Government Interventions to Promote Agricultural Innovation

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(1) Problem Definition: Agricultural innovation can help farmers improve their productivity, reduce their environmental impact, and address the challenges associated with ever-changing soil, weather, and market conditions. Promoting innovation often requires government support as a way to incentivize producers to experiment with (and then eventually adopt) cutting-edge practices. We investigate the effectiveness of a number of policy instruments, i.e., taxes and subsidies, in terms of their impact on the adoption of innovative production methods, producers' profits, consumer surplus, and return on government expenditure.

(2) Academic/Practical Relevance: We contribute to the existing literature by investigating not only the policy maker's role in encouraging innovation but also the role of consumer preferences and learning-by-doing benefits of new production methods.

(3) Methodology: Our setting features producers with access to traditional and innovative production methods and consumers that have a higher valuation for the output of the innovative method. We develop a model to analyze producers' decisions of whether to experiment with a new production method when facing uncertainty about their production yield as well as the benefits associated with learning-by-doing.

(4) Results: Our findings indicate that using only taxes encourages experimentation with new production methods but decreases social welfare. Utilizing only subsidies outperforms policies that involve both taxes and subsidies in achieving higher social welfare but the converse is true in achieving a higher experimentation rate. We show that zero-expenditure policies result in a decline in social welfare unless producers face financial barriers when making the costly transition to new methods.

(5) Managerial Implications: The insights we generate can help policy makers design policies to achieve specific objectives, e.g., target experimentation/adoption rates. We illustrate their applicability by conducting a numerical study using data on conventional and organic egg production in Denmark. The study generates concrete policy recommendations to achieve the organic production goal set by the Danish government.

Key words: government intervention; subsidies; agricultural innovation; sustainable agriculture

1. Introduction

Contributing 3.9% of the global gross domestic product, agriculture is a vital sector of the world economy (The World Bank 2016). Agricultural innovation can improve farmers' productivity and reduce their environmental impact as they face significant challenges in adapting to rapid changes in soil, weather, and market conditions. For instance, in recent years, increasing food security concerns has incentivized innovation to increase production yields. The hybrid rice program implemented in the Philippines (David 2006) and the system of rice intensification method undertaken in India (Vidal 2013) are examples of innovative practices aimed towards increasing yields. Sustainability concerns and market trends are also important drivers of agricultural innovation. Organic farming has attracted a lot of attention lately as a result of growing environmental and health concerns as well as increasing demand for organic produce.

Innovative production methods could lead to premium products, which in turn command higher prices, making it desirable from the producers' perspective to engage in innovation. For instance, improved irrigation methods may lead to higher quality wine grapes that sell at higher prices. Similarly, organic produce is typically sold at a price premium. However, there are important barriers that prevent the majority of producers from experimenting with and eventually adopting innovative methods. Organic farming is a good example of this. First, despite the cost savings due to the elimination of chemical inputs such as fertilizers, pesticides, and herbicides, organic farming, being much more labor intensive than conventional production methods, generally results in higher production costs. Second, organic production yields tend to be lower during the first few years of conversion. Lack of knowledge of best practices such as the use of manure, crop rotation, methods of pest and weed control contributes to yield losses encountered during the transition period, constituting a financial barrier for producers that intend to engage in organic farming. Studies show that farms that intensively use agrochemicals in conventional production are likely to experience yield losses estimated between 5%–20% in the initial years of conversion (Rundgren 2006). Another study suggests that the yield losses can be as high as 34% (Seufert et al. 2012). Even though production yields are likely to improve as farmers gain experience and learn organic management methods, it is not uncommon that some farmers are not able to master the expertise needed for organic farming, thus failing to recover yields. This trade-off between higher expected prices and the costly and low-yield transition period with uncertain future prospects shapes a producer's decision on whether to experiment with organic farming. Similar trade-offs are present in other instances of agricultural innovation. For example, using hybrid seeds increases the yield, improving farmers' expected income, while the high cost of hybrid seeds constitutes a barrier to experimentation.

Given that it might not always be financially attractive for producers to undertake experimentation with innovative production methods, policy makers can play an important role in encouraging innovation for reasons including enhancing productivity to secure food supply, improving environmental sustainability, and meeting increasing demand for premium products. There are various policy instruments that can be used to support the transition to new production methods. For instance, in the case of organic farming, Denmark constitutes a successful example of the use of government interventions. The Danish organic market is well established with a market share of 7.6%, which is the highest in the world. With the goal of reducing the use of pesticides and protecting the country's water resources, organic farming was first regulated in 1987 with the adoption of the Organic Farming Act, and permanent organic subsidies were introduced in 1994. Currently, an annual subsidy of €140 per hectare is provided to farmers during the first two years of conversion and €13 per hectare for the next three years. Moreover, certification is undertaken by the government and provided free of charge to farmers. In addition to subsidizing the organic sector, the Danish government levies taxes on chemical inputs to discourage their use.

Motivated by these examples, we examine the economic impact of policy instruments that are used to foster agricultural innovation. We investigate the following research questions: (i) How do tax and subsidy policies affect experimentation with new production methods, producers' income, and consumer surplus? (ii) Which intervention type is more effective? (iii) How do the policy characteristics impact the benefits to different stakeholders? (iv) What is the net effect of interventions after accounting for government spending?

We use a setting in which producers with access to traditional and innovative production methods, both subject to random yield, serve consumers who have a higher valuation for premium products, i.e., the output of the innovative method. We study a two-period model that incorporates the learning-by-doing aspect of experimentation. In the case of our motivating example, organic farming yields are low in the initial years of conversion given that farmers may lack familiarity with organic production methods. Some farmers may attain higher yields as they gain experience whereas others may fail in recovering yields due to a lack of access to learning resources or unsuitable soil conditions. To capture this heterogeneity, we assume that there are two types of producers with different learning capabilities. On the consumer side, the output of the innovative method is valued higher but consumers are heterogeneous in the additional utility they obtain from their consumption.

In this setting, our results indicate that when the total government expenditure is kept fixed, subsidies alone achieve higher social welfare compared to policies that use both taxes and subsidies. However, the converse is true when considering the experimentation rate and consumer surplus as the primary quantities of interest. Thus, in contrast to prior work that argues that taxes and subsidies should be used together (Acemoglu et al. 2012), we show that when increasing competition diminishes the profitability of the new method, fostering experimentation through subsidies is more beneficial as far as aggregate welfare is concerned. Moreover, we find that zero-expenditure policies that use the income from taxes to fund subsidies may benefit either the producers or the consumers but not both (assuming the producers are risk neutral and can withstand the potential losses associated with the transition to the new production method). We also consider a setting where a subset of producers are *financially constrained*; i.e., they engage in production with a given method only if their expected profits are nonnegative in both periods. In this context, we find that it is possible for the policy maker to increase social welfare by using a zero-expenditure policy that restores the profitability of the new method during the transition phase. Similar intuition holds for the case where producers are risk averse. Our findings indicate that the experimentation rate is lower under risk aversion, but the policy maker may generate a positive welfare impact through interventions that decrease welfare in the risk neutral case. Lastly, we conduct a numerical study using data on conventional and organic egg production in Denmark, and investigate the set of policies that can achieve the goals of the Danish government regarding organic production.

2. Related Literature

Our paper contributes to the literature that studies the role of government interventions in new technology adoption, including organic and sustainable farming methods in the agriculture sector, solar panels in the energy sector, and electric vehicles in the automotive sector. In the agricultural economics literature, a number of papers study the impact of government policies on conversion to organic farming in European countries. Lohr and Salomonsson (2000) analyze whether subsidies are needed to promote organic agriculture by contrasting the case in Europe where conversion subsidies are widely used with that in the U.S. where the transition to organic farming is mostly market-driven. Pietola and Lansink (2001) explore the factors that impact the conversion choice in Finland and find that economic incentives such as direct subsidies are key components in promoting the transition to organic farming. Using data from the Netherlands, Acs et al. (2009) investigate the impact of farmers' risk attitudes on their conversion decisions. Our paper differs from this stream of literature in that we use an analytical model to analyze the producers' decision-making process and explore the impact of taxes and subsidies not only on the experimentation/adoption rate and producers' profits but also on the overall social welfare.

Agricultural supply chains have attracted attention in the operations management literature as well. The majority of these papers study production planning problems in the context of agribusiness (Boyabatli et al. 2017, 2011, Kazaz 2004, Kazaz and Webster 2011, Devalkar et al. 2011). Additionally, Federgruen et al. (2015) and Kouvelis and Li (2016) study a manufacturer's problem of contracting with farmers. Huh and Lall (2013) investigate farmers' land allocation decisions under irrigation constraints while Boyabatli et al. (2019) study a farmer's production problem in the presence of two crops with rotation benefits.

Policy-making has also been studied in the operations management literature. Levi et al. (2017) analyze the role of uniform subsidies as a means of increasing the consumption of a good. Other papers investigate the role of subsidies in increasing the availability of malaria drugs (Taylor and Xiao 2014, Kazaz et al. 2016) and ensuring efficient distribution of surface water to farms in varying proximity to a water source (Dawande et al. 2013). Others study the impact of private and public market information provision (Chen and Tang 2015) and agricultural advice and market forecast provision (Chen and Tang 2015) on farmers' welfare. Additionally, Alizamir et al. (2019) explore two types of farm subsidies used widely in the US, in terms of their impact on farmers, consumers, and the government.

Furthermore, our paper contributes to the technology adoption literature (McCardle 1985, Ulu and Smith 2009, Smith and Ulu 2012, 2017) and to the literature that studies consumer subsidies as a means of fostering green technology adoption, e.g., for solar panels and electric vehicles (Lobel and Perakis 2011, Chemama et al. 2019, Cohen et al. 2015, 2016). Complementing this literature, our paper explores the role of providing direct incentives to producers in the form of taxes and subsidies. Moreover, we investigate how the uncertainty in the learning-by-doing benefits impacts experimentation with new production methods and the government's efforts to promote them.

The papers that are most closely related to our work study producer-based policy instruments with the goal of promoting green technology. Alizamir et al. (2016) study the policy maker's problem of determining the prices of the feed-in tariff policies that are used to promote renewable energy adoption. Wang et al. (2018) use a framework in which the benefit from green technology is uncertain, and explore whether the policy maker can motivate adoption more effectively by taking into account the capability of the industry to meet regulatory standards. Acemoglu et al. (2012) study the role of carbon taxes and research subsidies in technological innovation under environmental constraints. The authors show that the optimal policy consists of both carbon taxes and research subsidies while avoiding excessive use of the former. In contrast to this result, we show that fostering experimentation through subsidies alone is more beneficial for social welfare when increasing competition diminishes the profitability of the new production method.

3. Model

Since conversion to a new production technique often requires a transition period, we consider a two-period model. Producers have access to two production methods that can be implemented in each period, the traditional method, denoted by T, and the new method, denoted by N. Both production methods are subject to random yield. Period 1 is the transition phase and period 2 is considered to be the long-run steady state. To distinguish between the two periods, we say that producers *experiment* with the new production method in period 1 and *adopt* it in period 2.

3.1. Producers

We assume that the economy consists of a continuum of producers with unit mass. This framework is well suited for settings in which each farmer's decisions have a small impact on aggregate outcomes; i.e., producers act as price takers. Each producer has unit capacity and chooses whether to use the traditional or new production method in periods 1 and 2.

In practice, whether innovation will be implemented successfully is uncertain. For instance, in the case of organic farming, a producer's ability to farm organically depends on several factors including the extent to which synthetic inputs were used before the conversion to organic production, the farmer's expertise in controlling pests and weeds without the use of chemicals, and soil and weather conditions. As a result, while some farmers can easily convert to organic farming, some fail to recover the yields even after the transition phase. Motivated by this, we assume that the producer's capability in implementing new production methods is revealed once he experiments during the transition phase. There are two types of producers, high and low, denoted by H and L respectively. The fraction of high types in the producer population is assumed to be random. If the producer's type is high and he experiments with the new method in period 1, then the producer *learns*; i.e., the yield he obtains from the new method in period 2 is higher than the one in period 1 (note that the improved yield of the new method may still be lower than of the traditional method). Producers do not know their types prior to experimentation. If a producer uses the new production method in period 1, he discovers his type at the end of the period and exploits that information when choosing which method to use in period 2. On the other hand, producers that do not experiment with the new method in period 1 do not learn their types. Since the traditional method is well established, producers engaging in it do not experience the improvement in yield associated with learning. The notation is summarized in Table 1.

Table 1 Notation

Notation	Explanation
θ_i	Improvement in the expected yield of the new method incurred by a producer of type i in period 2, $\theta_i \in \{\theta_H, \theta_L\}$ where $\theta_H > \theta_L$
α	Fraction of high types in the producer population with mean $\bar{\alpha}$ and standard deviation σ_α
ϕ_T	Yield of the traditional method with mean μ_T and standard deviation σ_T
ϕ_N	Yield of the new method in period 1 with mean μ_N and standard deviation σ_N
ϕ_N^i	Yield of the new method in period 2 faced by a producer of type i with mean μ_N^i and standard deviation σ_N
σ_{TN}	Covariance between the yields of the traditional and new methods
c_j	Unit production cost of method j, $j \in \{T, N\}$ where $c_N > c_T$

In our model, learning does not change the yield variance of the new production method and the covariance between the yields of the two production methods as we assume that yield variability is mainly due to uncertain weather conditions and is not affected by producers' experience in implementing new production methods.[1] The improvement in the yield associated with the new

[1] In Section 7.2, we explore the case where learning results in a reduction in the yield variability of the new method.

production method is modeled as a shift in the corresponding distribution. That is, provided that a producer of type i experiments with the new method in period 1, the yield in period 2 is given by $\phi_N^i = \phi_N + \theta_i$. As a result, the expected yield in period 2 is given by $\mu_N^i = \mu_N + \theta_i$. For simplicity, we normalize the improvement incurred by low types to zero ($\theta_L = 0$). Lastly, we assume that the new method has a higher unit cost. In the case of our motivating example, even though organic farming induces a decline in input costs as the use of synthetic inputs is prohibited, it is more labor intensive than conventional farming, resulting in a higher overall unit cost (Bruinsma 2003).

3.2. Consumers

We consider a continuum of consumers with a total market size M. The valuation for the end product produced through method j is denoted by v_j, $j \in \{T, N\}$. Consumers value the output of the new method higher than its counterpart produced through the traditional method, resulting in $v_N > v_T$. Thus, in what follows, we will refer to the output of the new method as the *premium product*. We assume that there is heterogeneity in consumers' sensitivity, denoted by s, to the consumption of the premium product, and we assume that s is uniformly distributed over $[0,1]$. That is, the utility that a consumer of type s gets from the consumption of a product produced through method j in period t is given by $u + sv_j - p_{jt}$, where u is the common utility gained from the consumption of the final product and p_{jt} is the price of the product in period t.

3.3. Market-Clearing Price

The price of the product in our model economy is determined so that the market clears; i.e., the total supply matches the demand in each period. In what follows, we suppress the subscript for time to ease the notational burden.

In order to calculate prices, we first find the demand, given any price pair (p_T, p_N). In equilibrium, there is a consumer of type $\underline{s}$ that is indifferent between using the outside option, which is assumed to yield zero utility, and purchasing the product produced through the traditional method, i.e., $u + \underline{s}v_T - p_T = 0$, resulting in $\underline{s} = \frac{p_T - u}{v_T}$. There is another consumer of type $\bar{s} \geq \underline{s}$ that is indifferent between purchasing the product produced through the traditional method and the one produced through the new method, i.e., $u + \underline{s}v_T - p_T = u + \bar{s}v_N - p_N$, resulting in $\bar{s} = \frac{p_N - p_T}{v_N - v_T}$. Using $\underline{s}$ and $\bar{s}$, one can calculate the demand for the traditional and premium products. Let us denote the total demand for and supply of the product that is produced through method j as Q_j^{Demand} and Q_j^{Supply}, respectively, for $j \in \{T, N\}$. Then, Q_T^{Demand} and Q_N^{Demand} are given by

$$Q_T^{Demand} = M\,(\bar{s} - \underline{s}) = M\,\frac{(p_N - u)v_T - (p_T - u)v_N}{v_T(v_N - v_T)}, \qquad \text{and} \tag{1}$$

$$Q_N^{Demand} = M\,(1 - \bar{s}) = M\,\frac{v_N - p_N - v_T + p_T}{v_N - v_T}. \tag{2}$$

Consequently, the market-clearing condition, $Q_j^{Demand} = Q_j^{Supply}$ for $j \in \{T, N\}$, gives

$$p_{Tt} = u + v_T\left(1 - \frac{Q_{Tt}^{Supply}}{M} - \frac{Q_{Nt}^{Supply}}{M}\right)^+, \qquad \text{and} \tag{3}$$

$$p_{Nt} = u + v_N\left(1 - \frac{v_T}{v_N}\frac{Q_{Tt}^{Supply}}{M} - \frac{Q_{Nt}^{Supply}}{M}\right)^+. \tag{4}$$

Note that the premium product sells at a higher price as it is valued more than the traditional product. Consumers that are willing to pay higher prices for the premium product create incentives for the producers to experiment with the new production method despite the higher cost. From now on, for simplicity, we normalize the base utility gained from the consumption of the final product to zero, i.e., $u = 0$. Moreover, we assume that the production yields are not high enough to cover the total market size so that prices do not fall to zero.

3.4. Equilibrium Characterization

Here, for notational simplicity, we define $\kappa_j = \frac{\mu_j^2 + \sigma_j^2}{M}$ for $j \in \{T, N\}$ and $\kappa_{TN} = \frac{\sigma_{TN} + \mu_T \mu_N}{M}$. The parameters κ_N and κ_{TN} are used with superscript i whenever the type of the producer is known.

We assume that $v_N \mu_N < c_N$; i.e., it is not profitable to experiment with the new production method in a single-period setting due to the high cost and/or low expected yield. Thus, producers that choose not to experiment in period 1 continue using traditional production in period 2. This assumption reflects the fact that farmers that choose to experiment endure profit losses during the transition phase with the expectation of obtaining higher profits in future periods. Moreover, we assume that the expected profit obtained through the traditional method is nonnegative even if every other producer is also using the traditional method, i.e., $v_T \mu_T - c_T - v_T \kappa_T \geq 0$, or if every other producer is using the new method with the improved yield, i.e., $v_T \mu_T - c_T - v_T \kappa_{TN}^H \geq 0$. That is, the market size is large enough so that producers can always generate positive profits through the traditional method.

In the model, period 1 represents the duration of the initial phase in which a producer experimenting with the new method experiences low yields. In reality, this could be more than one season. For instance, farmers have to produce organically for a few years before they can get certification and have access to the organic market. Lower yields in period 1 can be representative of the barriers a producer encounters in reality when transitioning to organic agriculture. On the other hand, in the second period, the producer may start realizing higher yields, potentially lasting for a longer period of time than the first period. In order to account for the different durations of the two phases, one has to discount the profits and welfare gained in each period. We assign weights to periods 1 and 2 and normalize the weight in the first period to one. The weight of the second period is denoted by w, where $w > 1$ in order to capture the fact that the post-experimentation phase lasts longer than the transition phase.

Let β_t denote the fraction of the producer population that uses the new production method in period t. We refer β_1 as the *experimentation* rate and β_2 as the *adoption* rate. The characterization of the unique equilibrium is described in Appendix A. Given our model's assumptions, out of the producers that experiment with the new method in period 1, only high types adopt it in period 2 whereas low types convert back to the traditional method. Let us denote the total expected profit of producers that use method i in period 1 as Π_P^i for $i \in \{T, N\}$. In equilibrium, Π_P^T and Π_P^N are given as follows.

$$\Pi_P^T = v_T\mu_T - c_T - v_T\kappa_T\left(1-\beta_1\right) - v_T\kappa_{TN}\beta_1 + w\mathbb{E}_\alpha\left[v_T\mu_T - c_T - v_T\kappa_T\left(1-\alpha\beta_1\right) - v_T\kappa_{TN}^H\alpha\beta_1\right], \quad (5)$$

$$\begin{aligned}\Pi_P^N = {} & v_N\mu_N - c_N - v_T\kappa_{TN}\left(1-\beta_1\right) - v_N\kappa_N\beta_1 + w\mathbb{E}_\alpha\Big[\alpha\left(v_N\left(\mu_N+\theta_H\right) - c_N - v_T\kappa_{TN}^H\left(1-\alpha\beta_1\right) - v_N\kappa_N^H\alpha\beta_1\right) \\ & + \left(1-\alpha\right)\left(v_T\mu_T - c_T - v_T\kappa_T\left(1-\alpha\beta_1\right) - v_T\kappa_{TN}^H\alpha\beta_1\right)\Big]. \quad (6)\end{aligned}$$

Moreover, we define the expected *marginal gain* from experimentation (and potential adoption) and the *externality* imposed on the traditional method as a result of experimentation as follows.

$$\text{Marginal Gain (MG)} = v_N\mu_N - c_N - v_T\mu_T + c_T + w\bar{\alpha}(v_N\mu_N^H - c_N - v_T\mu_T + c_T), \quad (7)$$

$$\text{Externality (E)} = v_T\left(\kappa_T - \kappa_{TN} + w\bar{\alpha}\left(\kappa_T - \kappa_{TN}^H\right)\right). \quad (8)$$

Here, the marginal gain captures the difference between the producer's expected profits for the two production methods (experimenting with the new production method and adopting it conditional on being a high type vs. using traditional production) in the absence of any competition (i.e., if the producer acts as a monopolist). On the other hand, the externality captures the aggregate impact of producers' experimentation with and adoption of (if they are high types) the new method on the profits of the traditional method. The equilibrium experimentation rate β_1 is characterized by the indifference condition given by $\Pi_P^T = \Pi_P^N$. The resulting experimentation rate in period 1 is then obtained as $\beta_1 = \frac{MG+E}{X}$, with

$$X = \upsilon_N \kappa_N - 2\upsilon_T \kappa_{TN} + \upsilon_T \kappa_T + w\kappa_\alpha \left(\upsilon_N \kappa_N^H - 2\upsilon_T \kappa_{TN}^H + \upsilon_T \kappa_T\right) \text{ and } \kappa_\alpha = \bar{\alpha}^2 + \sigma_\alpha^2.$$

Then, we obtain the following proposition.

Proposition 1. *The rate of experimentation with the new production method is first increasing and then decreasing in the expected fraction of high types, whereas the adoption rate is increasing monotonically. Furthermore, both the experimentation and adoption rates are decreasing in the yield variability of the new method.*

The rate of experimentation is not monotonic in the expected fraction of high-type producers given that the increase in competition among eventual adopters results in a reduction in premiums, undermining the benefits from experimentation. Hence, in cases where the farmers' transition is expected to be straightforward, the experimentation rate in the initial phase may not be very high due to the amount of competition expected to occur in the production of premium products in the long run.

4. Interventions

Next, we investigate the effectiveness of utilizing taxes and subsidies in terms of their impact on experimentation, surplus allocation between producers and consumers, and social welfare. We assume that interventions are implemented during the transition phase (period 1) to promote experimentation with the new method and withdrawn in the long run (period 2).

Let Δc_T and Δc_N denote the unit tax applied to the traditional method and the unit subsidy applied to the new method, respectively. Note that if $\Delta c_N > 0$ and $\Delta c_T = 0$, the intervention serves as a subsidy-only policy, whereas if $\Delta c_T > 0$ and $\Delta c_N = 0$, it corresponds to a tax-only policy. Let

$\beta_1^{(\Delta c_N, \Delta c_T)}$ denote the equilibrium experimentation rate under a $(\Delta c_N, \Delta c_T)$ policy. The incentives provided by the government shift experimentation, resulting in

$$\beta_1^{(\Delta c_N, \Delta c_T)} = \frac{MG + E + \Delta c_N + \Delta c_T}{X} = \beta_1 + \eta, \text{ where } \eta = \frac{\Delta c_N + \Delta c_T}{X}.$$

Here, we assume that the total policy pressure exerted on the producers, that is, the total amount of taxes and subsidies, is not too high, i.e., $\Delta c_N + \Delta c_T < X(1 - \beta_1)$, so that experimentation is given by an interior solution, i.e., $\beta_1^{(\Delta c_N, \Delta c_T)} \in (0, 1)$.

Let $\Delta\Pi_P$ and $\Delta\Pi_C$ denote the impact of the intervention on producers' expected profits and consumer surplus, respectively. We define the sum of producers' profits and consumer surplus as the economy's social welfare and, consequently, we denote the intervention's impact on social welfare by $\Delta\Pi_{SW} = \Delta\Pi_C + \Delta\Pi_P$. Furthermore, we define the (government's) *net intervention expenditure* as the difference between the payments given out to producers as subsidies and the income collected as taxes. That is, under a $(\Delta c_N, \Delta c_T)$ policy, the net intervention expenditure ζ is given by

$$\zeta = \Delta c_N \beta_1^{(\Delta c_N, \Delta c_T)} - \Delta c_T \big(1 - \beta_1^{(\Delta c_N, \Delta c_T)}\big). \tag{9}$$

In the remainder of the paper, we use the term expenditure to refer to ζ, i.e., the net expenditure associated with a given intervention. Finally, we let $\Delta\Pi_G$ denote the government's *return* on its expenditure, which is defined as $\Delta\Pi_G = \Delta\Pi_{SW} - \zeta$.

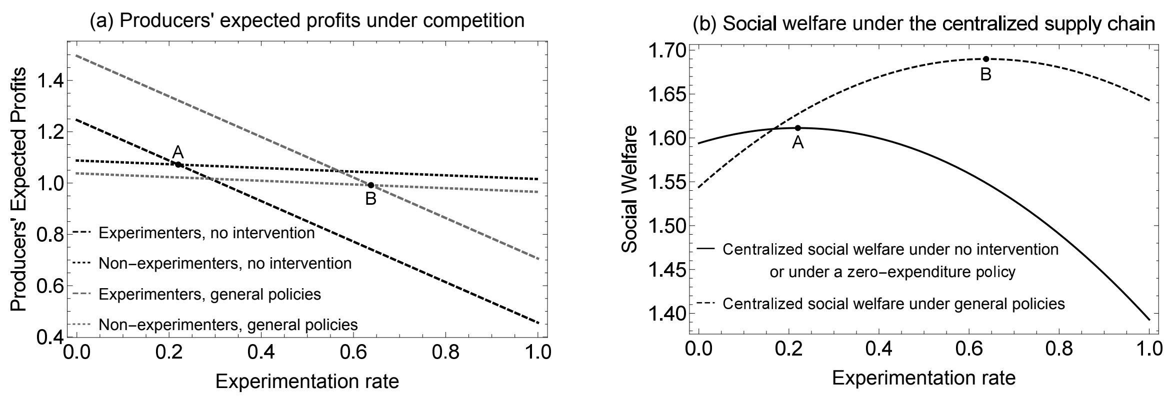
4.1. Zero-Expenditure Interventions

Zero-expenditure interventions, i.e., interventions for which $\zeta = 0$, entail the use of the income from the tax on the traditional method to subsidize the new method. Such policies might be desirable from the government's perspective as the resulting intervention is self-funded. However, in the following proposition, we show that zero-expenditure policies result in lower social welfare, failing to simultaneously improve consumer surplus and producers' profits.

Proposition 2. *Zero-expenditure policies always result in a reduction in social welfare.*

In this setting, the laissez-faire equilibrium achieves the highest social welfare. Consequently, interventions that do not involve a positive monetary transfer from the government cannot increase social welfare. Figure 1 illustrates this point. Point A is the equilibrium experimentation rate of the new method under the no-intervention benchmark. Point A also attains the maximum social welfare in the case of a centralized agricultural supply chain under no intervention or under a zero-expenditure policy. This observation implies that the equilibrium solution under competition among producers achieves supply-chain coordination. On the other hand, the competitive equilibrium under a zero-expenditure policy gives a higher experimentation rate, resulting in a reduction in social welfare compared to the competitive equilibrium under no intervention. However, even though social welfare decreases, either producers or consumers may benefit from the intervention, which is an important consideration as policy makers may not always place equal emphasis on producers and consumers. In the following proposition, we characterize the impact of a zero-expenditure policy on the producer and consumer sides of the market.

Figure 1 Experimentation rate under competition vs. centralized supply chain



Note. $v_T = 0.6$, $\mu_T = 1.5$, $\sigma_T = 0.4$, $c_T = 0.6$, $v_N = 1$, $\mu_N = 1.25$, $\sigma_N = 0.8$, $c_N = 1.35$, $\sigma_{TN} = 0.1$, $\theta_H = 0.55$, $\bar{\alpha} = 0.7$, $\sigma_\alpha = 0.1$, $w = 6$, $M = 10$, $\Delta c_T = 0.05$, $\Delta c_N = 0.25$.

PROPOSITION 3. *If the marginal gain from experimentation is positive, consumer surplus increases whereas expected profits of producers decrease under a zero-expenditure policy. Otherwise, if $\Delta c_N + \Delta c_T < -MG$, only producers benefit, whereas if $\Delta c_N + \Delta c_T > -2MG$, only consumers benefit. Finally, if $-MG < \Delta c_N + \Delta c_T < -2MG$, neither party benefits.*

Methods with positive marginal gain incentivize experimentation even in the absence of any intervention. In this case, a zero-expenditure policy increases competition among producers that choose to experiment and shrinks margins for those that do not, thus hurting the overall producer population. On the other hand, if the losses due to high costs and low initial yields cannot be recovered in the long run, it is possible to benefit producers. However, in this case, the total amount of policy pressure exerted on the producers determines which party extracts the benefits. If the pressure on the producers is high such that the experimentation rate is not justified by the long-run benefits, producers incur losses. Meanwhile, consumers are likely to suffer from the adverse characteristics of the new method that are not addressed by the intervention, such as low yields. Nevertheless, consumers may gain under a policy that exerts very high pressure on producers in order to foster experimentation, making up for the yield losses by substantially increasing experimentation/adoption and the availability of premium products.

Lastly, as illustrated by point B in Figure 1b, an increase in social welfare can be attained in the competitive equilibrium through a policy that entails positive government expenditure. We will explore such policies in the next section.

4.2. General Policies

We now turn to a broader class of policies with nonzero expenditure that can in fact achieve an improvement in social welfare while promoting innovation. The next proposition provides a characterization of such policies.

PROPOSITION 4. *Social welfare increases under a $(\Delta c_N, \Delta c_T)$ policy if and only if*

$$(\Delta c_N + \Delta c_T)^2 + 2(MG + E)\Delta c_N - 2(X - MG - E)\Delta c_T > 0, \tag{10}$$

implying that subsidy-only policies always increase social welfare whereas tax-only policies reduce social welfare.

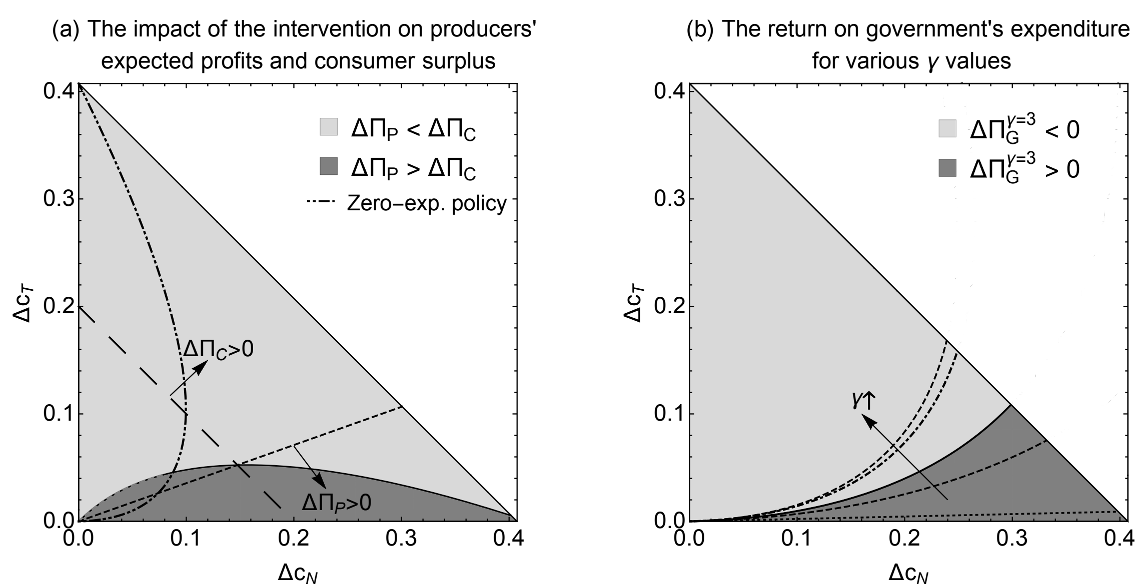
As the experimentation/adoption rate increases, the surge in competition diminishes the profitability of innovation. Since tax-only policies do not compensate experimenters for the adverse effects of increasing competition besides penalizing producers that do not experiment, social welfare decreases. On the other hand, policies that subsidize innovation reduce the impact of the negative externality each experimenter imposes on the others, creating an opportunity to improve overall welfare. Consequently, when both instruments are used, policies with high subsidy and low tax rates are more likely to enhance social welfare. Note that if learning reduces the yield variability of the new production method in addition to improving the expected yield, the condition presented in Proposition 4 becomes less restrictive, suggesting that social welfare can be improved under policies with higher tax rates.

The following proposition compares the impact of general policies on producers and consumers.

Proposition 5. *If the marginal gain from experimentation is higher than the externality imposed on the expected profit of traditional production, the impact of the intervention on producers' expected profits is lower than the impact on consumer surplus under any policy. Otherwise, the converse is true if and only if* $(\Delta c_N + \Delta c_T)^2 - 2(\Delta c_N + \Delta c_T)(E - MG) + 2X\Delta c_T < 0$.

Producers experimenting with the new method may impose a negative or positive externality on the producers engaged in traditional production. And, the difference between the externality and the marginal gain determines which party benefits more from the intervention. If experimentation is not very advantageous financially, either because it results in positive externalities on the profitability of the traditional method or the marginal gain from experimentation is low, under a high-subsidy, low-tax policy, producers extract greater benefit from the intervention compared to consumers. This is depicted in Figure 2a. Otherwise, producers are incentivized to experiment even in the absence of any intervention, and in this case, increased competition limits the benefit of the intervention.

Figure 2 The impact of the intervention on producers' expected profits, consumer surplus, and the return on the government's expenditure



Note. $v_T = 0.6$, $\mu_T = 1.5$, $\sigma_T = 0.45$, $c_T = 0.75$, $v_N = 1$, $\mu_N = 1.1$, $\sigma_N = 0.9$, $c_N = 1.2$, $\sigma_{TN} = 0.01$, $\theta_H = 0.3$, $\bar{\alpha} = 0.5$, $\sigma_\alpha = 0.1$, $w = 6$, $M = 10$.

Next, we focus on the government's return on expenditure, $\Delta\Pi_G$.

Proposition 6. *The return on the government's expenditure is negative for any policy.*

When a producer experiments with the new production method, he imposes a negative externality on the other experimenters (because of the increase in the supply of premium products), which results in lower prices. This negative externality causes the increase in social welfare induced by the intervention to be lower than the corresponding expenditure by the government. It is important to note that this result does not take into account other potential benefits of innovation. For instance, it is known that organic farming helps restore biodiversity and soil fertility. Also, eliminating the use of chemical inputs has important health benefits. If these factors play an important role in the welfare of producers and consumers, the policy maker may place more emphasis on social welfare improvement than on policy expenditure. To capture such cases, we define the γ-adjusted return on the government's expenditure, denoted by $\Delta\Pi_G^\gamma$, as $\Delta\Pi_G^\gamma = \gamma\Delta\Pi_{SW} - \zeta$ where $\gamma > 1$. As shown in Figure 2b, as γ increases, the policy maker can attain a positive adjusted return for a larger set of policies. Moreover, for a given subsidy rate, higher taxes can be levied while maintaining a positive return.

We now turn to the question of whether there is a dominating $(\Delta c_N, \Delta c_T)$ policy. From Proposition 4, we know that even though taxes increase the experimentation rate, such an increase is in fact not beneficial for welfare without having subsidies to compensate for the costs associated with the transition to the new equilibrium. The following propositions investigate the impact of coupling subsidies with taxes. We first explore the case where the unit subsidy is kept fixed.

Proposition 7. *When the unit subsidy* (Δc_N) *is kept fixed, a policy that entails both taxes and subsidies results in lower social welfare compared to a subsidy-only policy, and the same holds for the government's return on expenditure. However, utilizing both policy instruments generates a lower policy expenditure if and only if* $2\Delta c_N + \Delta c_T < (1-\beta_1)X$.

The following proposition compares policies that generate the same expenditure.

Proposition 8. *For any given policy that utilizes both taxes and subsidies, there exists a subsidy-only policy that incurs the same expenditure while achieving higher social welfare. However, the experimentation rate under such a subsidy-only policy is lower.*

Proposition 7 states that if the policy maker uses a specific subsidy rate, which might be the case when the policy maker aims to guarantee a minimum profit margin to producers that choose to experiment, using both taxes and subsidies achieves more experimentation as the pressure imposed on producers is higher compared to a subsidy-only policy. However, in the absence of taxes, the policy maker attains a greater improvement in social welfare due to the lack of punishment of producers that do not experiment. Furthermore, even if the inclusion of taxes may result in a lower policy expenditure, the return on the government's expenditure is higher when taxes are dispensed with. That is, the negative impact of taxes on producers' profits exceeds the reduction in policy expenditure (if any) due to the negative externalities that each experimenter imposes on the others. According to Proposition 8, these results continue to hold when we keep the policy expenditure fixed. Under a fixed expenditure, utilizing both taxes and subsidies provides the policy maker with more flexibility compared to a subsidy-only policy, thus resulting in a policy that exerts higher pressure on producers in order to foster experimentation. On the other hand, subsidies alone are more effective in improving the overall welfare. Hence, the policy maker faces a trade-off when choosing which policy instruments to utilize. Additionally, depending on whether the producers or consumers are prioritized, we find that the use of taxes together with subsidies may outperform subsidy-only policies, as shown in the following proposition.

PROPOSITION 9. *If the marginal gain from experimentation is positive, when the expenditure is kept the same, the policy that includes both taxes and subsidies achieves higher consumer surplus than the subsidy-only policy. Under the same condition, the converse is true for producers' profits.*

As shown earlier, positive marginal gain incentivizes experimentation even in the absence of any intervention. In such cases, due to the increase in competition in the production of premium products, policies that generate higher experimentation undermine the gain for producers whereas consumers benefit from the increased availability of premium products. Thus, our findings indicate that under similar expenditures, a policy using both taxes and subsidies outperforms a subsidy-only policy in achieving higher consumer surplus but the converse is true in achieving higher producers' profits.

5. Financially Constrained Producers

Due to high costs and low yields, implementing new production methods results in profit losses during the initial transition phase. Even if the losses are expected to be recovered in later periods, some producers may not have the financial resources to overcome the initial phase of experimentation. For instance, organic certification is a costly process constituting a financial barrier that prevents farmers from converting to organic farming (Rustin 2015). In this section, we will revisit the policy instruments studied earlier to analyze the impact of policy choice when producers face financial constraints.

Let δ denote the fraction of producers that are financially constrained. We assume that a financially constrained producer can engage in production with a given method only if his expected profits are nonnegative in both periods. Let us denote the equilibrium experimentation rate under no intervention and under a $(\Delta c_N, \Delta c_T)$ policy as $\tilde{\beta}_1$ and $\tilde{\beta}_1^{(\Delta c_N, \Delta c_T)}$, respectively. Note that under the no-intervention benchmark, innovation yields negative profits during the transition phase, thus preventing experimentation by the financially constrained producers. The following proposition characterizes the equilibrium experimentation rate.

Proposition 10. *In the presence of financial constraints, the experimentation rate in equilibrium is* $\tilde{\beta}_1 = \min\{1-\delta, \beta_1\}$.

Experimentation is adversely affected only if the fraction of financially constrained producers is high. If innovation is impeded due to the lack of financial flexibility on the producer side, the policy maker may need to intervene in order to not only increase the producers' flexibility to choose between the alternative methods but also enhance the welfare of consumers with an increase in the availability of premium products. The policy maker can achieve experimentation by the financially constrained producers only if the expected profit from the new method during the transition phase is nonnegative under the policy. From now on, we say that experimentation with the new method is *affordable* under a $(\Delta c_N, \Delta c_T)$ policy if the expected profit obtained through innovation in period 1 with an experimentation rate $\beta_1^{(\Delta c_N, \Delta c_T)}$ is positive. That is, a policy that makes innovation *affordable* ensures that financial constraints are eliminated.

Proposition 11. *If innovation is affordable under a* $(\Delta c_N, \Delta c_T)$ *policy, the equilibrium experimentation rate is the same as in the absence of financial constraints, i.e.,* $\tilde{\beta}_1^{(\Delta c_N, \Delta c_T)} =$

$\beta_1^{(\Delta c_N,\Delta c_T)}$. *Otherwise, if* $v_N\kappa_N < v_T\kappa_{TN}$*, none of the financially constrained producers experiment with the new production method. If* $v_N\kappa_N > v_T\kappa_{TN}$*, financially constrained producers can experiment with the new method only if all of the nonconstrained producers choose to experiment and experimentation yields nonnegative profits.*

From Proposition 11, we can conclude that the highest equilibrium experimentation rate is achieved when the policy maker enacts a policy that makes experimentation *affordable* at an experimentation rate of $\beta_1^{(\Delta c_N,\Delta c_T)}$. Otherwise, experimentation by constrained producers can occur only if all of the nonconstrained producers also experiment and experimentation generates nonnegative profits.

COROLLARY 1. *Using only taxes cannot induce experimentation by financially constrained producers. Moreover, there exists a threshold* $\bar{\sigma}_{TN}$ *such that no policy achieves experimentation by the constrained producers if the covariance between the yields is greater than* $\bar{\sigma}_{TN}$.

Using only taxes increases experimentation by nonconstrained producers while reducing the profit margins of producers that do not have the financial resources to experiment. Furthermore, if the covariance between the yields of the two methods is high enough, no policy can provide incentives to financially constrained producers to engage in innovation. In this case, the positive impact of the reduction in traditional production on the profits from the new method is not enough to overcome the negative impact of increasing competition among experimenters, resulting in a failure to achieve an affordable transition to the new production method. Next, we study the welfare impact of enabling financially constrained producers to experiment with new methods.

PROPOSITION 12. *Under a zero-expenditure policy that makes innovation affordable,*

(i) if $\delta \le 1-\beta_1$*, social welfare decreases;*

(ii) otherwise, social welfare increases if and only if $\Delta c_N + \Delta c_T < (\delta - (1-\beta_1))\,X$*, where* Δc_N *and* Δc_T *satisfy the zero-expenditure condition, i.e.,* $\Delta c_N \beta_1^{(\Delta c_N,\Delta c_T)} - \Delta c_T\big(1-\beta_1^{(\Delta c_N,\Delta c_T)}\big) = 0$.

Moreover, under any policy that ensures that innovation is affordable, the return on the government's expenditure is positive if and only if $\delta > 1-\beta_1$ *and* $\Delta c_N + \Delta c_T < (\delta-(1-\beta_1))\,X$.

Figure 3a depicts the case in which an improvement in social welfare can be attained under zero-expenditure policies. Due to subsidies being too low, policies that lie in region I do not

Figure 3 **The impact of the intervention on social welfare and the return on government's expenditure in the presence of financially constrained producers with** $\delta > 1 - \beta_1$

Note. $v_T = 0.8$, $\mu_T = 3$, $\sigma_T = 1$, $c_T = 0.6$, $v_N = 1.6$, $\mu_N = 1$, $\sigma_N = 0.3$, $c_N = 1.7$, $\sigma_{TN} = 0.1$, $\theta_H = 1.5$, $\bar{\alpha} = 0.9$, $\sigma_\alpha = 1$, $w = 8$, $M = 12$, $\delta = 0.95$.

make experimentation affordable, thus failing to incentivize financially constrained producers to experiment. In region II, even though financially constrained producers cannot experiment, social welfare increases since taxes imposed on those that do not experiment are low and the rest benefit from subsidies. Policies within region III achieve affordability by offering higher subsidies; however, social welfare decreases as the reduction in profit margins caused by high taxes reduces producers' profits. Lastly, policies lying in region IV, which includes a subset of zero-expenditure policies, induce experimentation by financially constrained producers as well as increase social welfare. Here, the policy maker enhances welfare by removing financial barriers and ensuring that financially constrained producers can benefit from higher profitability of the new production method in the long run. Moreover, as shown in Figure 3b, a positive return on the government's expenditure can be obtained in this case. This can be achieved by policies that are not too aggressive, i.e., taxes and subsidies are not too high. When the total amount of policy pressure is high, the profitability of innovation diminishes due to high competition, resulting in a negative return.

Overall, even though zero-expenditure policies cannot improve social welfare in the absence of financially constrained producers, such policies can in fact enhance welfare if financial constraints are a first-order consideration on producers' experimentation decisions.

6. Numerical Illustration

In this section, we conduct a numerical study using data on egg production in Denmark. Eggs are considered to be one of the products with the highest organic consumption in Denmark, along with dairy products and cereals. Currently, organic egg production amounts to approximately 20% of total egg production while nonorganic egg production dominates the market with three different production methods: cage, barn, and free range. We categorize these methods under conventional production when estimating model parameters.

We use the 2015 Danish Poultry Council Annual Report to obtain the data on prices, yields, and production costs. The kilograms of eggs sold for egg packing for human consumption are used as a proxy for supply and obtained from the Denmark Statistics website. Consumer valuations and the total market size of eggs are estimated using the price (adjusted for inflation) and supply data over the period 2007–2015. We refer the reader to Appendix D for details of the parameter estimation. As with our analytical model, we normalize the size of the producer population to 1 and report the relative size of the consumer population as $M = 85.85$.

The mean and standard deviations of production yields are calculated using data from 2007 to 2015. We assume that the expected yield of organic production over this time period corresponds to the long-run expected yield experienced by high-type producers as organic egg production has been practiced since the late 1990s. In order to calculate the expected yield during the transition period, we assume that the high types attain 20% improvement in the expected yield of organic production after the transition phase, i.e., $\mu_N^H = 1.2\mu_N$ (Rundgren 2006). Valuations for conventional and organic eggs and parameters of the yield distributions are presented in Table 2. Lastly, we find that organic and conventional yields are positively correlated with a correlation coefficient of 0.97.

Table 2 **Parameters of the numerical study**

Parameter	Conventional	Organic
Valuation (DKK/kg)	12.96	21.59
Expected long-run yield (kg/hen)	18.91	17.08
Standard deviation of yield (kg/hen)	0.49	0.83

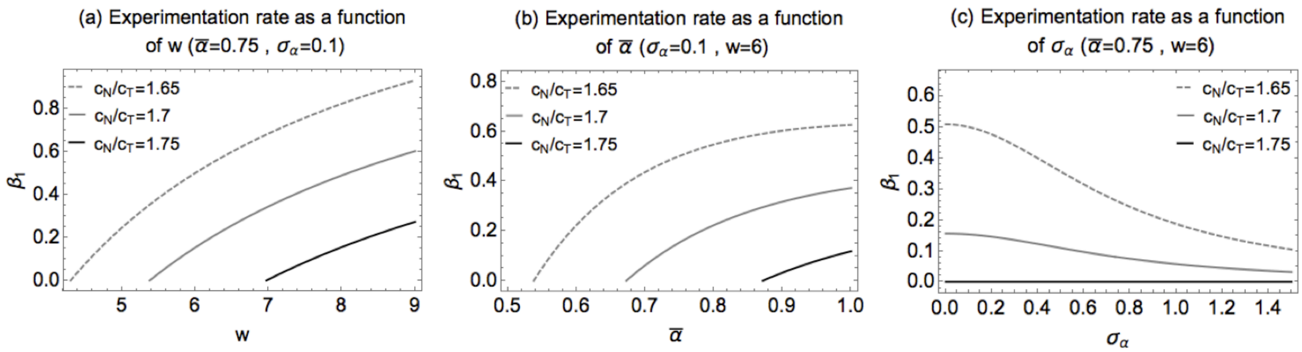
The data on per-hen production costs, consisting of the feed cost and depreciation, over the period 2013–2015 is used to compute the average unit costs, which are calculated as DKK 134.13

and DKK 214.38 for conventional and organic production, respectively, resulting in the ratio c_N/c_T being 1.6. However, we adjust this ratio to account for the differences in the labor cost of the two methods. Since organic production is labor-intensive, incorporating the labor cost would make a greater impact on the unit cost of organic production (Rundgren 2006, Anderson 2009). To capture this, we conduct a sensitivity analysis of the cost ratio (c_N/c_T) using values 1.65, 1.7, and 1.75. Lastly, we use $w=6$, $\bar{\alpha}=0.75$, and $\sigma_\alpha=0.1$ as benchmark values for the lifespan of organic production relative to the transition phase, the expected fraction of high types, and the variability in the fraction of high types, respectively, and we conduct a sensitivity analysis of these parameters as well. Setting $w=6$ reflects that once the transition period is successfully completed, producers expect to continue organic farming for a long period of time, which is the case in Denmark due to the country's emphasis on raising consumer awareness of organic production. Furthermore, setting $\bar{\alpha}=0.75$ and $\sigma_\alpha=0.1$ accords with the high success rates with low uncertainty in developed countries.

Figure 4 shows the equilibrium experimentation rate as a function of lifespan, the expected fraction of high types, i.e., the expected success rate, and the variability in the fraction of high types. Experimentation rates with different values of c_N/c_T are also depicted in order to show the impact of the relative size of the labor costs of the two production methods. As can be seen, an increase in the lifespan of organic production or the expected success rate motivates experimentation whereas higher uncertainty in the success rate discourages it. Figure 4b shows that as the difference between the costs of organic and conventional production decreases, the impact of the expected success rate on experimentation diminishes. The low cost difference incentivizes experimentation, resulting in high competition in organic production and thus mitigating the positive effect of the high expected success rate. Furthermore, an increase in the variability of the success rate is more detrimental to experimentation when the difference between organic and conventional production costs is low.

Under the benchmark parameter values with $c_N/c_T=1.7$, we obtain $\beta_1=15.36\%$ as the no-intervention equilibrium experimentation rate. The low experimentation rate can be attributed to high costs and low yields associated with organic production, indicating the need for an intervention. In fact, the 2015 adoption rate of organic egg production in Denmark is reported as approximately 26%, and the difference between the no-intervention experimentation rate we

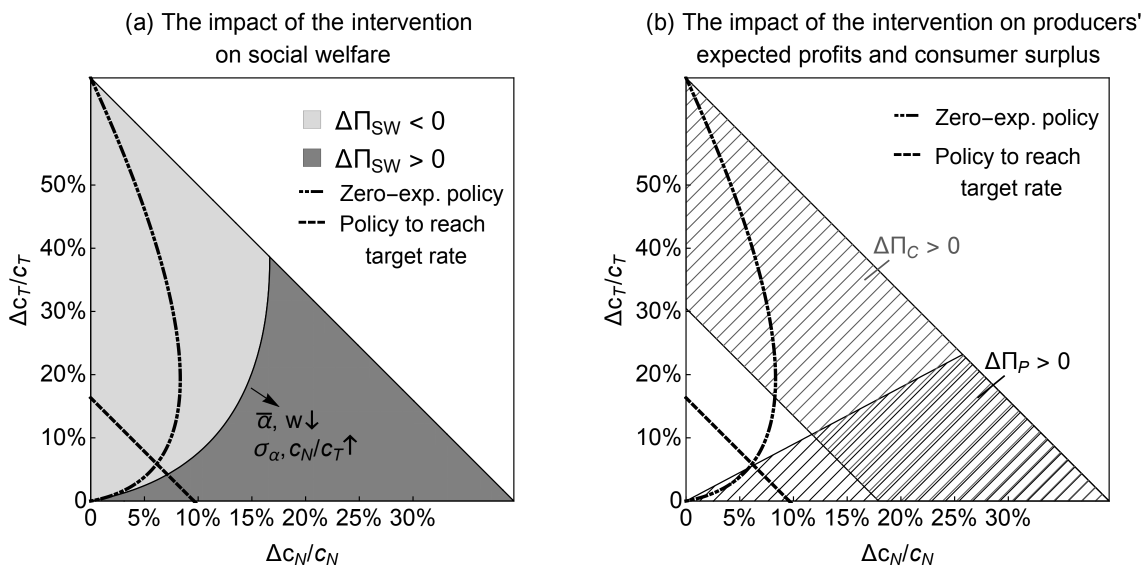
Figure 4 **Experimentation rate as a function of w, $\bar{\alpha}$ and σ_α with different values of c_N/c_T**



obtained and the observed rate is likely to be due to the numerous incentives provided to organic producers. For instance, as part of the EU rural development program, the Danish government offers subsidies to farmers for conversion to organic farming based on the area of land converted. However, from the data at hand, we cannot infer the amount of subsidy that organic egg producers receive. Nevertheless, the Danish government has announced that they aim to double the 2007 organic production rate by 2020 (The Ministry of Food, Agriculture and Fisheries of Denmark 2015). Applying this target to egg production would mean increasing the organic production rate to 36% (18% of hens were produced organically in 2007). Next, we will examine policies that can achieve this target rate. In what follows, we assume that the government's goal is to increase the experimentation rate, i.e., β_1, to 36% in the short term through policy interventions. The long-run adoption rate is then determined by the expected success rate.

Figure 5a shows the set of policies that improve social welfare as well as the policies that can increase the experimentation rate from 15.36% to 36%. One can see that assuming producers are not financially constrained, a zero-expenditure policy does not increase social welfare. The government can achieve the target experimentation rate while improving the overall welfare, in which case at least 7.14% of the organic production cost would have to be subsidized, translating to €2.41 million to be spent on subsidies over the course of the transition period. This subsidy rate would have to be coupled with a tax rate of 4.19% to reach the target experimentation rate, resulting in a tax income of €1.48 million. The government could attain the 36% goal through a policy with lower taxes, but in such a case the overall government expenditure would increase as the subsidy rate would have to be increased. In fact, if a subsidy-only policy were implemented, 9.6% of the organic production cost would have to be subsidized, amounting to a policy expenditure of €3.25 million.[2]

Figure 5 **The impact of the intervention on social welfare, producers' expected profits, and consumer surplus**



Note. $c_N/c_T = 1.7$.

Figure 5b shows that the policy maker could improve producers' expected profits while achieving the target experimentation rate through the aforementioned policies that increase social welfare. However, increasing the experimentation rate to 36% reduces consumer surplus under any policy. Since the expected yield of organic production is less than that of conventional production, the total supply is reduced when the rate of organic production increases. Even though the increase in the availability of organic products positively impacts consumers, it does not offset the negative impact of the reduction in supply, resulting in a decline in consumer surplus. Other types of interventions such as improving organic yields and raising consumer awareness of organic products are necessary to ensure benefits to consumers. Improving the yields would remedy the supply reduction problem and raising consumer awareness would result in higher utility to consumers from the consumption of organic products. Such interventions are in fact policies of the Danish government (The Ministry of Food, Agriculture and Fisheries of Denmark 2015). It may be possible to benefit both producers

[2] 1 DKK = 0.13 EUR.

and consumers while achieving the target experimentation rate by coupling monetary incentives with efforts to improve the yield and raise consumer awareness.

Lastly, we find that as the expected success rate decreases, or the uncertainty in the success rate increases, or the lifespan of organic production decreases, organic production becomes less desirable from the producers' perspective, resulting in a shrinkage in the set of policies that enhance social welfare (lower tax or higher subsidy rates are needed to preserve the welfare improvement). A similar intuition holds as organic production becomes financially less appealing due to an increase in the cost difference between the two production methods.

In summary, even though the motivation for the Danish government's goal of doubling organic production may be related to environmental concerns, the government would have to provide subsidies to producers amounting to at least 7.14% of the production cost in order to mitigate the negative economic impact on the overall welfare. However, since monetary incentives do not diminish the adverse characteristics that are inherent in organic production, e.g., low yields, other measures would have to be implemented to prevent a reduction in consumer surplus. These efforts could include raising consumer awareness of the benefits of organic products, which in turn would increase not only consumer surplus but also the profitability of organic production, thus benefiting producers as well. Additionally, the government could invest in yield-enhancing efforts to mitigate the negative impact on the total supply induced by the conversion to organics.

7. Extensions

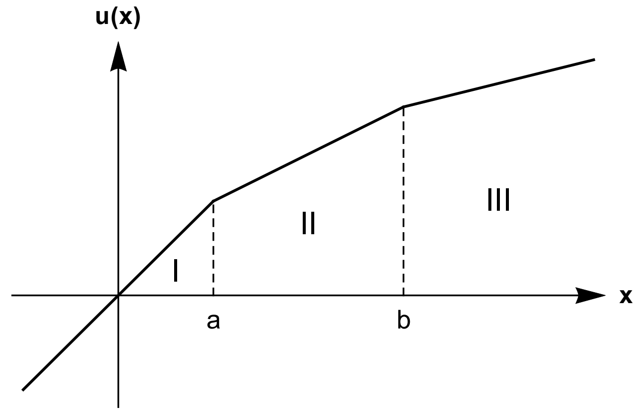
7.1. Risk aversion

So far, we have assumed that producers are expected-profit maximizers; however, in reality, producers are likely to exhibit risk-averse behavior. In this section, we investigate how risk aversion changes producers' production decisions as well as the impact of government interventions.

Using a generic concave utility function to model risk aversion results in intractability in the derivation of the equilibrium. To overcome this issue, we use a piecewise utility function as depicted in Figure 6. The slopes in regions I, II, and III are set to γ_1, 1, and γ_2, respectively, where $\gamma_1 > 1$ and $\gamma_2 < 1$, enabling us to obtain a concave utility function.

Note that since producers that experiment with the new production method incur losses in period 1, their expected profits fall within region I. Hence, the impact of losses is amplified compared

Figure 6 Producers' utility function



to the risk-neutral case. Moreover, we make the simplifying assumption that the expected profits from traditional production in periods 1 and 2 fall within region II, whereas the expected profits from the new method in period 2 fall within region III. Consequently, producers show risk-averse behavior toward the more risky new production method, partly because the losses in the transition period are amplified and partly because the uncertain gains in the long run are deemphasized.

For simplicity, we assume that the fraction of high-type producers, i.e., α, is deterministic and known. Let β_t^{RA} denote the fraction of producers that use the new method in period t in the risk-averse case. The characterization of the unique equilibrium is described in Appendix B. The marginal gain and externality under risk aversion are defined below.

$$MG^{RA} = \gamma_1(v_N\mu_N - c_N) - v_T\mu_T + c_T + w\alpha(\gamma_2(v_N\mu_N^H - c_N) - v_T\mu_T + c_T) - a(\gamma_1 - 1) + w\alpha b(1-\gamma_2), \tag{11}$$

$$E^{RA} = v_T\left(\kappa_T - \gamma_1\kappa_{TN} + w\alpha\left(\kappa_T - \gamma_2\kappa_{TN}^H\right)\right). \tag{12}$$

The experimentation rate is then given by $\beta_1^{RA} = \frac{MG^{RA}+E^{RA}}{X^{RA}}$, where $X^{RA} = \gamma_1 v_N\kappa_N - (\gamma_1+1)v_T\kappa_{TN} + v_T\kappa_T + w\alpha^2\left(\gamma_2 v_N\kappa_N^H - (1+\gamma_2)v_T\kappa_{TN}^H + v_T\kappa_T\right)$. In the following proposition, we characterize how the experimentation rate depends on the degree of risk aversion. As one might expect, risk aversion negatively impacts experimentation (and subsequent adoption).

PROPOSITION 13. *The rate of experimentation decreases as producers become more risk averse, i.e., β_1^{RA} is decreasing in γ_1 and increasing in γ_2. Hence, the experimentation rate under risk aversion is lower than the experimentation rate under risk neutrality, i.e., $\beta_1^{RA} < \beta_1$.*

We now turn our attention to investigating policy interventions under risk aversion. Note that under the current assumptions, without any government intervention, producers act as if they are risk averse to the new method and risk neutral to the traditional method. When studying interventions, we primarily focus on the case where the intervention is subtle enough not to alter producers' risk behavior. Under a $(\Delta c_N, \Delta c_T)$ policy, the experimentation rate becomes $\beta_1^{RA,(\Delta c_N, \Delta c_T)} = \beta_1^{RA} + \eta^{RA}$, where $\eta^{RA} = \frac{\gamma_1 \Delta c_N + \Delta c_T}{X^{RA}}$. Here, η^{RA} is a measure of the effectiveness of the policy in incentivizing experimentation.

Proposition 14. *The government's return on its expenditure under risk aversion is greater than it is under risk neutrality if $\eta^{RA} > \eta$. Moreover, if $\eta^{RA} > 2\eta$, its return under risk aversion is positive. This implies that under this condition, the impact of the intervention on social welfare under a zero-expenditure policy is also positive.*

Depending on the degree of risk aversion, policy interventions might yield higher experimentation rates in the case of risk aversion compared to risk neutrality. When that is the case, it suggests that the policy maker is generating a higher welfare impact under risk aversion. Even though higher experimentation implies that government expenditure will be higher, Proposition 14 suggests that the overall return will also be higher. Moreover, unlike in the case of risk neutrality, policy makers can achieve a positive return in the face of risk-averse producers, which also means that the government can induce a positive welfare impact through zero-expenditure policies.

7.2. Reduction in yield variability due to learning

So far, we have assumed that producers' gaining experience in new production techniques results in an improvement in the long-run expected yield of the new method. Another way learning can take effect is through a reduction in the variability of the yield. To capture that, in this section, we assume that learning improves the expected yield of the new production method and also reduces yield variability.

Let $\tilde{\theta}_i$ denote the reduction in the yield variability of the new method for a producer of type i. Similar to the case where learning improves the expected yield, we normalize the improvement attained by low-type producers to zero, i.e., $\tilde{\theta}_L = 0$. If a producer experiments with the new production method in period 1 and learns that he is a high type, the standard deviation of the yield in period 2 becomes $\sigma_N^H = \sigma_N - \tilde{\theta}_H$, while the improvement in the expected yield ($\mu_N^H = \mu_N + \theta_H$) holds as before. Below, we investigate how the reduction in yield variability impacts experimentation.

Proposition 15. *Under both risk neutrality and risk aversion, as the reduction in yield variability ($\tilde{\theta}_H$) increases, the experimentation rate increases. However, the marginal impact of $\tilde{\theta}_H$ on the experimentation rate decreases as producers become more risk averse when*

$$\frac{\kappa_{TN}}{\kappa_N} < \frac{v_N}{v_T} < \frac{\kappa_{TN}^H}{\tilde{\kappa}_N^H}. \tag{13}$$

The experimentation rate monotonically increases as the impact of learning on yield variability increases. However, the same does not necessarily hold for the impact on expected yield due to the reasoning underlying Proposition 1. Moreover, if the ratio of the valuation of the premium product to that of the traditional one is bounded as in Expression 13, the positive impact of the reduction in yield variability on experimentation diminishes as producers become more risk averse. This is due to the fact that when Expression 13 holds, risk averse producers have sufficient incentives to experiment and an additional reduction in yield variability might have an adverse effect due to the resulting increase in competition.

We can now turn to explore the impact of government interventions when learning reduces yield variability in addition to improving the expected yield.

Proposition 16. *Under both risk neutrality and risk aversion, the impact of government intervention on the experimentation rate is higher in the presence of yield variability reduction. Moreover, under risk neutrality, the government's return on its expenditure decreases as the reduction in yield variability increases.*

As one might expect, interventions become more effective when producers expect a reduction in yield variability as a result of learning in addition to an increase in the expected yield. This increases the burden on the government since a higher experimentation rate implies a lower tax income to be collected and a higher amount of subsidies to be paid out. At the same time, social welfare increases, but due to the adverse impact of a higher experimentation/adoption rate on prices, when producers are risk neutral, the increase in social welfare does not compensate for the surge in government expenditure, causing the government's return to decline. The same monotonic effect does not always hold for the risk-aversion case. Under risk aversion, the government may benefit from learning effects up to a certain point as the benefit from learning helps overcome the limitations of risk aversion. However, as the learning effect increases, the adverse externality effects start to dominate, causing the government's return to decrease.

8. Conclusion

Agricultural innovation serves as a means to improve farmers' productivity, reduce their environmental impact, and address the challenges associated with ever-changing soil, weather, and market conditions. Since high costs and low yields may undermine the profitability of innovation, policy makers often employ policy instruments to encourage producers to experiment with new production methods. In this paper, we investigate the use of taxes and subsidies to promote innovation and the resulting welfare impact.

We find that using only taxes increases experimentation but reduces social welfare. On the other hand, under similar expenditures or unit subsidies, a subsidy-only policy always outperforms a policy that utilizes both taxes and subsidies in attaining higher social welfare. However, the converse is true in achieving a higher experimentation rate and, under some conditions, consumer surplus. Thus, the policy objective, be it to improve environmental or social conditions by increasing the adoption of new production methods or to enhance social welfare, determines the intervention type that is most effective. Furthermore, we find that zero-expenditure policies reduce social welfare unless a large fraction of the producer population are financially constrained (they cannot afford the profit losses incurred by the new production method during the low-yield transition phase). In fact, when lack of financial resources restricts experimentation with the new production method, the policy maker may enhance social welfare by using a zero-expenditure policy that serves as a support for producers to overcome the financial barriers. Similarly, if producers are risk averse, interventions that generate a negative welfare impact or return on government expenditure under risk neutrality can achieve an increase in social welfare and positive return on expenditure.

Finally, we conduct a numerical study using data on conventional and organic egg production in Denmark. Given the Danish government's goal of doubling the 2007 organic production rate by 2020, we investigate the policies that can achieve this target. We find that the government would have to subsidize at least 7.14% of the organic production cost in order to enhance social welfare while reaching the desired rate. Even though producers benefit from these policies, consumer surplus decreases due to low organic yields. Hence, policies that involve monetary transfers to producers such as taxes and subsidies would have to be coupled with efforts to enhance yields and raise consumer awareness of organic products in order to benefit both sides of the market while achieving the intended organic production rate.

There are several avenues for future work. Additional research is required to understand producers' experimentation decisions in a dynamic environment where word-of-mouth communication may result in producers' learning from one another. In such a setting, the impact of early interventions may be amplified and deriving the policy maker's optimal policy may be considerably more involved. Moreover, consumer preferences for the output of innovative production methods might evolve in a dynamic manner, which would also affect producers' experimentation decisions as well as the effectiveness of government policies. Lastly, our study largely abstracts away from ancillary benefits of implementing innovative production methods. Hence, further investigation is warranted to understand the optimal policy choice when taking into account the social and environmental impact of each of the production alternatives.

References

Acemoglu, D., P. Aghion, L. Bursztyn, D. Hemous. 2012. The environment and directed technical change. *American Economic Review.* **102**(1) 131–166.

Acs, S., P. Berentsen, R. Huirne, M. van Asseldonk. 2009. Effect of yield and price risk on conversion from conventional to organic farming. *The Australian Journal of Agricultural and Resource Economics.* **53**(3) 393–411.

Alizamir, S., F. de Vericourt, P. Sun. 2016. Efficient feed-in-tariff policies for renewable energy technologies. *Operations Research.* **64**(1) 52–66.

Alizamir, S., F. Iravani, H. Mamani. 2019. An analysis of price vs. revenue protection: government subsidies in the agriculture industry. *Management Science.* **65**(1) 32–49.

Anderson, K. E. 2009. Overview of natural and organic egg production: Looking back to the future. *The Journal of Applied Poultry Research.* **18**(2) 348–354.

Boyabatli, O., P. R. Kleindorfer, S. R. Koontz. 2011. Integrating long-term and short-term contracting in beef supply chains. *Management Science.* **57**(10) 1771–1787.

Boyabatli, O., J. Nasiry, Y. H. Zhou. 2019. Crop planning in sustainable agriculture: Dynamic farmland allocation in the presence of crop rotation benefits. *Forthcoming in Management Science.*

Boyabatli, O., Q. D. Nguyen, T. Wang. 2017. Capacity management in agricultural commodity processing and application in the palm industry. *Manufacturing & Service Operations Management.* **19**(4) 551–567.

Bruinsma, J. 2003. World agriculture: Towards 2015/2030: an FAO perspective. London: Earthscan.

Chemama, J., M. C. Cohen, R. Lobel, G. Perakis. 2019. Consumer subsidies with a strategic supplier: Commitment vs. flexibility. *Management Science.* **65**(2) 681–713.

Chen, Y., C. S. Tang. 2015. The economic value of market information for farmers in developing economies. *Production & Operations Management.* **24**(9) 1441–1452.

Cohen, M. C., R. Lobel, G. Perakis. 2016. The impact of demand uncertainty on consumer subsidies for green technology adoption. *Management Science.* **62**(5) 1235–1258.

Cohen, M. C., G. Perakis, C. Thraves. 2015. Competition and externalities in green technology adoption. Working paper.

David, C. C. 2006. The philippine hybrid rice program: A case for redesign and scaling down. Research Paper Series No. 2006-03, Philippine Institute for Development Studies.

Dawande, M., S. Gavirneni, M. Mehrotra, V. Mookerjee. 2013. Efficient distribution of water between head-reach and tail-end farms in developing countries. *Manufacturing & Service Operations Management.* **15**(2) 221–238.

Devalkar, S. K., R. Anupindi, A. Sinha. 2011. Integrated optimization of procurement, processing, and trade of commodities. *Operations Research.* **59**(6) 1369–1381.

Federgruen, A., U. Lall, A. S. Simsek. 2015. Supply chain analysis of contract farming. Working paper.

Huh, W. T., U. Lall. 2013. Optimal crop choice, irrigation allocation, and the impact of contract farming. *Production and Operations Management.* **22**(5) 1126–1143.

Kazaz, B. 2004. Production planning under yield and demand uncertainty with yield-dependent cost and price. *Manufacturing & Service Operations Management.* **6**(3) 209–224.

Kazaz, B., S. Webster. 2011. The impact of yield-dependent trading costs on pricing and production planning under supply uncertainty. *Manufacturing & Service Operations Management.* **13**(3) 404–417.

Kazaz, B., S. Webster, P. Yadav. 2016. Interventions for an artemisinin-based malaria medicine supply chain. *Production & Operations Management.* **25**(9) 1576–1600.

Kouvelis, P., J. Li. 2016. Transfer price and yield risk-sharing contracts for cotton supply chains. Working paper.

Levi, R., G. Perakis, G. Romero. 2017. On the effectiveness of uniform subsidies in increasing market consumption. *Management Science.* **63**(1) 40–57.

Lobel, R., G. Perakis. 2011. Consumer choice model for forecasting demand and designing incentives for solar technology. Working paper.

Lohr, L., L. Salomonsson. 2000. Conversion subsidies for organic production: results from Sweden and lessons for the United States. *Agricultural Economics.* **22**(2) 133–146.

McCardle, K. F. 1985. Information acquisition and the adoption of new technology. *Operations Research.* **31**(11) 1335–1473.

Pietola, K. S., A. O. Lansink. 2001. Farmer response to policies promoting organic farming technologies in Finland. *European Review of Agricultural Economics.* **28**(1) 1–15.

Rundgren, G. 2006. Organic agriculture and food security. International Federation of Organic Agriculture Movements (IFOAM), Germany.

Rustin, S. 2015. Why are organic farmers across Britain giving up? *The Guardian.* Retrieved August, 2016 `https://www.theguardian.com/environment/2015/mar/14/why-are-organic-farmers-across-britain-giving-up`.

Seufert, V., N. Ramankutty, J. A. Foley. 2012. Comparing the yields of organic and conventional agriculture. *Nature.* **485** 229–232.

Smith, J. E., C. Ulu. 2012. Technology adoption with uncertain future costs and quality. *Operations Research.* **60**(2) 262–274.

Smith, J. E., C. Ulu. 2017. Risk aversion, information acquisition, and technology adoption. *Operations Research.* **65**(4) 1011–1028.

Taylor, T. A., W. Xiao. 2014. Subsidizing the distribution channel: Donor funding to improve the availability of malaria drugs. *Management Science.* **60**(10) 2461–2477.

The Ministry of Food, Agriculture and Fisheries of Denmark. 2015. Organic action plan for Denmark.

The World Bank. 2016. Agriculture, value added (% of gdp). Retrieved July, 2016 `http://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?display=graph`.

Ulu, C., J. E. Smith. 2009. Uncertainty, information acquisition, and technology adoption. *Operations Research.* **57**(3) 740–752.

Vidal, J. 2013. India's rice revolution. *The Guardian.* Retrieved May 2019, `http://www.theguardian.com/global-development/2013/feb/16/india-rice-farmers-revolution`.

Wang, X., S. H. Cho, A. Scheller-Wolf. 2018. Green technology development and adoption: Competition, regulation, and uncertainty - a global game approach. Working paper.

Appendix A: Derivation of the Equilibrium Experimentation Rate

First, let us introduce the following notation:

π_{T1}: Expected profit of a producer who adopts the traditional method in period 1,

π_{N1}: Expected profit of a producer who experiments with the new method in period 1,

$\pi_{T2}|\alpha$: Expected profit of a producer who adopts the traditional method in period 2 given α,

$\pi^i_{N2}|\alpha$: Expected profit of a producer of type i who adopts the new method in period 2 given α.

We can calculate π_{T1} and π_{N1} as

$$\pi_{T1} = \mathbb{E}\left[p_{T1}\phi_T\right] - c_T = \mathbb{E}\left[v_T\left(1 - \frac{\phi_T\left(1-\beta_1\right)}{M} - \frac{\phi_N\beta_1}{M}\right)\phi_T\right] - c_T = v_T\mu_T - c_T - v_T\kappa_T\left(1-\beta_1\right) - v_T\kappa_{TN}\beta_1, \tag{26}$$

$$\pi_{N1} = v_N\mu_N - c_N - v_T\kappa_{TN}\left(1-\beta_1\right) - v_N\kappa_N\beta_1. \tag{27}$$

In period 1, the equilibrium is given by the indifference condition such that a producer who uses the traditional method in periods 1 and 2 has the same expected profit as the producer who experiments with the new method in period 1 and decides whether to adopt it depending on the realization of his type. In order to derive $\pi_{T2}|\alpha$ and $\pi^i_{N2}|\alpha$, we need to establish the equilibrium fraction of high and low-type producers that adopt the new method in period 2 after experimenting with it in period 1.

Lemma 1. *There exists a unique equilibrium where out of the producers that experiment with the new production method in period 1, only the high types adopt the new method in period 2 whereas low types convert back to the traditional method. The equilibrium experimentation rate in period 1 is given by*

$$\beta_1 = \frac{v_N\mu_N - c_N - v_T\mu_T + c_T + v_T\kappa_T - v_T\kappa_{TN} + w\bar{\alpha}\left(v_N\mu_N^H - c_N - v_T\mu_T + c_T + v_T\kappa_T - v_T\kappa_{TN}^H\right)}{v_N\kappa_N - 2v_T\kappa_{TN} + v_T\kappa_T + w\kappa_\alpha\left(v_N\kappa_N^H - 2v_T\kappa_{TN}^H + v_T\kappa_T\right)}.$$

The expected fraction of the producer population that adopt the new method in period 2 is then given by $\mathbb{E}[\beta_2] = \bar{\alpha}\beta_1$.

Proof of Lemma 1: Note that the dominant strategy for low types is to revert to the traditional method in period 2 since $\theta_L = 0$ implies that $\pi^L_{N2}|\alpha < v_N\mu_N - c_N < 0$ for all $\alpha \in [0,1]$. On the other hand, $\pi_{T2}|\alpha > 0$ for all $\alpha \in [0,1]$ due to $v_T\mu_T - c_T - v_T\kappa_T > 0$ and $v_T\mu_T - c_T - v_T\kappa^H_{TN} > 0$. Thus, as listed below, there are two scenarios that can be part of the equilibrium in the continuation period. Out of the producers that experiment with the new method in period 1,

I. only some portion of the high-type producers adopt the new method in period 2 while the remaining high types and all of the low types revert to the traditional method,

II. all of the high-type producers adopt the new method in period 2 while all of the low types revert to the traditional method.

Case I : In this case, the indifference condition is given by

$$\pi_{T1} + w\mathbb{E}_\alpha\left[\pi_{T2}|\alpha\right] = \pi_{N1} + w\mathbb{E}_\alpha\left[\alpha\psi^H\pi^H_{N2}|\alpha + \alpha(1-\psi^H)\pi_{T2}|\alpha + (1-\alpha)\pi_{T2}|\alpha\right],$$

where ψ^H is the fraction of high types that choose to adopt the new method. Note that the second period condition contains an expectation over α. Since each experimenter only observes his own type at the end of period 1, not the realization of α, the expected profit of a producer in period 2 entails an expectation to be taken over α. For this to be the equilibrium, $\pi_{T2}|\alpha = \pi_{N2}^H|\alpha$ has to hold since high-type producers are indifferent between adopting the new method and reverting to the traditional method. Thus, the indifference condition reduces to $\pi_{T1} = \pi_{N1}$. However, this does not hold as $\pi_{T1} > 0$ (since $v_T\mu_T - c_T - v_T\kappa_T > 0$ and $v_T\mu_T - c_T - v_T\kappa_{TN}^H > 0$), whereas $\pi_{N1} < 0$ (since $v_N\mu_N < c_N$).

Case II : In this case $\psi^H = 1$. Thus, the indifference condition is given by

$$\pi_{T1} + w\mathbb{E}_\alpha\left[\pi_{T2}|\alpha\right] = \pi_{N1} + w\mathbb{E}_\alpha\left[\alpha\pi_{N2}^H|\alpha + (1-\alpha)\pi_{T2}|\alpha\right]. \tag{28}$$

We can calculate $\pi_{T2}|\alpha$ and $\pi_{N2}^i|\alpha$ for $\theta_i \in \{\theta_H, \theta_L\}$ as follows.

$$\pi_{T2}|\alpha = \mathbb{E}\left[v_T\left(1 - \frac{\phi_T(1-\beta_2)}{M} - \frac{\phi_N^H\beta_2}{M}\right)\phi_T\right] - c_T = v_T\mu_T - c_T - v_T\kappa_T(1-\alpha\beta_1) - v_T\kappa_{TN}^H\alpha\beta_1, \tag{29}$$

where the second equality follows from $\beta_2 = \alpha\beta_1$ as only high types adopt the new production method in period 2. Similarly,

$$\pi_{N2}^H|\alpha = v_N(\mu_N + \theta_H) - c_N - v_T\kappa_{TN}^H(1-\alpha\beta_1) - v_N\kappa_N^H\alpha\beta_1, \tag{30}$$

$$\begin{aligned}\pi_{N2}^L|\alpha &= v_N(\mu_N + \theta_L) - c_N - v_T\kappa_{TN}^L(1-\alpha\beta_1) - v_N\left(\kappa_N + \frac{\mu_N(\theta_H+\theta_L) + \theta_H\theta_L}{M}\right)\alpha\beta_1 \\ &= v_N\mu_N - c_N - v_T\kappa_{TN}(1-\alpha\beta_1) - v_N\left(\kappa_N + \frac{\mu_N\theta_H}{M}\right)\alpha\beta_1,\end{aligned} \tag{31}$$

where the last equality holds since $\theta_L = 0$. Note that $\pi_{N2}^L|\alpha < 0\ \forall\alpha \in [0,1]$.

In equilibrium, in order to avoid a profitable deviation to the outside option of not producing, it should be the case that $\pi_{T1} \geq 0$ and $\mathbb{E}_\alpha\left[\pi_{T2}|\alpha\right] \geq 0$. These conditions are satisfied since $v_T\mu_T - c_T - v_T\kappa_T \geq 0$ and $v_T\mu_T - c_T - v_T\kappa_{TN}^H \geq 0$. Moreover, since only the high-type producers adopt the new method in period 2, the condition $\mathbb{E}_\alpha\left[\pi_{N2}^H|\alpha\right] \geq \mathbb{E}_\alpha\left[\pi_{T2}|\alpha\right] \geq \mathbb{E}_\alpha\left[\pi_{N2}^L|\alpha\right]$ has to hold. The second inequality holds since $\mathbb{E}_\alpha\left[\pi_{T2}|\alpha\right] \geq 0$ and $\mathbb{E}_\alpha\left[\pi_{N2}^L|\alpha\right] < 0$ whereas the first inequality is satisfied when

$$\bar{\alpha}\beta_1(v_N\kappa_N^H - 2v_T\kappa_{TN}^H + v_T\kappa_T) \leq v_N\mu_N^H - c_N - v_T\mu_T + c_T + v_T\kappa_T - v_T\kappa_{TN}^H \tag{32}$$

holds. We will verify that this condition is satisfied once β_1 is derived.

To ensure an interior solution, we assume that there exists a profitable deviation to the new production method if all of the producers use the traditional method, which is given by the following condition.

$$v_N\mu_N - v_T\kappa_{TN} - c_N + w\bar{\alpha}\left(v_N\mu_N^H - v_T\kappa_{TN}^H - c_N\right) > (v_T\mu_T - v_T\kappa_T - c_T)(1 + w\bar{\alpha}). \tag{33}$$

Similarly, it is assumed that if all of the producers use the new method, there exists a profitable deviation to the traditional method, as given below.

$$\begin{aligned}&v_N\mu_N - v_N\kappa_N - c_N + w\mathbb{E}_\alpha\left[\alpha\left(v_N\mu_N^H - v_T\kappa_{TN}^H(1-\alpha) - v_N\kappa_N\alpha - c_N\right)\right] \\ &\qquad < v_T\mu_T - v_T\kappa_{TN} - c_T + w\mathbb{E}_\alpha\left[\alpha\left(v_T\mu_T - v_T\kappa_T(1-\alpha) - v_T\kappa_{TN}^H\alpha - c_T\right)\right].\end{aligned} \tag{34}$$

Given (26), (27), (29), and (30), it is straightforward to calculate the solution to (28), which is given by

$$\beta_1 = \frac{(v_N\mu_N - c_N - v_T\mu_T + c_T + v_T\kappa_T - v_T\kappa_{TN}) + w\bar{\alpha}\left(v_N\mu_N^H - c_N - v_T\mu_T + c_T + v_T\kappa_T - v_T\kappa_{TN}^H\right)}{v_N\kappa_N - 2v_T\kappa_{TN} + v_T\kappa_T + w\kappa_\alpha\left(v_N\kappa_N^H - 2v_T\kappa_{TN}^H + v_T\kappa_T\right)} = \frac{Y_0 + w\bar{\alpha}Y_1}{X_0 + w\kappa_\alpha X_1}, \tag{35}$$

where

$$
\begin{aligned}
Y_0 &= v_N\mu_N - c_N - v_T\mu_T + c_T + v_T\kappa_T - v_T\kappa_{TN},\\
Y_1 &= v_N\mu_N^H - c_N - v_T\mu_T + c_T + v_T\kappa_T - v_T\kappa_{TN}^H,\\
X_0 &= v_N\kappa_N - 2v_T\kappa_{TN} + v_T\kappa_T,\\
X_1 &= v_N\kappa_N^H - 2v_T\kappa_{TN}^H + v_T\kappa_T.
\end{aligned}
$$

Moreover, let $Y = Y_0 + w\bar{\alpha}Y_1$ and $X = X_0 + w\kappa_\alpha X_1$ (note that here, $Y = MG + E$). We have

$$
\begin{aligned}
X_0 &= \frac{1}{M}\Big(v_N\left(\mu_N^2+\sigma_N^2\right) - 2v_T\left(\sigma_{TN}+\mu_N\mu_T\right) + v_T\left(\mu_T^2+\sigma_T^2\right)\Big)\\
&> \frac{1}{M}\Big(v_T\left(\mu_N-\mu_T\right)^2 + v_T\left(\sigma_N^2 - 2\sigma_{TN} + \sigma_T^2\right)\Big) \quad \text{(since } v_N > v_T\text{)}\\
&> \frac{1}{M}\Big(v_T\left(\mu_N-\mu_T\right)^2 + v_T\left(\sigma_N - \sigma_T\right)^2\Big) \quad \text{(since } \sigma_{TN} < \sigma_N\sigma_T\text{)}\\
&> 0.
\end{aligned}
$$

Similarly, one can show that $X_1 > 0$. Moreover, $Y_0 < 0$ since $v_N\mu_N < c_N$ and $v_T\mu_T - c_T - v_T\kappa_T > 0$. Due to (33), we have $Y > 0$, so it has to be that $Y_1 > 0$. Now, (32) can be simplified as $\bar{\alpha}\beta_1 X_1 \le Y_1$. Given that $\beta_1 = \frac{Y_0 + w\bar{\alpha}Y_1}{X_0 + w\kappa_\alpha X_1}$, $X_0 > 0$, and $X_1 > 0$, we can rewrite the condition as $\bar{\alpha}Y_0X_1 + w\bar{\alpha}^2Y_1X_1 \le X_0Y_1 + w\kappa_\alpha X_1Y_1$. Note that this simplifies to $\bar{\alpha}Y_0X_1 \le (X_0 + w\sigma_\alpha^2 X_1)\,Y_1$. Since the left-hand side is negative whereas the right-hand side is positive, this inequality holds, meaning that the condition presented in (32) is satisfied.

Lastly, $\beta_2 = \alpha\beta_1$ since only the high-type producers adopt the new method in period 2, resulting in $\mathbb{E}_\alpha[\beta_2] = \bar{\alpha}\beta_1$.

□

Appendix B: Equilibrium Experimentation Rate under Risk Aversion

For simplicity, we assume that α is deterministic and known. Also, we make the following assumptions.

(A1) $a < v_T\mu_T - c_T - v_T\kappa_T < b$,

(A2) $a < v_T\mu_T - c_T - v_T\kappa_{TN} < b$,

(A3) $a < v_T\mu_T - c_T - v_T\kappa_{TN}^H < b$,

(A4) $b < v_N\mu_N^H - c_N - v_T\kappa_{TN}^H$,

(A5) $b < v_N\mu_N^H - c_N - v_N\kappa_N^H$.

It is straightforward to extend Lemma 1 given in Appendix A for the risk aversion case. Here, the equilibrium indifference condition is given by $\pi_{T1}^{RA} + w\alpha\pi_{T2}^{RA} = \pi_{N1}^{RA} + w\alpha\pi_{N2}^{H,RA}$, where the profit functions are given as follows.

$$\pi_{T1}^{RA} = \gamma_1 a + \mathbb{E}\left[p_{T1}\phi_T\right] - c_T - a = v_T\mu_T - c_T - v_T\kappa_T\left(1-\beta_1\right) - v_T\kappa_{TN}\beta_1 - (\gamma_1 - 1)a, \tag{36}$$

$$\pi_{N1}^{RA} = \gamma_1(\mathbb{E}\left[p_{N1}\phi_N\right] - c_N) = \gamma_1(v_N\mu_N - c_N - v_T\kappa_{TN}\left(1-\beta_1\right) - v_N\kappa_N\beta_1), \tag{37}$$

$$\pi_{T2}^{RA} = \gamma_1 a + \mathbb{E}\left[p_{T2}\phi_T\right] - c_T - a = v_T\mu_T - c_T - v_T\kappa_T\left(1-\alpha\beta_1\right) - v_T\kappa_{TN}^H\alpha\beta_1 - (\gamma_1 - 1)a, \tag{38}$$

$$\pi_{N2}^{H,RA} = \gamma_1 a + b - a + \gamma_2(\mathbb{E}\left[p_{N2}\phi_N^H\right] - c_N - b) = (\gamma_1 - 1)a + (1-\gamma_2)b - \gamma_2(v_N\mu_N^H - c_N - v_T\kappa_{TN}^H\left(1-\alpha\beta_1\right) - v_N\kappa_N^H\alpha\beta_1). \tag{39}$$

Here, (36) and (38) follow from the assumption that the expected profits obtained through traditional production in periods 1 and 2 fall within region II whereas (37) follows from the fact that the new production method generates negative profits in period 1, thus falling within region I. Finally, (39) is due to the assumption that the expected profits from the new production method in period 2 fall within region III. Assuming the counterparts of (33) and (34) for the risk averse case, we can calculate the equilibrium experimentation rate as $\beta_1^{RA} = \frac{MG^{RA}+E^{RA}}{X^{RA}}$. Here, we assume that $(\gamma_i\sigma_N - \sigma_T)(\sigma_N - \sigma_T) > 0$ for $\gamma_i \in \{\gamma_1, \gamma_2\}$, $(\gamma_1\mu_N - \mu_T)(\mu_N - \mu_T) > 0$, and $(\gamma_2\mu_N^H - \mu_T)(\mu_N^H - \mu_T) > 0$. Therefore, we obtain $X^{RA} > 0$.

Appendix C: Proofs

Proof of Proposition 1.

Using (35), we find

$$\frac{\partial\beta_1}{\partial\bar{\alpha}} = \frac{w\left(XY_1 - 2\bar{\alpha}YX_1\right)}{X^2},$$

and

$$\frac{\partial^2\beta_1}{\partial\bar{\alpha}^2} = -\frac{2wX_1\left(XY + 2w\bar{\alpha}\left(XY_1 - 2\bar{\alpha}YX_1\right)\right)}{X^3}.$$

Thus, β_1 is increasing in $\bar{\alpha}$ if $\bar{\alpha} < \dot{\alpha}$, where $\dot{\alpha}$ is given by $XY_1 - 2\dot{\alpha}YX_1 = 0$. Otherwise, β_1 is decreasing in $\bar{\alpha}$. Moreover,

$$\frac{\partial\left(\bar{\alpha}\beta_1\right)}{\partial\bar{\alpha}} = \frac{XY + w\bar{\alpha}\left(XY_1 - 2\bar{\alpha}X_1Y\right)}{X^2} \geq \frac{XY + w\bar{\alpha}\left(\bar{\alpha}X_1Y - 2\bar{\alpha}X_1Y\right)}{X^2} = \frac{Y\left(X_0 + w\sigma_\alpha^2X_1\right)}{X^2} > 0,$$

where the inequality is due to condition (32), combined with the fact that $\beta_1 = \frac{Y}{X}$.

□

Proof of Proposition 2.

We first derive the producers' expected profits and consumer surplus. Due to the indifference condition presented in (28), all producers incur the same total expected profit in equilibrium, resulting in

$$\Pi_P = \pi_{T1} + w\mathbb{E}_\alpha\left[\pi_{T2}|\alpha\right]. \tag{40}$$

Consumer surplus is calculated as shown below.

$$\begin{aligned}\Pi_C &= \mathbb{E}_{\phi_T,\phi_N,\alpha}\left[\sum_{t=1}^{2} M\left(\int_{\bar{s}_t}^{\bar{\bar{s}}_t}\left(sv_T - p_{Tt}\right)ds + \int_{\bar{\bar{s}}_t}^{1}\left(sv_N - p_{Nt}\right)ds\right)w\mathbf{1}\{t=2\}\right]\\ &= \frac{1}{2}\Big(v_T\kappa_T\left(1-\beta_1\right)^2 + 2v_T\kappa_{TN}\beta_1\left(1-\beta_1\right) + v_N\kappa_N\beta_1^2 + w\mathbb{E}_\alpha\left[v_T\kappa_T\left(1-\alpha\beta_1\right)^2 + 2v_T\kappa_{TN}^H\alpha\beta_1\left(1-\alpha\beta_1\right) + v_N\kappa_N^H\alpha^2\beta_1^2\right]\Big)\\ &= \frac{1}{2}\Big(v_T\kappa_T\left(1-\beta_1\right)^2 + 2v_T\kappa_{TN}\beta_1\left(1-\beta_1\right) + v_N\kappa_N\beta_1^2 + w\big(v_T\kappa_T + 2\bar{\alpha}\beta_1v_T\left(\kappa_{TN}^H - \kappa_T\right) + \kappa_\alpha\beta_1^2\left(v_N\kappa_N^H - 2v_T\kappa_{TN}^H + v_T\kappa_T\right)\big)\Big).\end{aligned} \tag{41}$$

Using Π_P and Π_C, it is straightforward to derive the impact on producers' expected profits and consumer surplus under a $(\Delta c_N, \Delta c_T)$ policy as follows.

$$\Delta\Pi_P = \left(\Delta c_N + \Delta c_T\right)\frac{E}{X} - \Delta c_T, \tag{42}$$

$$\Delta\Pi_C = \frac{1}{2}\left(\Delta c_N + \Delta c_T\right)\left(\beta_1 + \beta_1^{(\Delta c_N,\Delta c_T)} - \frac{2E}{X}\right). \tag{43}$$

Then, the impact of the intervention on social welfare, $\Delta\Pi_{SW} = \Delta\Pi_P + \Delta\Pi_C$, is given by

$$\Delta\Pi_{SW} = \frac{1}{2}\left(\Delta c_N + \Delta c_T\right)\left(\beta_1 + \beta_1^{(\Delta c_N,\Delta c_T)}\right) - \Delta c_T. \tag{44}$$

Using (44) and government expenditure as $\zeta^{(\Delta c_N,\Delta c_T)} = \Delta c_N \beta_1^{(\Delta c_N,\Delta c_T)} - \Delta c_T\big(1-\beta_1^{(\Delta c_N,\Delta c_T)}\big)$, we can rewrite $\Delta\Pi_{SW}$ as

$$\Delta\Pi_{SW} = \frac{1}{2}\left(\zeta^{(\Delta c_N,\Delta c_T)} + \Delta c_N\beta_1 - \Delta c_T\left(1-\beta_1\right)\right). \tag{45}$$

Under a zero-expenditure policy, we have

$$\zeta^{(\Delta c_N,\Delta c_T)} = \Delta c_N\beta_1 - \Delta c_T(1-\beta_1) + \frac{(\Delta c_N + \Delta c_T)^2}{X} = 0.$$

Thus, $\Delta c_N\beta_1 - \Delta c_T\left(1-\beta_1\right) = -\frac{(\Delta c_N+\Delta c_T)^2}{X} < 0$. This implies that $\Delta\Pi_{SW} < 0$ under a zero-expenditure policy since in that case, the expression given in (45) reduces to $\Delta\Pi_{SW} = \frac{1}{2}\left(\Delta c_N\beta_1 - \Delta c_T\left(1-\beta_1\right)\right)$.

□

Proof of Proposition 3.

Under a zero-expenditure policy, i.e., $\zeta^{(\Delta c_N,\Delta c_T)} = 0$, we have $(\Delta c_N + \Delta c_T)\beta_1^{(\Delta c_N,\Delta c_T)} = \Delta c_T$. Using this and (42), one can write

$$\begin{aligned}\Delta\Pi_P &= \left(\Delta c_N + \Delta c_T\right)\left(\frac{E}{X} - \beta_1^{(\Delta c_N,\Delta c_T)}\right)\\ &= \left(\Delta c_N + \Delta c_T\right)\left(\frac{E}{X} - \beta_1 - \frac{\Delta c_N + \Delta c_T}{X}\right).\end{aligned}$$

Thus, producers benefit from the intervention if and only if $\Delta c_N + \Delta c_T < E - Y = -MG$. Moreover, using (43), one can conclude that consumers benefit from the intervention if and only if $\Delta c_N + \Delta c_T > 2\left(E - Y\right) = -2MG$, proving the proposition.

□

Proof of Proposition 4.

Using (44), one can show that

$$\begin{aligned}\Delta\Pi_{SW} &= \frac{1}{2}\left(\Delta c_N + \Delta c_T\right)\left(2\beta_1 + \frac{\Delta c_N + \Delta c_T}{X}\right) - \Delta c_T\\ &= \frac{\left(\Delta c_N + \Delta c_T\right)^2}{2X} + \left(\Delta c_N + \Delta c_T\right)\frac{MG + E}{X} - \Delta c_T\\ &= \frac{\left(\Delta c_N + \Delta c_T\right)^2 + 2(MG+E)\Delta c_N - 2\left(X - MG - E\right)\Delta c_T}{2X},\end{aligned}$$

which is positive if and only if the numerator is positive (since $X > 0$). For a subsidy-only policy, the numerator simplifies to $(\Delta c_N)^2 + 2(MG+E)\Delta c_N$, which is positive (since $Y = MG + E > 0$ due to (33)). For a tax-only policy, the numerator becomes $\Delta c_T\left(\Delta c_T - 2X(1-\beta_1)\right)$. Since it is assumed that $\beta_1^{(\Delta c_T)} < 1$, i.e., $\Delta c_T < X(1-\beta_1)$, the numerator is negative, meaning that tax-only policies reduce social welfare.

□

Proof of Proposition 5.

Using (42) and (43), one can deduce that

$$\begin{aligned}\Delta\Pi_P - \Delta\Pi_C &= (\Delta c_N + \Delta c_T)\left(\frac{E-MG}{X} - \frac{\Delta c_N + \Delta c_T}{2X}\right) - \Delta c_T \\ &= \frac{-(\Delta c_N + \Delta c_T)^2 + 2(\Delta c_N + \Delta c_T)(E-MG) - 2X\Delta c_T}{2X}.\end{aligned}$$

Thus, if $E < MG$, $\Delta\Pi_P < \Delta\Pi_C$. Otherwise, $\Delta\Pi_P > \Delta\Pi_C$ if and only if $(\Delta c_N + \Delta c_T)^2 - 2(\Delta c_N + \Delta c_T)(E - MG) + 2X\Delta c_T < 0$, proving the proposition.

$\square$

Proof of Proposition 6.

Using (45), we can write the return on government's expenditure as follows.

$$\begin{aligned}\Delta\Pi_G &= \frac{1}{2}\left(\Delta c_N\beta_1 - \Delta c_T(1-\beta_1) - \zeta^{(\Delta c_N,\Delta c_T)}\right) \\ &= \frac{1}{2}(\Delta c_N + \Delta c_T)\left(\beta_1 - \beta_1^{(\Delta c_N,\Delta c_T)}\right) \\ &= -\frac{(\Delta c_N + \Delta c_T)^2}{2X}.\end{aligned}$$

Hence, the return on government's expenditure is negative under any policy.

$\square$

Proof of Proposition 7.

Since $\beta_1^{(\Delta c_N,\Delta c_T)} < 1$, i.e., $\Delta c_N + \Delta c_T < (1-\beta_1)X$, we have $\beta_1^{(\Delta c_N)} < 1$. Using (44), one can deduce that

$$\begin{aligned}\Delta\Pi_{SW}^{(\Delta c_N)} - \Delta\Pi_{SW}^{(\Delta c_N,\Delta c_T)} &= \frac{1}{2}\Delta c_N\big(\beta_1 + \beta_1^{(\Delta c_N)}\big) - \frac{1}{2}(\Delta c_N + \Delta c_T)\big(\beta_1 + \beta_1^{(\Delta c_N,\Delta c_T)}\big) + \Delta c_T \\ &= -\frac{1}{2}\Delta c_N\frac{\Delta c_T}{X} - \Delta c_T\beta_1 - \frac{1}{2}\Delta c_T\frac{\Delta c_N + \Delta c_T}{X} + \Delta c_T \\ &= \frac{\Delta c_T}{X}\left((1-\beta_1)X - \Delta c_N - \frac{\Delta c_T}{2}\right),\end{aligned}$$

which is positive since $\Delta c_N + \Delta c_T < (1-\beta_1)X$. Moreover, using (45), we can write

$$\begin{aligned}\Delta\Pi_G^{(\Delta c_N)} - \Delta\Pi_G^{(\Delta c_N,\Delta c_T)} &= \frac{1}{2}\left(\Delta c_N\beta_1 - \zeta^{(\Delta c_N)}\right) - \frac{1}{2}\left(\Delta c_N\beta_1 - \Delta c_T(1-\beta_1) - \zeta^{(\Delta c_N,\Delta c_T)}\right) \\ &= \frac{1}{2}\Delta c_N\left(\beta_1 - \beta_1^{(\Delta c_N)}\right) - \frac{1}{2}(\Delta c_N + \Delta c_T)\left(\beta_1 - \beta_1^{(\Delta c_N,\Delta c_T)}\right) \\ &= \frac{1}{2}\big(\Delta c_N\big(\beta_1^{(\Delta c_N,\Delta c_T)} - \beta_1^{(\Delta c_N)}\big) + \Delta c_T\big(\beta_1^{(\Delta c_N,\Delta c_T)} - \beta_1\big)\big),\end{aligned}$$

which is positive since $\beta_1^{(\Delta c_N,\Delta c_T)}$ is greater than $\beta_1^{(\Delta c_N)}$ and β_1. Lastly, we have

$$\begin{aligned}\zeta^{(\Delta c_N)} - \zeta^{(\Delta c_N,\Delta c_T)} &= \Delta c_N\beta_1^{(\Delta c_N)} - \left(\Delta c_N\beta_1^{(\Delta c_N,\Delta c_T)} - \Delta c_T\big(1 - \beta_1^{(\Delta c_N,\Delta c_T)}\big)\right) \\ &= -\Delta c_N\frac{\Delta c_T}{X} - \Delta c_T\beta_1 - \Delta c_T\frac{\Delta c_N + \Delta c_T}{X} + \Delta c_T \\ &= \frac{\Delta c_T}{X}((1-\beta_1)X - 2\Delta c_N - \Delta c_T),\end{aligned}$$

which implies that $\zeta^{(\Delta c_N)} > \zeta^{(\Delta c_N,\Delta c_T)}$ if and only if $2\Delta c_N + \Delta c_T < (1-\beta_1)X$.

$\square$

Proof of Proposition 8.

Let $\overline{\Delta c}_N$ denote the unit subsidy under the subsidy-only policy. Given that $\beta_1^{(\Delta c_N, \Delta c_T)} < 1$, it has to be that $\beta_1^{\left(\overline{\Delta c}_N\right)} < 1$, i.e., $\overline{\Delta c}_N < (1-\beta_1)X$, since otherwise, expenditure equivalence cannot be satisfied. As the total expenditure is kept the same, we have

$$\overline{\Delta c}_N \beta_1^{\left(\overline{\Delta c}_N\right)} = \Delta c_N \beta_1^{(\Delta c_N, \Delta c_T)} - \Delta c_T \left(1 - \beta_1^{(\Delta c_N, \Delta c_T)}\right),$$

which can be reduced to

$$\Delta c_N + \Delta c_T - \overline{\Delta c}_N = \frac{\Delta c_T}{\beta_1 + \frac{\left(\Delta c_N + \Delta c_T + \overline{\Delta c}_N\right)}{X}}.$$

Since the right-hand side is positive, we have $\overline{\Delta c}_N < \Delta c_N + \Delta c_T$, meaning that $\beta_1^{\left(\overline{\Delta c}_N\right)} < \beta_1^{(\Delta c_N, \Delta c_T)}$. Moreover, using (44), we have

$$\begin{aligned}
\Delta\Pi_{SW}^{\left(\overline{\Delta c}_N\right)} - \Delta\Pi_{SW}^{(\Delta c_N, \Delta c_T)} &= \frac{1}{2}\left(\overline{\Delta c}_N \left(\beta_1 + \beta_1^{\left(\overline{\Delta c}_N\right)}\right) - (\Delta c_N + \Delta c_T)\left(\beta_1 + \beta_1^{(\Delta c_N, \Delta c_T)}\right)\right) + \Delta c_T \\
&= \frac{1}{2}\left(-\beta_1\left(\Delta c_N + \Delta c_T - \overline{\Delta c}_N\right) + \underbrace{\overline{\Delta c}_N \beta_1^{\left(\overline{\Delta c}_N\right)} - (\Delta c_N + \Delta c_T)\,\beta_1^{(\Delta c_N, \Delta c_T)}}_{\text{reduces to } -\Delta c_T \text{ due to expenditure equivalence}}\right) + \Delta c_T \\
&= \frac{1}{2}\Delta c_T \left(1 - \frac{\beta_1}{\beta_1 + \frac{\Delta c_N + \Delta c_T + \overline{\Delta c}_N}{X}}\right) > 0,
\end{aligned}$$

proving the proposition.

□

Proof of Proposition 9.

Using (43), we obtain

$$\begin{aligned}
\Delta\Pi_C^{\left(\overline{\Delta c}_N\right)} - \Delta\Pi_C^{(\Delta c_N, \Delta c_T)} &= \frac{1}{2}\overline{\Delta c}_N\big(\beta_1 + \beta_1^{\left(\overline{\Delta c}_N\right)} - \frac{2E}{X}\big) - \frac{1}{2}(\Delta c_N + \Delta c_T)\big(\beta_1 + \beta_1^{(\Delta c_N, \Delta c_T)} - \frac{2E}{X}\big) \\
&= \left(\beta_1 - \frac{E}{X}\right)\left(\overline{\Delta c}_N - \Delta c_N - \Delta c_T\right) + \frac{\overline{\Delta c}_N^2}{2X} - \frac{(\Delta c_N + \Delta c_T)^2}{2X} \\
&= \left(\overline{\Delta c}_N - \Delta c_N - \Delta c_T\right)\left(\frac{MG}{X} + \frac{\Delta c_N + \Delta c_T + \overline{\Delta c}_N}{2X}\right).
\end{aligned}$$

As shown in the proof of Proposition 8, we have $\overline{\Delta c}_N < \Delta c_N + \Delta c_T$. Thus, if $MG > 0$, i.e., $w\bar{\alpha}\big(v_N\mu_N^H - c_N - v_T\mu_T + c_T\big) > v_T\mu_T - c_T - v_N\mu_N + c_N$, we have $\Delta\Pi_C^{\left(\overline{\Delta c}_N\right)} < \Delta\Pi_C^{(\Delta c_N, \Delta c_T)}$.

Moreover, using (42), we get

$$\begin{aligned}
\Delta\Pi_P^{\left(\overline{\Delta c}_N\right)} - \Delta\Pi_P^{(\Delta c_N, \Delta c_T)} &= \left(\overline{\Delta c}_N - \Delta c_N - \Delta c_T\right)\frac{E}{X} + \Delta c_T \\
&= \Delta c_T\left(1 - \frac{E/X}{\left(Y + \Delta c_N + \Delta c_T + \overline{\Delta c}_N\right)/X}\right) \\
&= \Delta c_T\left(\frac{MG + \Delta c_N + \Delta c_T + \overline{\Delta c}_N}{Y + \Delta c_N + \Delta c_T + \overline{\Delta c}_N}\right),
\end{aligned}$$

where the second equality follows due to expenditure equivalence. Hence, if $MG > 0$, we have $\Delta\Pi_P^{\left(\overline{\Delta c}_N\right)} > \Delta\Pi_P^{(\Delta c_N, \Delta c_T)}$.

□

Proof of Proposition 10.

If $\delta \leq 1-\beta_1$, the solution to the indifference condition presented in (15) is given by $\tilde{\beta}_1 = \beta_1 = \frac{MG+E}{X}$, meaning that some portion of the producers that are not financially constrained choose to use the traditional method instead of experimenting with the new method. On the other hand, if $\delta > 1-\beta_1$, the presence of financially constrained producers prevents the experimentation rate, $\tilde{\beta}_1$, from reaching the experimentation rate in the absence of financial constraints, β_1, meaning that $\tilde{\beta}_1 < \beta_1$. Note that when the experimentation rate is less than β_1, the right-hand side of the indifference condition presented in (15), $\pi_{N1} + w\mathbb{E}_\alpha\left[\alpha\pi_{N2}^H|\alpha + (1-\alpha)\pi_{T2}|\alpha\right]$, is greater than the left-hand side, $\pi_{T1} + w\mathbb{E}_\alpha\left[\pi_{T2}|\alpha\right]$. Thus, for producers that are not financially constrained, a profitable deviation to the new method exists if $\tilde{\beta}_1 < 1-\delta$. Also, it cannot be that $\tilde{\beta}_1 > 1-\delta$ since financially constrained producers cannot afford experimenting with the new method. Thus, we have $\tilde{\beta}_1 = 1-\delta$, proving the proposition.

□

Proof of Proposition 11.

Given that $\beta_1^{(\Delta c_N, \Delta c_T)} = \beta_1 + \frac{\Delta c_N + \Delta c_T}{X}$, if the $(\Delta c_N, \Delta c_T)$ policy is such that

$$\begin{aligned}\pi_{N1}^{(\Delta c_N, \Delta c_T)} &= v_N\mu_N - c_N + \Delta c_N - v_T\kappa_{TN}\left(1-\beta_1^{(\Delta c_N, \Delta c_T)}\right) - v_N\kappa_N\beta_1^{(\Delta c_N, \Delta c_T)} \\ &= v_N\mu_N - c_N - v_T\kappa_{TN}\left(1-\beta_1\right) - v_N\kappa_N\beta_1 + \Delta c_N + \frac{\Delta c_N + \Delta c_T}{X}\left(v_T\kappa_{TN} - v_N\kappa_N\right) \qquad (33)\end{aligned}$$

is greater than or equal to zero, then any producer can experiment with the new method, meaning that the problem reduces to the case where there is no financial constraints. This implies that $\tilde{\beta}_1^{(\Delta c_N, \Delta c_T)} = \beta_1^{(\Delta c_N, \Delta c_T)}$. On the other hand, if $\pi_{N1}^{(\Delta c_N, \Delta c_T)} < 0$, i.e., $\Delta c_N + \frac{\Delta c_N + \Delta c_T}{X}(v_T\kappa_{TN} - v_N\kappa_N) < -(v_N\mu_N - c_N - v_T\kappa_{TN}(1-\beta_1) - v_N\kappa_N\beta_1)$, we investigate the following two cases.

Case I : We assume that $v_N\kappa_N < v_T\kappa_{TN}$. Then, if $\beta_1^{(\Delta c_N, \Delta c_T)} < 1-\delta$, in equilibrium, all of the financially constrained producers as well as some portion of the non-constrained producers choose not to experiment with the new method, so $\tilde{\beta}_1^{(\Delta c_N, \Delta c_T)} = \beta_1^{(\Delta c_N, \Delta c_T)}$. If $\beta_1^{(\Delta c_N, \Delta c_T)} \geq 1-\delta$, the equilibrium experimentation rate cannot be $\beta_1^{(\Delta c_N, \Delta c_T)}$ as the financially constrained producers cannot afford experimentation. In this case, the equilibrium experimentation rate is $1-\delta$, and only the non-constrained producers experiment with the new method. Note that there is no profitable deviation to the traditional method from the perspective of non-constrained producers as the right-hand side of (15) is in fact greater than or equal to the left-hand side since $\beta_1^{(\Delta c_N, \Delta c_T)} \geq 1-\delta$. Also, none of the financially-constrained producers can deviate to the new method since the new production method yields negative profits in period 1. Thus, we have $\tilde{\beta}_1^{(\Delta c_N, \Delta c_T)} = \min\left(\beta_1^{(\Delta c_N, \Delta c_T)}, 1-\delta\right)$.

Case II : We assume that $v_N\kappa_N > v_T\kappa_{TN}$. Then, if $\beta_1^{(\Delta c_N, \Delta c_T)} < 1-\delta$, we have $\tilde{\beta}_1^{(\Delta c_N, \Delta c_T)} = \beta_1^{(\Delta c_N, \Delta c_T)}$ by the same reasoning as above. If $\beta_1^{(\Delta c_N, \Delta c_T)} \geq 1-\delta$, $\exists\tilde{\tilde{\beta}}_1$ such that

$$v_N\mu_N - c_N + \Delta c_N - v_T\kappa_{TN}\left(1-\tilde{\tilde{\beta}}_1\right) - v_N\kappa_N\tilde{\tilde{\beta}}_1 = 0, \qquad (34)$$

resulting in $\tilde{\tilde{\beta}}_1 = \frac{v_N\mu_N - c_N - v_T\kappa_{TN} + \Delta c_N}{v_N\kappa_N - v_T\kappa_{TN}}$. Note that $\tilde{\tilde{\beta}}_1 < \beta_1^{(\Delta c_N, \Delta c_T)}$. Now, if $\tilde{\tilde{\beta}}_1 > 1-\delta$, then the equilibrium experimentation rate is $\tilde{\tilde{\beta}}_1$, and all of the non-constrained along with some financially constrained producers experiment with the new method. Note that there is no profitable deviation since the expected profit from the new method in period 1 is zero and the total expected profit from the new method (the right-hand side of (15)) exceeds that of the traditional method (the left-hand side of (15)). If $\tilde{\tilde{\beta}}_1 \leq 1-\delta$, then the equilibrium experimentation rate is $1-\delta$ since it is profitable for all of the non-constrained producers to experiment with the new method. But in this case, the expected profit from the new method in period 1 is negative, so the financially constrained producers cannot afford experimentation. Overall, we have $\tilde{\beta}_1^{(\Delta c_N,\Delta c_T)} = \min\big(\beta_1^{(\Delta c_N,\Delta c_T)}, \max\big(\tilde{\tilde{\beta}}_1, 1-\delta\big)\big)$.

□

Proof of Corollary 1.

Using only taxes results in $\pi_{N1}^{(\Delta c_T)} = v_N\mu_N - c_N - v_T\kappa_{TN}\big(1-\tilde{\beta}_1^{(\Delta c_T)}\big) - v_N\kappa_N\tilde{\beta}_1^{(\Delta c_T)} < 0$, $\forall \Delta c_T \geq 0$. Hence, financially constrained producers cannot afford experimentation under tax-only policies.

Using (33), one can see that under a $(\Delta c_N, \Delta c_T)$ policy, if

$$X + v_T\kappa_{TN} - v_N\kappa_N = -v_T\kappa_{TN} + v_T\kappa_T + w\kappa_\alpha\left(v_N\kappa_N^H - 2v_T\kappa_{TN}^H + v_T\kappa_T\right) < 0, \tag{35}$$

i.e., $\sigma_{TN} > \frac{1}{2w\kappa_\alpha+1}\big(\kappa_T - \mu_T\mu_N + w\kappa_\alpha\big(\frac{v_N}{v_T}\kappa_N^H - 2\mu_T\mu_N^H + \kappa_T\big)\big)$, then $\pi_{N1}^{(\Delta c_N,\Delta c_T)} < 0$. In addition to that, as shown in Proposition 11, if $v_N\kappa_N < v_T\kappa_{TN}$, i.e., $\sigma_{TN} > \frac{v_N}{v_T}\kappa_N - \mu_T\mu_N$, then the equilibrium is always such that under any policy, a fraction of the non-constrained producers experiment with the new production method and the financially constrained producers do not engage in experimentation. Thus, no policy achieves experimentation by the constrained producers if $\sigma_{TN} > \bar{\sigma}_{TN}$ where $\bar{\sigma}_{TN} = \max\Big(\frac{1}{2w\kappa_\alpha+1}\big(\kappa_T - \mu_T\mu_N + w\kappa_\alpha\big(\frac{v_N}{v_T}\kappa_N^H - 2\mu_T\mu_N^H + \kappa_T\big)\big), \frac{v_N}{v_T}\kappa_N - \mu_T\mu_N\Big)$.

□

Proof of Proposition 12.

Under a zero-expenditure policy that makes innovation *affordable*, i.e., $\pi_{N1}^{(\Delta c_N,\Delta c_T)} \geq 0$, the financially constrained producers can afford experimentation, resulting in $\tilde{\beta}_1^{(\Delta c_N,\Delta c_T)} = \beta_1^{(\Delta c_N,\Delta c_T)}$. Here, we examine the following two cases.

Case I : $\delta \leq 1-\beta_1$: In this case, the no-intervention experimentation rate is given by $\tilde{\beta}_1 = \beta_1$. We can then use Proposition 2 to conclude that zero-expenditure policies result in a reduction in social welfare. Also, as shown in Proposition 6, the return on the government's expenditure is negative.

Case II : $\delta > 1-\beta_1$: In this case, the no-intervention experimentation rate is given by $\tilde{\beta}_1 = 1-\delta$. The impact of the intervention on social welfare is given as follows.

$$\begin{aligned}
\Delta\Pi_{SW}^{(\Delta c_N,\Delta c_T)} &= \frac{1}{2}\Big(\big(\beta_1^{(\Delta c_N,\Delta c_T)}\big)^2 X + (1-\delta)^2 X - 2\beta_1(1-\delta)X - 2\Delta c_T\Big) \\
&= \big(\delta-(1-\beta_1)\big)^2\frac{X}{2} + \underbrace{\Delta c_N\beta_1 - \Delta c_T(1-\beta_1)}_{\zeta^{(\Delta c_N,\Delta c_T)} - \frac{(\Delta c_N+\Delta c_T)^2}{X}} + \frac{(\Delta c_N+\Delta c_T)^2}{2X} \\
&= \big(\delta-(1-\beta_1)\big)^2\frac{X}{2} - \frac{(\Delta c_N+\Delta c_T)^2}{2X} \quad (\text{since } \zeta^{(\Delta c_N,\Delta c_T)} = 0) \\
&= \frac{1}{2X}\big(\big(\delta-(1-\beta_1)\big)X - \Delta c_N - \Delta c_T\big)\underbrace{\big(\big(\delta-(1-\beta_1)\big)X + \Delta c_N + \Delta c_T\big)}_{\geq 0}.
\end{aligned}$$

So, $\Delta\Pi_{SW}^{(\Delta c_N,\Delta c_T)} > 0$ if and only if $\Delta c_N + \Delta c_T < (\delta - (1-\beta_1))\, X$. Also, from the above calculation, note that

$$\Delta\Pi_{G}^{(\Delta c_N,\Delta c_T)} = \Delta\Pi_{SW}^{(\Delta c_N,\Delta c_T)} - \zeta^{(\Delta c_N,\Delta c_T)} = \big(\delta - (1-\beta_1)\big)^2 \frac{X}{2} - \frac{(\Delta c_N + \Delta c_T)^2}{2X},$$

proving the proposition.

□

Proof of Proposition 13.

Note that

$$\frac{\partial \beta_1^{RA}}{\partial \gamma_1} = \frac{v_N\mu_N - c_N - v_T\kappa_T(1-\beta_1^{RA}) - v_N\kappa_N\beta_1^{RA} - a}{X^{RA}} < 0,$$

since $v_N\mu_N - c_N < 0$ and $X^{RA} > 0$. Moreover,

$$\frac{\partial \beta_1^{RA}}{\partial \gamma_2} = w\alpha \frac{v_N\mu_N^H - c_N - v_T\kappa_{TN}^H(1-\alpha\beta_1^{RA}) - v_N\kappa_N^H\alpha\beta_1^{RA} - b}{X^{RA}} > 0,$$

due to (A4) and (A5). Consequently, since β_1 is a special case of β_1^{RA} when $\gamma_1 = \gamma_2 = 1$, $\beta_1^{RA} < \beta_1$.

□

Proof of Proposition 14.

Similar to the risk neutral case, the total expected profit of producers is given by $\Pi_P^{RA} = \pi_{T1}^{RA} + w\mathbb{E}_\alpha\pi_{T2}^{RA}$. Hence, the impact of the intervention on the total expected profit of producers is given by

$$\Delta\Pi_P^{RA} = (\gamma_1\Delta c_N + \Delta c_T)\,\frac{E}{X^{RA}} - \Delta c_T. \tag{36}$$

Consumer surplus is calculated as in (23), with the only difference being the use of β_1^{RA} instead of β_1. Then, the impact of the intervention on consumer surplus is given by

$$\Delta\Pi_C^{RA} = \frac{1}{2X^{RA}}\,(\gamma_1\Delta c_N + \Delta c_T)\left(X\left(\beta_1^{RA} + \beta_1^{RA,(\Delta c_N,\Delta c_T)}\right) - 2E\right). \tag{37}$$

Consequently, the impact on social welfare, $\Delta\Pi_{SW}^{RA} = \Delta\Pi_P^{RA} + \Delta\Pi_C^{RA}$, is given by

$$\Delta\Pi_{SW}^{RA} = \frac{1}{2X^{RA}} X\,(\gamma_1\Delta c_N + \Delta c_T)\left(\beta_1^{RA} + \beta_1^{RA,(\Delta c_N,\Delta c_T)}\right) - \Delta c_T. \tag{38}$$

Government expenditure is $\zeta^{(\Delta c_N,\Delta c_T)} = \Delta c_N\beta_1^{RA,(\Delta c_N,\Delta c_T)} - \Delta c_T\left(1 - \beta_1^{RA,(\Delta c_N,\Delta c_T)}\right)$. Thus, the return on government's expenditure under risk aversion is given by

$$\Delta\Pi_G^{RA} = \frac{1}{2X^{RA}} X\,(\gamma_1\Delta c_N + \Delta c_T)\left(\beta_1^{RA} + \beta_1^{RA,(\Delta c_N,\Delta c_T)}\right) - (\Delta c_N + \Delta c_T)\beta_1^{RA,(\Delta c_N,\Delta c_T)}. \tag{39}$$

We can now study the difference between the return on government's expenditure under risk aversion and risk neutrality.

$$\begin{aligned}
\Delta\Pi_G^{RA} - \Delta\Pi_G &= \frac{\gamma_1\Delta c_N + \Delta c_T}{2X^{RA}} X\left(\beta_1^{RA} + \beta_1^{RA,(\Delta c_N,\Delta c_T)}\right) - (\Delta c_N + \Delta c_T)\beta_1^{RA,(\Delta c_N,\Delta c_T)} - \frac{(\Delta c_N + \Delta c_T)}{2}\left(\beta_1 - \beta_1^{(\Delta c_N,\Delta c_T)}\right) \\
&= \left(\frac{\gamma_1\Delta c_N + \Delta c_T}{X^{RA}} - \frac{\Delta c_N + \Delta c_T}{X}\right) X\left(\beta_1^{RA} + \frac{1}{2}\left(\frac{\gamma_1\Delta c_N + \Delta c_T}{X^{RA}} - \frac{\Delta c_N + \Delta c_T}{X}\right)\right).
\end{aligned}$$

Hence, if $\eta^{RA} = \frac{\gamma_1\Delta c_N + \Delta c_T}{X^{RA}} > \eta = \frac{\Delta c_N + \Delta c_T}{X}$, $\Delta\Pi_G^{RA} > \Delta\Pi_G$. Moreover, we can rewrite the return on government's expenditure as follows.

$$\begin{aligned}
\Delta\Pi_G^{RA} &= \beta_1^{RA} X\left(\frac{\gamma_1\Delta c_N + \Delta c_T}{X^{RA}} - \frac{\Delta c_N + \Delta c_T}{X}\right) + \frac{\gamma_1\Delta c_N + \Delta c_T}{X^{RA}} X\left(\frac{\gamma_1\Delta c_N + \Delta c_T}{2X^{RA}} - \frac{\Delta c_N + \Delta c_T}{X}\right) \\
&> \left(\frac{\gamma_1\Delta c_N + \Delta c_T}{2X^{RA}} - \frac{\Delta c_N + \Delta c_T}{X}\right) X\beta_1^{RA,(\Delta c_N,\Delta c_T)}.
\end{aligned}$$

Thus, if $\eta^{RA} > 2\eta$, the return on government's expenditure is positive. This implies that the impact of the intervention on social welfare is also positive under a zero-expenditure policy since $\Delta\Pi_{SW}^{RA} = \Delta\Pi_G^{RA}$ in that case.

□

Proof of Proposition 15.

In the case of learning in yield variability, the derivation of the equilibrium given in Appendix A continues to hold. In the risk neutral case, the experimentation rate becomes $\tilde{\beta}_1 = \frac{MG+E}{\tilde{X}}$ where $\tilde{X} = v_N\kappa_N - 2v_T\kappa_{TN} + v_T\kappa_T + w\kappa_\alpha\left(v_N\tilde{\kappa}_N^H - 2v_T\kappa_{TN}^H + v_T\kappa_T\right)$ and $\tilde{\kappa}_N^H = (\mu_N^H)^2 + (\sigma_N^H)^2$. Here, $\tilde{X} > 0$ by the same reasoning as $X > 0$.

Consequently, we have

$$\frac{\partial\tilde{\beta}_1}{\partial\tilde{\theta}_H} = \frac{2v_N w\alpha^2\gamma_2\sigma_N^H\tilde{\beta}_1}{\tilde{X}} > 0.$$

Similarly, one can derive the experimentation rate when producers are risk averse and learning results in a reduction in yield variability. Under risk aversion, we have

$$\frac{\partial\tilde{\beta}_1^{RA}}{\partial\tilde{\theta}_H} = \frac{2v_N w\alpha^2\gamma_2\sigma_N^H\tilde{\beta}_1^{RA}}{\tilde{X}^{RA}} > 0,$$

since $\tilde{X}^{RA} > 0$.

Lastly, we can derive

$$\frac{\partial\tilde{\beta}_1^{RA}}{\partial\tilde{\theta}_H\partial\gamma_1} = \frac{2v_N w\alpha^2\gamma_2\sigma_N^H}{(\tilde{X}^{RA})^2}\left(v_N\mu_N - c_N - v_T\kappa_{TN} - a - 2\tilde{\beta}_1^{RA}(v_N\kappa_N - v_T\kappa_{TN})\right), \quad \text{and}$$
$$\frac{\partial\tilde{\beta}_1^{RA}}{\partial\tilde{\theta}_H\partial\gamma_2} = \frac{2v_N w\alpha^2\sigma_N^H}{(\tilde{X}^{RA})^2}\left(Y^{RA} + w\alpha\gamma_2(v_N\mu_N^H - c_N - v_T\kappa_{TN}^H - b) - 2w\alpha^2\gamma_2\tilde{\beta}_1^{RA}(v_N\tilde{\kappa}_N^H - v_T\kappa_{TN}^H)\right).$$

This implies that $\frac{\partial\tilde{\beta}_1^{RA}}{\partial\tilde{\theta}_H\partial\gamma_1} < 0$ if $v_N\kappa_N > v_T\kappa_{TN}$ since $v_N\mu_N - c_N < 0$. Also, $\frac{\partial\tilde{\beta}_1^{RA}}{\partial\tilde{\theta}_H\partial\gamma_2} > 0$ if $v_N\tilde{\kappa}_N^H < v_T\kappa_{TN}^H$ since $v_N\mu_N^H - c_N - v_T\kappa_{TN}^H - b > 0$ by (A4), proving the proposition.

□

Proof of Proposition 16.

Since both $\tilde{X}$ and $\tilde{X}^{RA}$ are decreasing in $\tilde{\theta}_H$, η and η^{RA} are higher when learning results in a reduction in yield variability. Moreover, as shown in the proof of Proposition 6, under risk neutrality, the return on government's expenditure becomes $\widetilde{\Delta\Pi}_G = -\frac{(\Delta c_N + \Delta c_T)^2}{2\tilde{X}}$. Hence, $\frac{\partial\widetilde{\Delta\Pi}_G}{\partial\tilde{\theta}_H} < 0$ since $\frac{\partial\tilde{X}}{\partial\tilde{\theta}_H} < 0$.

□

Appendix D: Estimation of Model Parameters

Given the analytical expressions for market-clearing prices, (3) and (4), we use the following linear price functions to estimate the model parameters,

$$p_T = \alpha_0 - \alpha_1 Q_T^{Supply} - \alpha_2 Q_N^{Supply} + \epsilon_T,$$
$$p_N = \beta_0 - \beta_1 Q_T^{Supply} - \beta_2 Q_N^{Supply} + \epsilon_N,$$

with parameter restrictions $\alpha_1 = \alpha_2 = \beta_1$ and $\alpha_0/\alpha_1 = \beta_0/\beta_1$. Note that the valuations for conventional and organic products are given by α_0 and β_0, respectively, and the total market size is calculated as α_0/α_1. We use Generalized Method of Moments to estimate the parameters. In order to obtain unbiased estimates, we use the total number of hens as an instrumental variable. We assume that the number of hens only affects price through the total supply, and hence is uncorrelated with the error term.

Valuations for conventional and organic eggs are estimated as 12.96 and 21.59 DKK/kg, respectively, and the total market size is found to be 271.89 million of eggs. The number of hens that are used to satisfy the demand in the market in 2015 is calculated as 3.167 million using the kilograms of eggs produced for human consumption and the production yields in the same year. Here, we can think of the size of the producer population to be equivalent to the total number of hens used to satisfy the demand. This fits to our model setting where each producer is infinitesimally small compared to the total producer population. Note that in our model, the size of the producer population is normalized to 1. To capture that, we take $M = 85.85$ to be the relative size of the consumer population.

In practice, farmers have to implement organic farming for several years before they can obtain certification and benefit from premium prices. To capture this, we assume that organic produce is sold at conventional prices during the transition period. Thus, the experimentation rate used in the numerical study is given as

$$\beta_1 = \frac{v_T(\mu_N - \mu_T + \kappa_T - \kappa_{TN}) - c_N + c_T + w\bar{\alpha}\left(v_N \mu_N^H - c_N - v_T \mu_T + c_T + v_T \kappa_T - v_T \kappa_{TN}^H\right)}{v_T(\kappa_N - 2\kappa_{TN} + \kappa_T) + w\kappa_\alpha\left(v_N \kappa_N^H - 2 v_T \kappa_{TN}^H + v_T \kappa_T\right)}.$$