

Subsidy policies for the grain supply chain considering postharvest loss of grain and agricultural pollutant emission in China

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Electronic supplementary material

APPENDIX A**Appendix A1**

$$\pi_p^{\text{NEL}} = (p_1^{\text{NEL}} - c + \beta) D^{\text{NEL}} (1 - \lambda)$$

$$\pi_r^{\text{NEL}} = (p_2^{\text{NEL}} - p_1^{\text{NEL}}) D^{\text{NEL}} (1 - \lambda_1)$$

$$\pi_g^{\text{NEL}} = \pi_p^{\text{NEL}} + \pi_r^{\text{NEL}} + CS^{\text{NEL}} - \beta D^{\text{NEL}}$$

$$D^{\text{NEL}} = M - \delta e_0 - p_2^{\text{NEL}}$$

Appendix A2

$$\pi_p^{\text{ENL}} = (p_1^{\text{ENL}} - c + \beta) D^{\text{ENL}} (1 - \lambda) - \frac{(1-s)k\gamma^2}{2}$$

$$\pi_r^{\text{ENL}} = (p_2^{\text{ENL}} - p_1^{\text{ENL}}) D^{\text{ENL}} (1 - \lambda)(1 - \lambda_1)$$

$$\pi_g^{\text{ENL}} = \pi_p^{\text{ENL}} + \pi_r^{\text{ENL}} + CS^{\text{ENL}} - \beta D^{\text{ENL}} - \frac{sk\gamma^2}{2}$$

$$D^{\text{ENL}} = M - \delta e_0 - p_2^{\text{ENL}}$$

Appendix A3

$$\pi_p^{\text{EL}} = (p_1^{\text{EL}} - c + \beta) D^{\text{EL}} (1 - \alpha_1 \lambda) - \frac{(1-s)k\gamma^2 + (1-s_1)k_1(1-\alpha_1\lambda)^2}{2}$$

$$\pi_r^{\text{EL}} = (p_2^{\text{EL}} - p_1^{\text{EL}}) D^{\text{EL}} (1 - \alpha_1 \lambda)(1 - \lambda_1)$$

$$\pi_g^{\text{EL}} = \pi_p^{\text{EL}} + \pi_r^{\text{EL}} + CS^{\text{EL}} - \frac{sk\gamma^2}{2} - \frac{s_1 k_1 (1 - \alpha_1 \lambda)^2}{2} - \beta D^{\text{ENL}}$$

$$D^{\text{EL}} = M - \delta \gamma e_0 - p_2^{\text{EL}}$$

Appendix A4

$$\pi_p^{\text{ELB}} = (p_1^{\text{ELB}} - c + \beta) D^{\text{ELB}} (1 - \alpha_1 \lambda) - \frac{(1-s)k\gamma^2 + (1-s_1)k_1(1-\alpha_1\lambda)^2}{2}$$

$$\pi_r^{\text{ELB}} = (p_1^{\text{ELB}} - p_1^{\text{ELB}}) D^{\text{ELB}} (1 - \alpha_1 \lambda)(1 - \alpha_2 \lambda_1) - \frac{(1-s_2)k_1(1-\alpha_2\lambda_1)^2}{2}$$

$$\pi_g^{\text{ELB}} = \pi_p^{\text{ELB}} + \pi_r^{\text{ELB}} + CS^{\text{ELB}} - \frac{sk\gamma^2 + s_1 k_1 (1 - \alpha_1 \lambda)^2 + s_2 k_2 (1 - \alpha_2 \lambda_1)^2}{2} - \beta D^{\text{ELB}}$$

$$D^{\text{ELB}} = M - \delta \gamma e_0 - p_1^{\text{ELB}}$$

APPENDIX B

Appendix B1

According to proof 2, we can obtain, $\frac{\partial p_1^{ENL^*}}{\partial s} = 0$, $\frac{\partial p_2^{ENL^*}}{\partial s} = 0$, $\frac{\partial \pi_p^{ENL^*}}{\partial s} = \frac{k\gamma^2}{2} > 0$, $\frac{\partial \pi_r^{ENL^*}}{\partial s} = 0$, $\frac{\partial \pi_g^{ENL^*}}{\partial s} = 0$,

$$\frac{\partial p_1^{ENL^*}}{\partial \gamma} = -\frac{\delta e_0}{2} < 0, \frac{\partial p_2^{ENL^*}}{\partial \gamma} = -\frac{3\delta e_0}{4} < 0, \frac{\partial \pi_p^{ENL^*}}{\partial \gamma} = \frac{4\gamma + A\delta e_0(\lambda - 1)}{4} < 0, \frac{\partial \pi_r^{ENL^*}}{\partial \gamma} = -\frac{A\delta e_0(\lambda - 1)(\lambda_1 - 1)}{8} < 0$$

$$\frac{\partial \pi_g^{ENL^*}}{\partial \gamma} = -\frac{A\delta e_0[1 + 2(1 - \lambda)(3 - \lambda_1)]}{16} + \frac{\beta e_0 \delta}{4} - \gamma < 0,$$

here, $E = M + \beta - c - \delta e_0 \gamma$. We know that M in E is the largest compared to the other values, so we can determine that the first-order derivative of the supply chain members is less than zero, and the same is true for the sign in the subsequent proof.

Appendix B2

According to proof 3, we can obtain $\frac{\partial p_1^{EL^*}}{\partial s} = 0$, $\frac{\partial p_2^{EL^*}}{\partial s} = 0$, $\frac{\partial \pi_p^{EL^*}}{\partial s} = \frac{k\gamma^2}{2} > 0$, $\frac{\partial \pi_r^{EL^*}}{\partial s} = 0$, $\frac{\partial \pi_g^{EL^*}}{\partial s} = 0$,

$$\frac{\partial p_1^{EL^*}}{\partial \gamma} = -\frac{\delta e_0}{2} < 0, \frac{\partial p_2^{EL^*}}{\partial \gamma} = -\frac{3\delta e_0}{4} < 0, \frac{\partial \pi_p^{EL^*}}{\partial \gamma} = (s - 1)\gamma + \frac{\delta e_0 E(\alpha_1 \lambda - 1)}{4} < 0, \frac{\partial \pi_r^{EL^*}}{\partial \gamma} = -\frac{\delta e_0 E(\alpha_1 \lambda - 1)(\lambda_1 - 1)}{8} < 0$$

$$\frac{\partial p_1^{EL^*}}{\partial s_1} = 0, \frac{\partial p_2^{EL^*}}{\partial s_1} = 0, \frac{\partial \pi_g^{EL^*}}{\partial \gamma} = -\frac{\delta e_0 E[1 - 4(\alpha_1 \lambda - 1) + 2\alpha_1(\lambda - 1)(\lambda_1 - 1)]}{16} - \frac{4k\gamma + 3\beta\delta e_0}{4} < 0, \frac{\partial \pi_p^{EL^*}}{\partial s_1} = \frac{k_1 \alpha_1^2 \lambda^2}{2} > 0$$

$$\frac{\partial \pi_r^{EL^*}}{\partial s_1} = 0, \frac{\partial \pi_g^{EL^*}}{\partial s_1} = 0, \frac{\partial p_1^{EL^*}}{\partial \alpha_1} = 0, \frac{\partial p_2^{EL^*}}{\partial \alpha_1} = 0, \frac{\partial \pi_p^{EL^*}}{\partial \alpha_1} = k_1 \alpha_1 \lambda^2 (s_1 - 1) - \frac{\lambda A}{8} < 0, \frac{\partial \pi_r^{EL^*}}{\partial \alpha_1} = \frac{\lambda A(\lambda_1 - 1)}{16} < 0$$

$$\frac{\partial \pi_g^{EL^*}}{\partial \alpha_1} = \frac{A[(\lambda - 1)(\lambda_1 - 1) - 2\lambda]}{16} - k_1 \alpha_1 \lambda^2 < 0.$$

Here, $A = (M + \beta - c - \delta e_0 \gamma)^2$, $E = M + \beta - c - \delta e_0 \gamma$.

Appendix B3

According to proof 4, we can obtain $\frac{\partial p_1^{ELB^*}}{\partial s} = 0$, $\frac{\partial p_2^{ELB^*}}{\partial s} = 0$, $\frac{\partial \pi_p^{ELB^*}}{\partial s} = \frac{k\gamma^2}{2} > 0$, $\frac{\partial \pi_r^{ELB^*}}{\partial s} = 0$, $\frac{\partial \pi_g^{ELB^*}}{\partial s} = 0$,

$$\frac{\partial p_1^{ELB^*}}{\partial \gamma} = -\frac{\delta e_0}{2} < 0, \frac{\partial p_2^{ELB^*}}{\partial \gamma} = -\frac{3\delta e_0}{4} < 0, \frac{\partial \pi_p^{ELB^*}}{\partial \gamma} = (s - 1)\gamma + \frac{\delta e_0 E(\alpha_1 \lambda - 1)}{4} < 0,$$

$$\frac{\partial \pi_r^{ELB^*}}{\partial \gamma} = -\frac{\delta e_0 E(\alpha_1 \lambda - 1)(\alpha_2 \lambda_1 - 1)}{8} < 0, \frac{\partial \pi_p^{ELB^*}}{\partial s_1} = \frac{k_1 \alpha_1^2 \lambda^2}{2} > 0, \frac{\partial \pi_g^{ELB^*}}{\partial s_1} = 0, \frac{\partial \pi_r^{ELB^*}}{\partial s_1} = 0,$$

$$\frac{\partial \pi_g^{ELB^*}}{\partial \gamma} = -\frac{\delta e_0 E[5 + 2(\alpha_1 \lambda - 1)(\alpha_2 \lambda_1 - 1) - 4\alpha_1 \lambda]}{16} - \frac{4k\gamma + 3\beta\delta e_0}{4} < 0, \frac{\partial p_1^{ELB^*}}{\partial s_1} = 0, \frac{\partial p_2^{ELB^*}}{\partial s_1} = 0, \frac{\partial p_1^{ELB^*}}{\partial s_2} = 0,$$

$$\frac{\partial p_2^{ELB^*}}{\partial s_2} = 0, \frac{\partial \pi_p^{ELB^*}}{\partial s_2} = 0, \frac{\partial \pi_r^{ELB^*}}{\partial s_2} = \frac{k_2 \alpha_2^2 \lambda_1^2}{2} > 0, \frac{\partial \pi_g^{ELB^*}}{\partial s_2} = 0, \frac{\partial p_1^{ELB^*}}{\partial \alpha_1} = 0, \frac{\partial p_2^{ELB^*}}{\partial \alpha_1} = 0,$$

$$\frac{\partial \pi_p^{ELB^*}}{\partial \alpha_1} = k_1 \alpha_1 \lambda^2 (s_1 - 1) - \frac{\lambda A}{8} < 0, \frac{\partial \pi_r^{ELB^*}}{\partial \alpha_1} = \frac{\lambda A(\alpha_2 \lambda - 1)}{16} < 0, \frac{\partial \pi_g^{ELB^*}}{\partial \alpha_1} = \frac{\lambda A(\alpha_2 \lambda_1 - 3)}{16} - k_1 \alpha_1 \lambda^2 < 0$$

Here, $A = (M + \beta - c - \delta e_0 \gamma)^2$, $E = M + \beta - c - \delta e_0 \gamma$.

APPENDIX C

Appendix C1

Proof: If $\pi_p^{ENL*} \geq \pi_p^{NEL*}$; the producer will use APE technology, so we get

$$s > 1 + \frac{\delta e_0(1-\lambda)(\gamma-1)(2M-2\beta-2c-\delta e_0-\delta e_0\gamma)}{4k^2}$$

we called it $s > \psi_1$. If $\pi_g^{ENL*} \geq \pi_g^{NEL*}$, the government will get more social benefits by subsidizing the producer's

APE subsidy to reduce investment, so we can get $\frac{A(1-\lambda)(1-\lambda_1)}{8} + \frac{\beta\delta e_0(\gamma-1)}{4} \geq \frac{k\gamma^2}{2}$ we called it $C(\gamma) < \psi_2$.

If $\pi_p^{ENL*} \geq \pi_p^{NEL*}$ and $\pi_g^{ENL*} \geq \pi_g^{NEL*}$, for the producer and the government, it is feasible to invest in APE technology and subsidize this investment. Only when $1 \geq s \geq \psi_1$, $C(\gamma) < \psi_2$, investing in APE technology and subsidizing that investment is feasible.

Appendix C2

Proof: If $\pi_p^{EL*} \geq \pi_p^{ENL*}$, the producer will use both APE and PHLG technology, and we get

$$s_1 > \xi_1 = 1 + \frac{A\lambda(\alpha_1-1)}{4k_1(\alpha_1\lambda-1)^2}, \text{ we called } s_1 > \xi_1. \text{ If } \pi_g^{EL*} \geq \pi_g^{ENL*}, \text{ by subsidizing the APE and PHLG inputs of the}$$

producer, the government will get more social benefits and we can get $\frac{\lambda A(\lambda_1-3)(\alpha_1-1)}{16} \geq \frac{k_1(\alpha_1\lambda-1)^2}{2}$,

it is called $C(\alpha_1, \lambda) < \xi_2$. If $\pi_p^{EL*} \geq \pi_p^{ENL*}$ and $\pi_g^{EL*} \geq \pi_g^{ENL*}$ for the producer and the government, it is feasible to invest in APE and PHLG technology and subsidize this investment. Only when $C(\alpha_1, \lambda) < \xi_2$, it is feasible to invest in APE technology and subsidize this investment.

Appendix C3

Proof: If $\pi_r^{ELB*} \geq \pi_r^{EL*}$, the retailer will adopt PHLG technology and we get $s_2 > \phi_1 = 1 + \frac{A\lambda_1(\alpha_1\lambda-1)(1-\alpha_2)}{8k_2(\alpha_2\lambda_1-1)^2}$

it is called $s_2 > \phi_1$. If $\pi_g^{ELB*} \geq \pi_g^{EL*}$, by subsidizing the PHLG technology for the retailer, the government will get

more social benefits and we can get $\frac{A\lambda_1(\alpha_2-1)(\alpha_1\lambda-1)}{16} > \frac{k_2(\alpha_2\lambda-1)^2}{2}$, it is called $C(\alpha_2, \lambda_1) < \phi_2$. If $\pi_r^{ELB*} \geq \pi_r^{EL*}$

and $\pi_g^{ELB*} \geq \pi_g^{EL*}$, it is feasible for the retailer and the government to invest in PHLG technology and subsidize this investment. When $C(\alpha_2, \lambda_1) < \phi_2$, for the retailer and the government, it is feasible to not invest in PHLG technology.

APPENDIX D

Table S1. Policies of grain loss subsidy in China

Date	Policy name	Policy content
2004	Grow grain subsidies	The government subsidizes farmers to encourage them to grow grain and gives them a certain amount of subsidy based on the area planted.
2004	Agricultural machinery purchase subsidies	Subsidies are given to farmers who purchase agricultural machinery and appliances to improve the level of agricultural mechanization. A certain percentage of subsidy is generally given according to the value of agricultural machinery.
2006	Grain production subsidies	The National Plan for the Development of Grain Production (2006-2020) mentions the improvement of the subsidy system with an organic combination of special and comprehensive subsidies for grain production.
2006	Comprehensive Agricultural Subsidy Policy	The central government implements comprehensive agricultural subsidies for grain farmers, following certain principles to subsidize funds to reasonably make up for the increased costs of agricultural production materials for grain farmers.
2015	Arable land protection and quality improvement Subsidy Policy	The government encourages and supports large grain farmers and farmers to return straw to their fields and apply more organic fertilizer to improve soil fertility, rural ecological environment and arable land quality.
2018	Agricultural machinery purchase subsidies again optimization	The Ministry of Agriculture and Rural Affairs mentioned the comprehensive optimization of agricultural machinery purchase subsidies for the process, and effectively speed up the progress of subsidy funds payment to enhance policy implementation satisfaction.
2020	Agricultural Products Loss Reduction and Efficiency Policy	The Ministry of Agriculture issued the “Guidance on Promoting Loss Reduction and Efficiency in the Processing of Agricultural Products” proposed that in 2025, the loss rate in the processing of agricultural products will be reduced to less than 5%.
2021	Agricultural production link saving and loss reduction policy	The General Office of the CPC Central Committee and the General Office of the State Council issued the “Grain Conservation Action Program” proposed to strengthen agricultural production link saving and loss reduction efforts.

Data source: <http://www.moa.gov.cn/>

Table S2. Policies on agricultural pollution emission management in China

Date	Policy Content
2010	The Technical Policy on the Prevention and Control of Pollution in Rural Areas is designed to prevent and control pollution by means of ‘subsidies in lieu of prizes’ and ‘prizes to promote treatment’, and to recycle pollutants to reduce pollution emissions.
2014	In order to reduce agricultural pollution emissions, used agricultural films are recycled to prevent agricultural surface pollution, protect the agricultural ecological environment and promote sustainable agricultural development.
2015	The Ministry of Agriculture’s ‘Opinions on Accelerating Cleaner Agricultural Production’ calls for enhancing the sense of responsibility and urgency of cleaner agricultural production, strengthening efforts to prevent pollution at source in the origin of agricultural products, promoting cleaner agricultural production processes and increasing efforts to control agricultural surface source pollution.
2017	The National Agricultural Pollution Source Census Program proposes to grasp the emissions of major pollutants in the production process of the plantation industry and their destinations, to find out the amount of mulch used and residue, the amount of straw produced and utilized, to clarify the emission patterns of agricultural pollution sources, and to clarify the dynamic trends of agricultural pollutants.
2018	The ‘agricultural and rural pollution control action plan’ mentioned that in order to effectively prevent and control pollution in the planting industry, we should continue to promote the reduction of chemical fertilizers, pesticides and increase efficiency; strengthen the resource utilization of straw and agricultural film waste and vigorously promote the ecological planting industry model.
2020	The Notice on Solid Promotion of Plastic Pollution Control mentioned to improve the recycling system of used agricultural films, polyethylene agricultural film with thickness less than 0.01 mm, irregularities in the use of agricultural mulch packaging plastic film, etc. into agricultural counterfeit action.
2022	The Agricultural and Rural Pollution Control Action Plan (2021–2025) mentions fertilizer and pesticide reduction and efficiency, agricultural film recycling as key areas to strengthen source reduction, resource utilization, pollution reduction and ecological restoration.

Data source: <http://www.moa.gov.cn/> and <https://www.mee.gov.cn/>

APPENDIX E

Appendix E1: Hybrid subsidies in the extended model

In the FENL model, the revenue functions of the grain producer, the retailer and the government are as follows:

$$\pi_p^{FENL} = (p_1^{ENL} - c + \beta)D^{FENL}(1 - \lambda) - \frac{(1 - s)k\gamma^2}{2} + C_1$$

$$\pi_r^{FENL} = (p_2^{ENL} - p_1^{ENL})D^{FENL}(1 - \lambda)(1 - \lambda_1)$$

$$\pi_g^{FENL} = \pi_p^{ENL} + \pi_r^{ENL} + CS^{ENL} - \beta D^{FENL} - \frac{sk\gamma^2}{2} - C_1$$

On this basis, the optimal solution is found for the retail price, the level of the producer's effort to reduce APE, and the benefit to the grain producer and the government.

$$\begin{cases} p_1^{FENL*} = \frac{M - \beta + c - \delta e_0 \gamma}{2} \\ p_2^{FENL*} = \frac{3M - \beta + c - 3\delta e_0 \gamma}{4} \\ D^{FENL*} = \frac{M + \beta - c - \delta e_0 \gamma}{4} \end{cases} \begin{cases} \pi_p^{FENL*} = \frac{k\gamma^2(s-1)}{2} - \frac{A(\lambda-1)}{8} + C_1 \\ \pi_r^{FENL*} = \frac{A(\lambda-1)(\lambda_1-1)}{16} \\ \pi_g^{FENL*} = \frac{(1+2(1-\lambda)(3-\lambda_1))A}{32} - \frac{\beta(M+\beta-c-\delta e_0 \gamma)}{4} - \frac{k\gamma^2}{2} - C_1 \end{cases}$$

Accordingly, the following table (Table S3) is derived by combining the assumptions.

Table S3. Optimal decision-making by supply chain members

C_1	s	p_1^{FENL*}	p_2^{FENL*}	π_p^{FENL*}	π_r^{FENL*}	π_g^{FENL*}
10	0.1	24.512	36.753	277.4657	129.4636	461.3555
	0.3	24.512	36.753	277.9657	129.4636	461.3555
	0.5	24.512	36.753	278.4657	129.4636	461.3555
	0.7	24.512	36.753	278.9657	129.4636	461.3555
	0.9	24.512	36.753	279.4657	129.4636	461.3555
30	0.1	24.512	36.753	297.4657	129.4636	441.3555
	0.3	24.512	36.753	297.9657	129.4636	441.3555
	0.5	24.512	36.753	298.4657	129.4636	441.3555
	0.7	24.512	36.753	298.9657	129.4636	441.3555
	0.9	24.512	36.753	299.4657	129.4636	441.3555
50	0.1	24.512	36.753	317.4657	129.4636	421.3555
	0.3	24.512	36.753	317.9657	129.4636	421.3555
	0.5	24.512	36.753	318.4657	129.4636	421.3555
	0.7	24.512	36.753	318.9657	129.4636	421.3555
	0.9	24.512	36.753	319.4657	129.4636	421.3555
70	0.1	24.512	36.753	337.4657	129.4636	401.3555
	0.3	24.512	36.753	337.9657	129.4636	401.3555
	0.5	24.512	36.753	338.4657	129.4636	401.3555
	0.7	24.512	36.753	338.9657	129.4636	401.3555
	0.9	24.512	36.753	339.4657	129.4636	401.3555

C – fixed subsidies; s – subsidy coefficient; FENL – fixed subsidy model; p – price; π – benefit

Source: Author's own elaboration

The computational process in the FEL and FELB models is like that in the FENL model and will not be repeated here.

Appendix E2: Fixed subsidies in the extended model

In the FENL model, the revenue functions of the grain producer, the retailer and the government are as follows:

$$\pi_r^{FENL} = (p_2^{ENL} - p_1^{ENL})D^{FENL}(1-\lambda)(1-\lambda_1)$$

$$\pi_g^{FENL} = \pi_p^{ENL} + \pi_r^{ENL} + CS^{ENL} - \beta D^{FENL} - \frac{k\gamma^2}{2} - C_1$$

On this basis, the optimal solution is found for the retail price, the level of the producer's efforts to reduce APE, and the benefits to the grain producer and the government.

$$\begin{cases} p_1^{FENL^*} = \frac{M - \beta + c - \delta e_0 \gamma}{2} \\ p_2^{FENL^*} = \frac{3M - \beta + c - 3\delta e_0 \gamma}{4} \\ D^{FENL^*} = \frac{M + \beta - c - \delta e_0 \gamma}{4} \end{cases} \begin{cases} \pi_p^{FENL^*} = \frac{k\gamma^2}{2} - \frac{A(\lambda - 1)}{8} + C_1 \\ \pi_r^{FENL^*} = \frac{A(\lambda - 1)(\lambda_1 - 1)}{16} \\ \pi_g^{FENL^*} = \frac{(1 + 2(1 - \lambda)(3 - \lambda_1))A}{32} - \frac{\beta(M + \beta - c - \delta e_0 \gamma)}{4} - \frac{k\gamma^2}{2} - C_1 \end{cases}$$

Based on these, we obtain the fixed subsidies C_1 have no effect on equilibrium prices but have a positive effect on the producer's revenue parameter and a negative effect on the government's revenue. the calculation process in the models of FEL and FELB is like that in the FENL model and will not be repeated here.