under the QS scheme is the largest, while that under the ES scheme is the smallest, and the BS is in the middle. Moreover, an increase in the subsidy rate under the ES scheme would decrease social welfare, while an increase in the subsidy rate under the other two subsidy schemes would increase social welfare.

These findings suggest that the social welfare under the BS scheme is the highest among the three subsidy schemes, as long as the subsidy rate provided by the government is not too high. Once the subsidy rate exceeds the threshold of s_2, the social welfare under the QS scheme will be the highest. However, such improvement of social welfare comes at the expense of



(a) The high-cost firm as a leader. (b) The low-cost firm as a leader.

Fig. 8. Comparison of consumer surplus under the three subsidy schemes ($\alpha = 0.2$, $M = 10$, $\lambda = 0.8$, $\gamma = 0.5$, $\tau = 0.3$).



(a) The high-cost firm as a leader. (b) The low-cost firm as a leader.

Fig. 9. Comparison of social welfare under the three subsidy schemes ($\alpha = 0.2$, $M = 10$, $\lambda = 0.8$, $\gamma = 0.5$, $\tau = 0.3$).

environmental quality. Therefore, for the government to truly achieve sustainable agricultural development, it should not provide too high subsidy rate. Besides, these findings also suggest that the ES scheme is not a viable option and that its implementation would reduce social welfare.

6. Managerial insights

The three proposed subsidy schemes, together with the models, can be utilized by the government and agricultural firms to deal with the relationship between agricultural production and environmental protection.

6.1. Insight 1: reduction of agricultural pollution emissions

The deterioration of the agricultural ecological environment has become a bottleneck restricting the sustainable development of agriculture and has attracted the attention of governments around the world. Many governments have formulated severe tax punishment measures, which forces agricultural firms to pay attention to the emission reduction of pollutants in the process of production. Today, responsible agricultural firms also have obligations to reduce environmental pollution for the benefit of future generations. The proposed model takes government taxes, environmental awareness of consumers, and pollution emissions into account. By using this model, agricultural managers can accurately know the amount of pollution emissions generated in the production process and the pollutant taxes that should be paid. Moreover, as consumers are environmentally conscious, they pay attention to the pollution emission of agricultural products, if the pollution emission is relatively high, the demand would be reduced. Therefore, agricultural managers should consider consumers' environmental awareness when making production decisions. The proposed model is a step forward in addressing inevitable agricultural pollution and protecting the environment.

6.2. Insight 2: improvement of environmental innovation investment

The seriousness of environmental pollution urgently requires responsible agricultural firms to invest in environmental innovation to improve agricultural production processes, control pollutant emissions, and achieve sustainable agricultural development. Some governments have promulgated green agricultural subsidy schemes to promote the application of green and ecological agricultural technologies. For instance, in 2016, the Chinese government issued a plan to establish a green ecology-oriented agricultural subsidy system. Agricultural managers not only need to fully comprehend the government's environmental innovation subsidy policies, but also need to make accurate environmental innovation investment decisions. Innovation investment, environmental innovation subsidies, and different innovation investment costs are all incorporated into the model. By using this model, agricultural production managers are able to make reasonable decisions about whether and how to invest in environmental innovation under different government subsidy schemes. Specifically, when the government provides subsidies that are environmentally innovative, agricultural managers should actively invest in environmental innovation activities and invest more under the mixed subsidy than under the single subsidy. This could help improve the decision-making efficiency of managers and help maintain a sustainable agricultural operating system.

6.3. Insight 3: reduction of cost

The cost is an essential factor affecting the profitability of a firm. The goal of any firm is to pursue the maximization of profits, which requires managers to have the ability to control and reduce the operating costs. In the production process of agricultural products, there are a variety of costs, such as production cost, waste disposal cost, and labor cost. To better describe the production and investment decisions of agricultural firms, this study mainly incorporated production cost and innovation investment cost into the model. Meanwhile, competition is common in agricultural markets. Therefore, we model the competition between a high-cost agricultural firm and a low-cost agricultural firm to depict this phenomenon. Our research results show that the low-cost firm consistently outperforms the high-cost firm in terms of agricultural output, environmental innovation investment, and profitability. Therefore, for the managers of agricultural firms, to reduce the production and investment costs is the best way to face competition. The proposed model extends the agricultural model presented by Chen et al. (2017) by incorporating different firms' cost factors, competition factors and market structure factors.

6.4. Insight 4: provision of a hybrid subsidy scheme

The government provides many kinds of subsidy policies to promote the healthy development of agriculture, such as the production subsidy scheme and the environmental innovation subsidy scheme. But the effectiveness of subsidies varies, and it is not clear which policies would benefit both agricultural production and environmental protection. This study models three types of subsidy schemes and compares them in terms of output, innovation investment, pollution emissions, corporate profits, consumer surplus, and social welfare, thus providing some valuable insights for policy makers. This study finds that the output quantity subsidy scheme can increase production, but worsen the environment. The environmental innovation subsidy scheme can effectively control pollution emissions, but has little effect on production. Therefore, for policymakers, the implementation of any single environmental innovation subsidy or output quantity subsidy scheme cannot realize the development goal of ensuring adequate food supply and protecting the environment. The ideal choice for the government is to take a hybrid subsidy scheme combined with the two. The applicability of subsidy schemes depends on agricultural development goals. If production is a priority, then both the output-innovation and single output subsidy scheme are feasible. If the task of environmental protection is first, then the environmental innovation subsidy scheme will be the best. If it aims to ensure the food supply and to control the pollution, the best choice, of course, is the output-innovation subsidy scheme.

6.5. Insight 5: establishment of a reasonable subsidy rate

For policy makers, once the type of subsidy policy is determined, the establishment of the subsidy rate will have a bearing on the effect of the policy. Different subsidy rates will make different social welfare under different subsidy policies. If the subsidy rate is too high, the social welfare under the output-innovation subsidy scheme will no longer be optimal, while the social welfare under the output subsidy scheme will be maximized. Thus, sustainable development of agriculture cannot be achieved, and the improvement of social welfare under such output subsidy will come at the expense of environmental quality. Therefore, policymakers should not set the subsidy rate too high if they want to adopt the output-innovation subsidy. The subsidy rate needs to be determined according to the region of agricultural development. In some poor and remote areas, securing food supplies is a top priority. Therefore, a high subsidy rate can be set to stimulate the enthusiasm of agricultural producers, so as to give full play to the effect of increasing production. In some relatively mature areas, where food production is basically stable, special attention needs to be paid to environmental issues and, therefore, excessive subsidy rates should not be set to better implement the output-innovation subsidy scheme.

7. Conclusion

Food supply security is closely related to the stable development of a country, and environmental quality will affect the sustainable development of future generations. Governments around the world have formulated various subsidy policies to deal with the relationship between food supply and environmental protection. Based on this, this study focuses on an agricultural supply chain composed of a *high-cost* agricultural firm and a *low-cost* agricultural firm to investigate the effects of different subsidy policies. This model captures the impact of agricultural market competition, market structure, and product differentiation on the implementation effect of three subsidy schemes (i.e., output quantity subsidy, environmental innovation subsidy, and output-innovation subsidy).

First, by solving Stackelberg game models, the equilibrium results of output quantity, innovation investment, pollution emissions, profit, consumer surplus, and social welfare are obtained. Then, by comparing the equilibrium results of the three subsidy schemes, we find that neither an output subsidy scheme alone nor an environmental innovation subsidy scheme alone can solve the dilemma between environmental protection and adequate food supply. The only viable solution to this dilemma is a hybrid subsidy policy, that is, the output-innovation subsidy scheme. This scheme can not only increase corporate profits and consumer surplus, but also maximize social welfare under the condition of moderate subsidy rate, so as to achieve a win-win-win situation among firms, consumers and the government. In addition, the results indicate that cost factors do have an impact on production operations and profitability. Due to cost advantages, the *low-cost* agricultural firm occupies a larger market share and gains more profits. However, changes in market structure have no impact on the outcome.

It is an important attempt to jointly incorporate cost factors, market structure, and different types of subsidy schemes into an agricultural supply chain model, which extends the research of Chen et al. (2017) on agricultural subsidies and enriches the literature on agricultural supply chains. This study also can provide meaningful policy insights for policy makers and managers of agricultural firms, enabling the government to formulate reasonable subsidy programs to solve the dilemma of food supply and environmental protection, and providing accurate model reference for managers to make production and investment decisions.

This study has several limitations, and there is still room for further research. First, we assume that the subsidy rates of the three types of subsidy schemes are the same. But in reality, the subsidy rates of different subsidy schemes vary. It is an interesting extension to examine how different subsidy rates affect the effectiveness of subsidy policies. Second, the model is limited to a single period. The implementation of subsidy policies is often a long-term process. Thus, it would be of great significance to consider a dual-period or multi-period model in the future. Third, this model assumes that government subsidies are exogenous and independent of the production and investment decisions of firms. The endogenicity of government subsidies in the model would be more realistic. Fourth, this model assumes that consumers are environmentally conscious. In reality, there also exists non-environmentally conscious consumers. It makes more sense to consider the impact of the coexistence of environmentally conscious and non-environmentally conscious consumers on government subsidy schemes.

CRediT authorship contribution statement

Ranran Zhang: Conceptualization, Methodology, Writing - original draft, Project administration, Software. **Weimin Ma:** Conceptualization, Supervision. **Jinjin Liu:** Formal analysis, Writing - review & editing.

Declaration of competing interest

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

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Appendix A

Proof 1. Proof of Proposition 1

We use backward induction to solve the equilibrium solutions of the model. First, we consider the *low-cost* firm's production decisions. The first derivative and the second derivative of q_1^{QH} from Eq. (1) are obtained: $\partial\pi_1^{QH}/\partial q_1^{QH} = M + s - \alpha\tau - (2\alpha\gamma + 3)q_1^{QH} - \lambda q_2^{QH}$ and $\partial^2\pi_1^{QH}/\partial q_1^{QH^2} = -(2\alpha\gamma + 3) < 0$. Therefore, $\pi_1^{QH}$is concave in q_1^{QH}, by setting $\partial\pi_1^{QH}/\partial q_1^{QH} = 0$, we can get the optimal solution of q_1^{QH}, and $q_1^{QH} = (M + s - \alpha\tau - \lambda q_2^{QH})/(2\alpha\gamma + 3)$.

Then, we consider the high-cost firm's production decisions. Substitute the optimal solution of q_1^{QH}into Eq. (2) and obtain the first-order and second-order derivative of $\pi_2^{QH}$with respect to q_2^{QH}as:

$\partial\pi_2^{QH}/\partial q_2^{QH} = ((2\alpha\gamma + 3 - \lambda)(M + s - \alpha\tau) - 2(6 + \alpha\gamma(7 + 2\alpha\gamma) - \lambda^2)q_2^{QH})/(2\alpha\gamma + 3)$ and $\partial^2\pi_2^{QH}/\partial q_2^{QH^2} = (-(2\alpha\gamma + 4)(2\alpha\gamma + 3) + 2\lambda^2)/(2\alpha\gamma + 3) < 0$. By setting $\partial\pi_2^{QH}/\partial q_2^{QH} = 0$, we can obtain the optimal equilibrium solution: $q_2^{QH} = (2\alpha\gamma + 3 - \lambda)(M + s - \alpha\tau)/(2(6 + \alpha\gamma(7 + 2\alpha\gamma) - \lambda^2))$. By putting the optimal q_2^{QH}into $q_1^{QH}$and e_i^{QH}, we get the equilibrium values of q_1^{QH}, e_1^{QH}, and e_2^{QH}in Proposition 1.

Proof 2. Proof of Proposition 2

First, we consider the high-cost firm's production decisions. The first derivative and the second derivative of $q_2^{QL}$from Eq. (2) are obtained: $\partial\pi_2^{QL}/\partial q_2^{QL} = M + s - \alpha\tau - 2(\alpha\gamma + 2)q_2^{QL} - \lambda q_1^{QL}$and $\partial^2\pi_2^{QL}/\partial q_2^{QL^2} = -(2\alpha\gamma + 4) < 0$. Therefore, $\pi_2^{QL}$is concave in q_2^{QL}, we can get the optimal solution of $q_2^{QL}$by setting $\partial\pi_2^{QL}/\partial q_2^{QL} = 0$. $q_2^{QL} = (M + s - \alpha\tau - \lambda q_1^{QL})/(2(\alpha\gamma + 2))$.

Then, we consider the low-cost firm's production decisions. Substitute the optimal solution of q_2^{QL}into Eq. (1) and obtain the first-order and second-order derivative of $\pi_1^{QL}$with respect to q_1^{QL}: $\partial\pi_1^{QL}/\partial q_1^{QL} = ((M + s - \alpha\tau)(4 + 2\alpha\gamma - \lambda) - 2(6 + \alpha\gamma(7 + 2\alpha\gamma) - \lambda^2)q_1^{QL})/(4 + 2\alpha\gamma)$and $\partial^2\pi_1^{QL}/\partial q_1^{QL^2} = -3 - 2\alpha\gamma + \lambda^2/(2 + \alpha\gamma) < 0$. By setting $\partial\pi_1^{QL}/\partial q_1^{QL} = 0$, we can obtain the optimal equilibrium solutions: $q_1^{QL} = ((2\alpha\gamma + 4 - \lambda)(M + s - \alpha\tau))/(2(6 + \alpha\gamma(7 + 2\alpha\gamma) - \lambda^2))$. Putting the optimal q_1^{QL} into $q_2^{QL}$and e_i^{QL}, we get the equilibrium values of q_2^{QL}, e_1^{QL}, and e_2^{QL}in Proposition 2.

Proof 3. Proof of Proposition 3

First, we consider the low-cost firm's production and investment decisions. We obtain the first derivative of $\pi_1^{EH}$with respect to q_1^{EH} and I_1^{EH} from Eq. (3): $\partial\pi_1^{EH}/\partial q_1^{EH} = M - \alpha\tau - (3 + 2\alpha\gamma)q_1^{EH} - \lambda q_2^{EH} + \alpha\gamma I_1^{EH}$and $\partial\pi_1^{EH}/\partial I_1^{EH} = s + \alpha\tau + \alpha\gamma q_1^{EH} - 3I_1^{EH}$. The Hessian matrix is as follows:

$$\begin{bmatrix} \dfrac{\partial^2\pi_1^{EH}}{\partial q_1^{EH^2}} & \dfrac{\partial^2\pi_1^{EH}}{\partial q_1^{EH}\partial I_1^{EH}} \\ \dfrac{\partial^2\pi_1^{EH}}{\partial I_1^{EH}\partial q_1^{EH}} & \dfrac{\partial^2\pi_1^{EH}}{\partial I_1^{EH^2}} \end{bmatrix} = \begin{bmatrix} -3 - 2\alpha\gamma & \alpha\gamma \\ \alpha\gamma & -3 \end{bmatrix} = 18 - (\alpha\gamma - 3)^2 > 0. \tag{A.1}$$

From Eq.(A.1), we can know that $\pi_1^{EH}$is a strictly concave function of q_1^{EH} and I_1^{EH}. Then, by setting $\partial\pi_1^{EH}/\partial q_1^{EH} = 0$and $\partial\pi_1^{EH}/\partial I_1^{EH} = 0$, we can obtain the optimal equilibrium solutions: $q_1^{EH} = (3M + \alpha(s\gamma - 3\tau + \alpha\gamma\tau) - 3\lambda q_2^{EH})/(9 + \alpha\gamma(6 - \alpha\gamma))andI_1^{EH} = (s(3 + 2\alpha\gamma) + \alpha(M\gamma + 3\tau + \alpha\gamma\tau) - \alpha\gamma\lambda q_2^{EH})/(9 + \alpha\gamma(6 - \alpha\gamma))$. Putting the optimal $q_1^{EH}$and I_1^{EH}into Eq. (4), we obtain the first derivative of $\pi_2^{EH}$with respect to $q_2^{EH}$and I_2^{EH}: $\partial\pi_2^{EH}/\partial q_2^{EH} = M - \alpha\tau - (4 + 2\alpha\gamma)_{q_2}^{EH} + \alpha\gamma I_2^{EH} + (6\lambda q_2^{EH} - 3M - \alpha s\gamma + 3\alpha\tau - \alpha^2\gamma\tau)\lambda/(9 + \alpha\gamma(6 - \alpha\gamma))$and $\partial\pi_2^{EH}/\partial I_2^{EH} = s + \alpha\tau + \alpha\gamma q_2^{EH} - 4I_2^{EH}$. The Hessian matrix is as follows:

$$\begin{bmatrix} \dfrac{\partial^2 \pi_2^{EH}}{\partial q_2^{EH^2}} & \dfrac{\partial^2 \pi_2^{EH}}{\partial q_2^{EH} \partial I_2^{EH}} \\ \dfrac{\partial^2 \pi_2^{EH}}{\partial I_2^{EH} \partial q_2^{EH}} & \dfrac{\partial^2 \pi_2^{EH}}{\partial I_2^{EH^2}} \end{bmatrix} = \begin{bmatrix} -2(2+\alpha\gamma)+\dfrac{6\lambda^2}{9+\alpha\gamma(6-\alpha\gamma)} & \alpha\gamma \\ \alpha\gamma & -4 \end{bmatrix}$$
$$= 32-(\alpha\gamma-4)^2-\frac{24\lambda^2}{9+\alpha\gamma(6-\alpha\gamma)}>0. \tag{A.2}$$

From Eq.(A.2), we can know that π_2^{EH} is a strictly concave function of q_2^{EH} and I_2^{EH}. By setting $\partial\pi_2^{EH}/\partial q_2^{EH} = 0$and $\partial\pi_2^{EH}/\,\partial I_2^{EH} = 0$at the same time, we can get the equilibrium results: $q_2^{EH}=(4M(9+\alpha\gamma(6-\alpha\gamma)-3\lambda)+s\alpha\gamma(9+\alpha\gamma(6-\alpha\gamma)-4\lambda)-\alpha\tau(12(3-\lambda)+\alpha\gamma(15-\alpha\gamma(10-\alpha\gamma)+4\lambda)))/(\alpha\gamma(168+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma)))+24(6-\lambda^2))$ and $I_2^{EH}=(M\alpha\gamma(9+\alpha\gamma(6-\alpha\gamma)-3\lambda)+s(36+2\alpha\gamma(7-\alpha\gamma)(3+\alpha\gamma)-\alpha^2\gamma^2\lambda-6\lambda^2)+\alpha\tau(36+\alpha\gamma(33+\alpha\gamma(2-\alpha\gamma))+\alpha\gamma(3-\alpha\gamma)\lambda-6\lambda^2))/(\alpha\gamma(168+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma)))+24(6-\lambda^2))$.. By putting the optimal q_2^{EH} and I_2^{EH}into q_1^{EH}, I_1^{EH}, and e_i^{EH}, we can get the equilibrium values of q_1^{EH}, I_1^{EH}, e_1^{EH}, and e_2^{EH}in Proposition 3.

Proof 4. Proof of Proposition 4

First, we consider the high-cost firm's production and investment decisions. The first derivative of $\pi_2^{EL}$with respect to $q_2^{EL}$and $I_2^{EL}$from Eq. (4) are obtained: $\partial\pi_2^{EL}/\partial q_2^{EL} = M-\alpha\tau-\lambda q_1^{EL}-2(2+\alpha\gamma)q_2^{EL}+\alpha\gamma I_2^{EL}$and $\partial\pi_2^{EL}/\partial I_2^{EL} = s+\alpha\tau+\alpha\gamma q_2^{EL}-4I_2^{EL}$. The Hessian matrix is as follows:

$$\begin{bmatrix} \dfrac{\partial^2 \pi_2^{EL}}{\partial q_2^{EL^2}} & \dfrac{\partial^2 \pi_2^{EL}}{\partial q_2^{EL} \partial I_2^{EL}} \\ \dfrac{\partial^2 \pi_2^{EL}}{\partial I_2^{EL} \partial q_2^{EL}} & \dfrac{\partial^2 \pi_2^{EL}}{\partial I_2^{EL^2}} \end{bmatrix} = \begin{bmatrix} -4-2\alpha\gamma & \alpha\gamma \\ \alpha\gamma & -4 \end{bmatrix} = 32$$
$$-(\alpha\gamma-4)^2>0. \tag{A.3}$$

From Eq.(A.3), we can know that π_2^{EL} is a strictly concave function of $q_2^{EL}$and I_2^{EL}. By setting $\partial\pi_2^{EL}/\partial q_2^{EL} = 0$and $\partial\pi_2^{EL}/\,\partial I_2^{EL} = 0$, we can obtain the optimal equilibrium solutions: $q_2^{EL} = (4M+\alpha(s\gamma-4\tau+\alpha\gamma\tau)-4\lambda q_1^{EL})/(16+\alpha\gamma(8-\alpha\gamma))$ and $I_2^{EL} = (2s(2+\alpha\gamma)+\alpha(M\gamma+4\tau+\alpha\gamma\tau)-\alpha\gamma\lambda q_1^{EL})/(16+\alpha\gamma\,(8-\alpha\gamma))$. By putting the optimal $q_2^{EL}$and I_2^{EL} into Eq. (3), we obtain the first derivative of π_1^{EL} with respect to q_1^{EL} and I_1^{EL}: $\partial\pi_1^{EL}/\partial q_1^{EL} = M-\alpha\tau-(3+2\alpha\gamma)_{q_1}^{EL}+\alpha\gamma I_1^{EL}+(8\lambda q_{q_1}^{EL}-4M-s\alpha\gamma-+\alpha(4-\alpha\gamma)\tau)\lambda/(16+\alpha\gamma(8-\alpha\gamma))$ and $\partial\pi_1^{EL}/\partial I_1^{EL} = s+\alpha\tau+\alpha\gamma q_1^{EL}-3I_1^{EL}$. The Hessian matrix is as follows:

$$\begin{bmatrix} \dfrac{\partial^2 \pi_1^{EL}}{\partial q_1^{EL^2}} & \dfrac{\partial^2 \pi_1^{EL}}{\partial q_1^{EL} \partial I_1^{EL}} \\ \dfrac{\partial^2 \pi_1^{EL}}{\partial I_1^{EL} \partial q_1^{EL}} & \dfrac{\partial^2 \pi_1^{EL}}{\partial I_1^{EL^2}} \end{bmatrix} = \begin{bmatrix} -(3+2\alpha\gamma)+\dfrac{8\lambda^2}{16+\alpha\gamma(8-\alpha\gamma)} & \alpha\gamma \\ \alpha\gamma & -3 \end{bmatrix}$$
$$= 18-(\alpha\gamma-3)^2-\frac{24\lambda^2}{16+\alpha\gamma(8-\alpha\gamma)}>0. \tag{A.4}$$

From Eq.(A.4), we can know that π_1^{EL} is a strictly concave function of q_1^{EL} and I_1^{EL}. By setting $\partial\pi_1^{EL}/\partial q_1^{EL}=0$ and $\partial\pi_1^{EL}/\,\partial I_1^{EL}=0$ at the same time, we can get the equilibrium results: $q_1^{EL}=(3M(16+\alpha\gamma(8-\alpha\gamma)-4\lambda)+s\alpha\gamma(16+\alpha\gamma(8-\alpha\gamma)-3\lambda)-\alpha\tau(48+\alpha\gamma(8-\alpha\gamma(11-\alpha\gamma)+3\lambda)-12\lambda))/(\alpha\gamma(168-+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma)))+24(6-\lambda^2))$ and $I_1^{EL}=(M\alpha\gamma(16+\alpha\gamma(8-\alpha\gamma)-4\lambda)+s(48+56\alpha\gamma-2\alpha^3\gamma^3+\alpha^2\gamma^2(13-\lambda)-8\lambda^2)+\alpha\tau(48+\alpha\gamma(40+\alpha\gamma(5--\alpha\gamma))+\alpha\gamma(4-\alpha\gamma)\lambda-8\lambda^2))/+(\alpha\gamma(168+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma)))+24(6-\lambda^2))$. Putting the optimal q_1^{EL} and I_1^{EL} into q_2^{EL}, I_2^{EL}, and e_i^{EL}, we can get the equilibrium values of q_1^{EL}, I_1^{EL}, e_1^{EL}, and e_2^{EL} in Proposition 4.

Proof 5. Proof of Proposition 5

First, we consider the low-cost firm's production and investment decisions. The first derivative of π_1^{BH} with respect to q_1^{BH} and I_1^{BH} from Eq. (5) are obtained as: $\partial\pi_1^{BH}/\partial q_1^{BH} = M+s-\alpha\tau-(3+2\alpha\gamma)q_1^{BH}-\lambda q_2^{BH}+\alpha\gamma I_1^{BH}$ and $\partial\pi_1^{BH}/\partial I_1^{BH} = s+\alpha\tau+\alpha\gamma q_1^{BH}-3I_1^{BH}$. The Hessian matrix is as follows:

$$\begin{bmatrix} \dfrac{\partial^2 \pi_1^{BH}}{\partial q_1^{BH^2}} & \dfrac{\partial^2 \pi_1^{BH}}{\partial q_1^{BH} \partial I_1^{BH}} \\ \dfrac{\partial^2 \pi_1^{BH}}{\partial I_1^{BH} \partial q_1^{BH}} & \dfrac{\partial^2 \pi_1^{BH}}{\partial I_1^{BH^2}} \end{bmatrix} = \begin{bmatrix} -3-2\alpha\gamma & \alpha\gamma \\ \alpha\gamma & -3 \end{bmatrix} = 18$$
$$-(\alpha\gamma-3)^2>0. \tag{A.5}$$

From Eq.(A.5), we can know that π_1^{BH} is a strictly concave function of q_1^{BH} and I_1^{BH}. By setting $\partial\pi_1^{BH}/\partial q_1^{BH} = 0$ and $\partial\pi_1^{BH}/\partial I_1^{BH} = 0$, we can obtain the optimal equilibrium solutions: $q_1^{BH} = (3M+s(3+\alpha\gamma)-\alpha(3-\alpha\gamma)\tau-3\lambda q_2^{BH})\ /(9+\alpha\gamma(6-\alpha\gamma))$ and $I_1^{BH} = (3s(1+\alpha\gamma)+\alpha(M\gamma+3\tau+\alpha\gamma\tau)-\alpha\gamma\lambda q_2^{BH})/(9+\alpha\gamma(6-\alpha\gamma))$. Putting the optimal q_1^{BH} and I_1^{BH} into Eq. (6), we obtain the first derivative of π_2^{BH} with respect to q_2^{BH} and I_2^{BH}: $\partial\pi_2^{BH}/\partial q_2^{BH} = M+s-\alpha\tau-(4+2\alpha\gamma)q_2^{BH}+\alpha\gamma I_2^{BH}+((6\lambda q_2^{BH}-3M-s(3+\alpha\gamma)+\alpha(3--\alpha\gamma)\tau)\lambda)/(9+\alpha\,\gamma(6-\alpha\gamma))$ and $\partial\pi_2^{BH}/\partial I_2^{BH} = s+\alpha\tau+\alpha\gamma q_2^{BH}-4I_2^{BH}$. Therefore, the Hessian matrix is:

$$\begin{bmatrix} \dfrac{\partial^2 \pi_2^{BH}}{\partial q_2^{BH^2}} & \dfrac{\partial^2 \pi_2^{BH}}{\partial q_2^{BH} \partial I_2^{BH}} \\ \dfrac{\partial^2 \pi_2^{BH}}{\partial I_2^{BH} \partial q_2^{BH}} & \dfrac{\partial^2 \pi_2^{BH}}{\partial I_2^{BH^2}} \end{bmatrix} = \begin{bmatrix} -(4+2\alpha\gamma)+\dfrac{6\lambda^2}{9+\alpha\gamma(6-\alpha\gamma)} & \alpha\gamma \\ \alpha\gamma & -4 \end{bmatrix}$$
$$= 32-(\alpha\gamma-4)^2-\frac{24\lambda^2}{9+\alpha\gamma(6-\alpha\gamma)}>0. \tag{A.6}$$

From Eq.(A.6), we can know that π_2^{BH} is a strictly concave function of q_2^{BH} and I_2^{BH}. By setting $\partial\pi_2^{BH}/\partial q_2^{BH}=0$ and $\partial\pi_2^{BH}/\partial I_2^{BH}=0$ at the same time, we can get the equilibrium results: $q_2^{BH}=(4M(9+\alpha\gamma(6-\alpha\gamma)-3\lambda)+s(\alpha\gamma(33+\alpha\gamma(2-\alpha\gamma)-4\lambda))+12(3-\lambda)(s-\alpha\tau)-\alpha^2\gamma(15-\alpha\gamma(10-\alpha\gamma)-+4\lambda)\tau)/(\alpha\gamma(168+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma)))+24(6-\lambda^2))$ and $I_2^{BH}=(M\alpha\gamma(9+\alpha\gamma(6-\alpha\gamma)-3\lambda)+s(36+\alpha\gamma(51+\alpha\gamma(14-3\alpha\gamma))-\alpha\gamma(3+\alpha\gamma)\lambda-6\lambda^2)+\alpha\tau(36-+\alpha\gamma(33+\alpha\gamma(2-\alpha\gamma))+\alpha\gamma(3-\alpha\gamma)\lambda-6\lambda^2))/(\alpha\gamma(168+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma)))-+24(6-\lambda^2))$. By putting the optimal q_2^{BH} and I_2^{BH} into q_1^{BH}, I_1^{BH} and

e_i^{BH}, we can get the equilibrium values of q_1^{BH}, I_1^{BH}, e_1^{BH}, and e_2^{BH} in Proposition 5.

Proof 6. Proof of Proposition 6

First, we consider the high-cost firm's production and investment decisions. The first derivative of π_2^{BL} with respect to q_2^{BL} and I_2^{BL} from Eq. (6) are obtained: $\partial\pi_2^{BL}/\partial q_2^{BL} = M + s - \alpha\tau - 2(2+\alpha\gamma)q_2^{BL} - \lambda q_1^{BL} + \alpha\gamma I_2^{BL}$ and $\partial\pi_2^{BL}/\ \partial I_2^{BL} = s + \alpha\tau + \alpha\gamma q_2^{BL} - 4I_2^{BL}$. The Hessian matrix is as follows:

$$\begin{bmatrix} \dfrac{\partial^2\pi_2^{BL}}{\partial q_2^{BL^2}} & \dfrac{\partial^2\pi_2^{BL}}{\partial q_2^{BL}\partial I_2^{BL}} \\ \dfrac{\partial^2\pi_2^{BL}}{\partial I_2^{BL}\partial q_2^{BL}} & \dfrac{\partial^2\pi_2^{BL}}{\partial I_2^{BL^2}} \end{bmatrix} = \begin{bmatrix} -4-2\alpha\gamma & \alpha\gamma \\ \alpha\gamma & -4 \end{bmatrix} = 32 - (\alpha\gamma - 4)^2 > 0. \tag{A.7}$$

From Eq. (A.7), we can know that π_2^{BL} is a strictly concave function of q_2^{BL} and I_2^{BL}. By setting $\partial\pi_2^{BL}/\partial q_2^{BL} = 0$ and $\partial\pi_2^{BL}/\ \partial I_2^{BL} = 0$, we can obtain the optimal equilibrium solutions of q_2^{BL} and I_2^{BL}. $q_2^{BL} = (4M + s(4+\alpha\gamma) - \alpha(4 - \alpha\gamma)\tau - 4\lambda q_1^{BL})/(16+\alpha\gamma(8-\alpha\gamma))$ and $I_2^{BL} = (s(4+3\alpha\gamma) + \alpha(M\gamma + 4\tau + \alpha\gamma\tau) - \alpha\gamma\lambda q_1^{BL})/(16 + \alpha\gamma(8 - \alpha\gamma))$. By putting the optimal q_2^{BL} and I_2^{BL} into Eq. (5), we obtain the first derivative of π_1^{BL} with respect to q_1^{BL} and I_1^{BL}. $\partial\pi_1^{BL}/\partial q_1^{BL} = M + s - \alpha\tau - (3+2\alpha\gamma)q_1^{BL} + \alpha\gamma I_1^{BL} + ((8\lambda q_1^{BL} - 4M - s(4+\alpha\gamma) + \alpha(4-\alpha\gamma)\tau)\lambda)/(16+\alpha\gamma(8-\alpha\gamma))$ and $\partial\pi_1^{BL}/\ \partial I_1^{BL} = s + \alpha\tau + \alpha\gamma q_1^{BL} - 3I_1^{BL}$. The Hessian matrix is:

$$\begin{bmatrix} \dfrac{\partial^2\pi_1^{BL}}{\partial q_1^{BL^2}} & \dfrac{\partial^2\pi_1^{BL}}{\partial q_1^{BL}\partial I_1^{BL}} \\ \dfrac{\partial^2\pi_1^{BL}}{\partial I_1^{BL}\partial q_1^{BL}} & \dfrac{\partial^2\pi_1^{BL}}{\partial I_1^{BL^2}} \end{bmatrix} = \begin{bmatrix} -(3+2\alpha\gamma) + \dfrac{8\lambda^2}{16+\alpha\gamma(8-\alpha\gamma)} & \alpha\gamma \\ \alpha\gamma & -3 \end{bmatrix}$$

$$= 18 - (\alpha\gamma - 3)^2 - \frac{24\lambda^2}{16+\alpha\gamma(8-\alpha\gamma)} > 0. \tag{A.8}$$

From Eq. (A.8), we can know that π_1^{BL} is a strictly concave function of q_1^{BL} and I_1^{BL}. By setting $\partial\pi_1^{BL}/\partial q_1^{BL} = 0$ and $\partial\pi_1^{BL}/\ \partial I_1^{BL} = 0$ at the same time, we can get the equilibrium results: $q_1^{BL} = (3M(16+\alpha\gamma(8-\alpha\gamma)-4\lambda)) + s(\alpha\gamma(40+\alpha\gamma(5-\alpha\gamma)-3\lambda)) + 12(4-\lambda)(s-\alpha\tau) - \alpha^2\gamma(8-\alpha\gamma(11-\alpha\gamma)+3\lambda)\tau)/(\alpha\gamma(168+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma))) + 24(6-\lambda^2))$ and $I_1^{BL} = (M\alpha\gamma(16+\alpha\gamma(8-\alpha\gamma)-4\lambda)) + s(3(1+\alpha\gamma)(16+\alpha\gamma(8-\alpha\gamma)) - \alpha\gamma(4+\alpha\gamma)\lambda - 8\lambda^2) + \alpha\tau(48+\alpha\gamma(40+\alpha\gamma(5-\alpha\gamma)) + \alpha\gamma(4-\alpha\gamma)\lambda - 8\lambda^2))(\alpha\gamma(168+\alpha\gamma(23-\alpha\gamma(14-\alpha\gamma)))-+24(6-\lambda^2))$. By putting the optimal q_1^{BL} and I_1^{BL} into q_2^{BL}, I_2^{BL}, and e_i^{BL}, we can get the equilibrium values of q_2^{BL}, I_2^{BL}, e_1^{BL}, and e_2^{BL} in Proposition 6.

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