Risk Management Externalities in Agrifood Supply Chains *

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Abstract

Firms may under- or over-invest in risk management from the social planner's perspective, resulting in a negative externality on other economic agents in the supply chain. The externality of risk management provides justification for policy intervention and is particularly relevant for agrifood supply chains that constantly experience shocks and play a primary role in preventing major social losses from food insecurity. We build a theoretical model to characterize such externalities in US food supply chains where intermediary firms choose the quantity of output and the investment in managing risks. The model allows for flexible market structures and interdependence of risk management among firms. Risk interdependence captures the unique feature of biotic hazards (e.g., animal and plant diseases) in agrifood supply chains, where the effectiveness of a firm's risk management depends on peer firms' behavior. We offer novel insights on the role of risk interdependence in driving the externality in risk management under different market structures. We show that private firms invest less than the socially optimal level under perfect competition, but risk interdependence and market power introduce complex incentives in risk-reducing investment that shape the externality. The critical implications for the social efficiency of policy interventions are demonstrated via simulations based on the model and empirical literature on biotic hazards in agrifood markets.

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1 Introduction

Supply chain disruptions have become increasingly frequent in the United States and globally (Baldwin and Freeman, 2022). In response, governments have discussed and implemented a variety of policy interventions, trying to make supply chains more resilient to shocks (Elliott and Golub, 2022; Grossman, Helpman, and Sabal, 2024). Agrifood markets, in particular, have garnered the attention of policymakers because recent disruptions like extreme weather and disease outbreaks have resulted in stock-outs and elevated prices of staple food products (Hobbs, 2021; Hobbs and Hadachek, 2024). These events affect all agents along the supply chain, including agribusiness firms that can endogenously reduce their exposure to hazards through risk management. A critical open question for policy making is whether private firms arrive at the socially optimal level of risk management on their own, and if not, how large the externality is, and what policy intervention is warranted.

To characterize the externality in risk management in the context of the US agrifood sector, we build a theoretical model of a vertical supply chain where intermediary processing/retailing firms are exposed to hazards that threaten their ability to produce or deliver the final products to consumers. Firms may invest in risk management to reduce exposure to hazards. The model allows for a flexible market structure and interdependence in risk management among firms (e.g., the effectiveness of vaccines for animal diseases on a farm supplier depends on actions by peers), both of which are key features of the US agricultural sector (Hennessy, Roosen, and Jensen, 2005; Sexton, 2013). We calibrate the model based on empirical literature on biotic hazards (biohazards hereafter) in US agrifood markets to quantify the externality under various market and risk conditions and measure the subsequent welfare implications of policy intervention.

In the model, profit-maximizing firms in the middle of the supply chain anticipate hazards and can endogenously reduce their exposure to the hazards by investing in risk management before the realization of shocks.[1] At the same time, each firm chooses the output level to maximize its

[1] Importantly, we consider *ex ante* risk management strategies. Firms may also invest in insurance that provides *ex post* revenue protection in the event of a hazard, but we focus on protective strategies that shield against potential inventory or production losses.

own expected profits. With the two choice variables, firms may collude (explicitly or tacitly) in production — the conventional force behind market power — and in risk management, which is a key modeling innovation introduced in this study. Each firm also considers how the effectiveness of its investment depends on other firms, which is the other modeling innovation.

To compare firms' choices against the social optimum, we consider an alternative scenario in which the social planner manages risk. The social planner first chooses the level of risk-reducing investment by firms that maximizes total social welfare (i.e., consumer surplus, producer surplus, and total firm profits). In the second stage, given the risk environment set by the social planner, firms choose profit-maximizing outputs. This setup captures the realistic context where the government imposes policies on supply chain resilience (e.g., requiring vaccines to prevent animal diseases or biohazard protocols), but allows the market to dictate equilibrium outputs and prices.

To calibrate the model, the parameter values are drawn from distributions based on empirical literature on biohazards and US agrifood markets. We perform Monte-Carlo simulations under counterfactual risk and market structure scenarios to demonstrate externality in risk management and gains from policy intervention. The baseline scenario considers a simple context without collusion among firms or interdependence in risk management. Simulations reveal a positive *public-private wedge in risk management*: Firms invest less than the social optimum, and the wedge plateaus once the hazard is sufficiently large. Intuitively, this wedge reflects a risk management externality that arises because private firms fail to incorporate the welfare impacts caused by the propagation of disruptions in food supply on the greater society (i.e., consumers and farmers) and, thus, under-invest in risk reduction from the social planner's perspective (Baldwin and Freeman, 2022).

We then examine the role of interdependence in risk management among firms. Risk investments can be substitutes or complements among firms (Wang and Hennessy, 2015). If the investment is complementary, but such interdependence is not fully incorporated due to limited coordination in risk management among firms, the externality tends to be larger than that in the baseline. In contrast, if the substitution among firm investments is not fully accounted for due to low coordination in risk management, the firm mitigates free-riding and tends to invest more than in a setting of independent investment, narrowing the risk externality. Simulations suggest that potential welfare gains vary considerably with the degree of investment interdependence, highlighting the contextual importance of risk interdependence for policy making.

Next, we study the interactions between market power and the externality by imposing flexible assumptions on competition in the style of the Flexible Oligopology/Oligopsony Market (FOOM) model (e.g., Russo, Goodhue, and Sexton, 2011). Market power is characterized by the conjectural variations in input procurement (i.e., the conventional buyer power), final output (i.e., the conventional seller power), and a risk conjectural variation. Intuitively, the conjectural variation reflects the degree of firm collusion in conducting an action. The higher the degree of collusion, the larger the market power. We show that the three forms of market power play critical, and sometimes opposing roles in determining the sign and magnitude of the risk management externality.

Specifically, given the degree of coordination in risk management, increased conventional market power affects the size and direction of externality due to two effects: A *social welfare* effect and an *investment collusion* effect. On the one hand, as market power increases, firm profits represent a greater share of the total welfare, all else the same. Effectively, firms internalize a greater share of the total social losses of the hazard and invest more in risk management, and the wedge narrows and stays positive (i.e., the *social welfare* effect). On the other hand, firms tend to invest more in risk management, when a larger potential profit may be captured with larger market power. As long as collusion of firms in risk management is imperfect, they tend to over-invest relative to the socially optimum because firms fail to incorporate negative impacts of investing on competitors' profits. The social planner who imposes an equal risk investment among firms effectively improves the coordination in investment and may achieve a lower level of equilibrium investment than firms do (the *investment collusion* effect). The collusion effect is weak if firms already coordinate well in risk management or if firms' investments form substitutes, and the social welfare effect dominates.

We mainly contribute to the discussion of the resilience of agrifood supply chains (Barrot and Sauvagnat, 2016; Carvalho et al., 2020). Our study is one of the first to offer a flexible conceptual framework that characterizes firms' risk management decisions, unpacks the driving mechanisms, and weighs the equilibrium values against socially efficient risk management in the context of US food supply chains. Theoretical evidence on the externality of managing risks by firms and the corresponding impacts on welfare along the supply chain is provided under various market and risk conditions.

We also contribute directly to the literature that explores the implications of market structure on agrifood supply chain resilience. Past work has empirically measured how market structure (Gnutzmann, Kowalewski, and Śpiewanowski, 2020) and diversification in production/sourcing (Stevens and Teal, 2024) affect economic outcomes in the presence of historical shocks. Other theoretical work has measured how market power (Hadachek, Ma, and Sexton, 2024) or flexible marketing options (Chenarides et al., 2023) can make agrifood supply chains more resilient. Our findings are applicable to the management of hazards, especially biohazards, which present unique challenges to agrifood supply chains. In particular, risk management taken by an agent in the supply chain may inadvertently affect the risk exposure of other agents, due to the nature of how biohazards are transmitted and spread (Wang and Hennessy, 2014). We show that the nature of this risk dependence has critical implications for the size of risk management externality. In practice, the interdependent nature of biohazards may also increase the likelihood of collective management between firms (Flowers, Kaplan, and Singh, 2025) and government intervention (Hennessy and Wolf, 2018).[2] Our findings are the first to highlight the interactions of these factors on risk management decisions and to quantify the welfare consequences of firm-driven decisions relative to the social optimum.

[2]A growing body of theoretical work endogenizes risk strategies by firms and governments via endogenous supply network formation and measures the welfare implications of disruptions within the network (Capponi, Du, and Stiglitz, 2024; Grossman, Helpman, and Sabal, 2024; Kopytov et al., 2024). Some empirical work has documented that firms adapt to climate risks or natural disasters by adjusting the composition of suppliers (Castro-Vincenzi et al., 2024; Grover and Kahn, 2024). These studies, though, do not incorporate the characteristics of biohazards because they are tailored to fit non-agrifood industries.

2 Biohazards in Agrifood Supply Chains

Agribusiness firms manage a long list of abiotic and biohazards that affect their business (Oerke, 2006), and the firms invest in programs or operating inputs to mitigate exposure to such hazards. Regarding many abiotic hazards (e.g., fire, weather, and geopolitics), managing a hazard is isolated to an individual firm; the effectiveness of the risk management by one firm does not significantly affect or depend on the risk exposure of other firms. Managing biotic factors introduces more complex relationships. In particular, biohazards are known to be interdependent — risk investments between firms can be substitutes or complements to each other due to the transmission of disease or the mobility of pests (Hendrichs et al., 2007; Hutchison, 2010; Wang and Hennessy, 2015).

Every year, the US agricultural sector suffers substantial losses due to plant and animal diseases caused by pests and pathogens. For instance, crop losses due to plant pathogens are estimated to cause losses of $21 billion per year (USDA, 2021). In response, the US agricultural sector, both public and private entities, invests substantially each year in preventing and managing plant and animal diseases. Every year, more than $20 billion (about 5% of farm production expenditure) are spent on agricultural pesticides, fungicides, and animal vaccines (USDA, 2023).

Plant diseases Pests are organisms, including insects, mites, nematodes, and pathogens that can damage economically valuable agricultural crops. They cause profit losses due to yield reductions and increased chemical and labor costs worth hundreds of millions of dollars every year in US crops (Fan et al., 2020; Fernandes-Cornejo and Jans, 1999).

Citrus greening is a recent major plant disease caused by Asian citrus psyllid. The disease was first detected in Florida in 2005 and spread to California, Texas, and other citrus-producing states over the last 20 years. Infected trees exhibit yellow shoots, blotchy-mottled leaves, lopsided and sour fruit, premature fruit drop, and canopy thinning. Trees typically decline and die within two to five years of infection. From 2006 to 2016, the disease resulted in an estimated loss of $9 billion in Florida alone (Fuchs et al., 2021). In response, neighboring agents try to collaborate to ensure widespread disease control. For example, Flowers, Kaplan, and Singh (2025) show that citrus growers in California have engaged in collective risk management strategies, like area-wide pesticide application.

Another example in wheat is Fusarium Head Blight, also known as scab. Scab is a perennial management challenge for wheat farmers, which causes lower yields and quality. The disease is primarily caused by a fungus that infects wheat heads during flowering, especially under warm and humid conditions. Infected wheat kernels become shriveled and discolored, often exhibiting an orange-pink hue. In 2019 alone, the northern United States experienced over 45 million bushels of wheat yield losses due to the disease (The-Crop-Protection-Network, 2022). Crop rotation and fungicide applications are key responsive actions taken by producers. Like farmers protecting against citrus greening, wheat growers promote region-wide communication, joint field trials, and shared data systems to help prevent the fungus from harming their crops (McMullen et al., 2012).

Animal diseases Infectious animal diseases carried by bacteria and viruses impose constant threats to input sourcing by meat processors. For example, blue ear disease in swine, bird flu, swine flu, and hoof and mouth disease in cattle have all been prominent in recent decades. Many outbreaks result in considerable losses to animal herds, causing supply shortages and long-lasting impacts in the corresponding industries (Ma, Delgado, and Wang, 2024).

For instance, the United States experienced a highly pathogenic avian influenza (HPAI) outbreak from December 2014 to June 2015. Approximately 48 million chickens, turkeys, and other poultry were euthanized as a result of the disease outbreak. When including costs of herd, restocking, and lost future production, the total economic losses were estimated at $3.3 billion (Greene, 2015). The losses were spatially concentrated within Iowa and Minnesota, bearing 87% of the total damages in the nation (Ramos, MacLachlan, and Melton, 2017). In early 2024, HPAI spread to dairy cattle as well, and subsequent cases of dairy herd infection were identified in at least 17 US states.

A Porcine Epidemic Diarrhea Virus (PEDv) outbreak occurred in the US hog industry in 2013. Within a year of the emergence of the disease, it had spread to 31 states and led to a 5-7%

(about 7 million head) loss in US hog production (Crawford et al., 2015). PEDv is estimated to cause a $0.9-1.7 billion annual loss to US swine producers alone (Langel et al., 2016). To help prevent the spread of the disease, the USDA made PEDv a reportable disease in 2014 and required tracking of pigs, vehicles, and equipment leaving the impacted places. The USDA further announced a $5 million transfer to the industry to help with disease surveillance measures, movement tracking, herd monitoring, and epidemiological and research support for the development of a vaccine (U.S. Department of Agriculture, 2014). Due to the highly contagious nature of PEDv, biosecurity programs and data sharing networks are formed among producers, sometimes with support from the government.[3]

2.1 Risk Mitigation by Agribusiness Against Biohazards

Although the protective actions against biohazards tend to be performed on farms (e.g., immunization of livestock), processing firms also play critical roles — agribusinesses that buy raw farm outputs often enforce production and risk management protocols via formal and informal contracts with producers, especially in the highly contractualized livestock sector (Hennessy, 2005; Crespi and Saitone, 2018). Losses due to biohazards as well as the costs of protective actions on farms are effectively factored into the prices paid by processors to farmers. Therefore, in supply chains with vertical production contracts, processors effectively bear the potential losses and the costs of risk management (Spalding et al., 2023).[4]

Given the realities of modern agrifood supply chains, we focus on a theoretical framework where the intermediary firms' optimizing actions dictate equilibrium outcomes at every stage of the supply chain, including the level where biohazards often materialize and are managed. This is consistent with the well-established literature of agrifood supply chains that model decisions from

[3] One such example is the Secure Pork Supply organization (https://www.securepork.org/) that is a coalition between the swine industry, researchers, and government agencies to enhance disease preparedness.

[4] In the livestock sector, details of contractual obligations, including requirements for animal health and handling, can be found through USDA Agricultural Marketing Service contract library. For example, swine contracts can be found at https://www.ams.usda.gov/rules-regulations/packers-and-stockyards-act/regulated-entities/swine-contract-library. In the contracts, hog farmers are obligated to meet a set of sanitation, immunization, and other biosecurity protocols set by slaughter firms.

the intermediary firm's perspective (e.g., Gardner, 1975; Schroeter, 1988; Russo, Goodhue, and Sexton, 2011).

3 Model

We consider a two-stage supply chain with M farms and $N < M$ homogeneous processors/retailers that provide perishable food to consumers.[5] Consistent with past supply-chain models (Gardner, 1975; Sexton, 2000), we assume an integrated processing-retailing sector for simplicity. We impose fixed proportions in production throughout the supply chain, such that a constant volume of the farm product is required to produce a unit of the consumer good. Therefore, the output produced at each stage of the supply chain can be equalized given the appropriate scale of units and is denoted by Q.

We specify the upward-sloping, inverse supply function of farmers as:

$$P^f(Q) = S(Q|X), \tag{1}$$

where P^f captures farm price, Q is market quantity, and X denotes exogenous supply shifters. Similarly, the downward-sloping, inverse consumer demand for the processed product is:

$$P^r(Q) = D(Q|Y), \tag{2}$$

where P^r is retail price, Q is market quantity, and Y captures exogenous demand shifters.

Each risk-neutral firm faces a hazard common to other firms in its market that may restrict its ability to sell or deliver products due to threats such as animal diseases. The risk is partially endogenous to the firms in the sense that firms can reduce their exposure to hazards. Hazards themselves are exogenous to firms, while the actual probability and size of an experienced shock can

[5] Many major food products are perishable and have limited shelf life, limiting the use of stored products in the case of shuttered production. For non-perishable agricultural products like grain, there is a long strand of literature on storage and commodity price-stabilization policies (Wright, 1979; Miranda and Helmberger, 1988; Gouel, 2013).

be reduced by firms that invest in risk-reducing technology or risk management (e.g., biosecurity measures or vaccination).

Denote the investment per output in risk management by I_j for firm j. Then, $\phi_j(I_j)$ equals the firm's realized probability of experiencing a shock. We allow individual investments to be technical complements or substitutes among firms to reflect a key attribute of biohazards. Specifically, when firm investments are complements (substitutes), $\frac{\partial^2 \phi_j}{\partial I_j \partial \bar{I}} < 0$ (> 0) with $\bar{I}$ being the average investment of peer firms in the industry. Intuitively, this means that the marginal risk reduction from increasing I_j is larger if a firm's own investment, I_j, and other firm's investments, $\bar{I}$, reinforce each other, and *vice versa*.

3.1 Private Equilibrium

Suppressing the notation for the shifters, we express the objective function for the risk-neutral firm j that chooses the output q_j and resilience investment I_j to maximize the expected profits under the hazard:

$$\max_{q_j, I_j} E[\pi_j] = E\left[(P^r(Q) - P^f(Q))q_j\right] - C(q_j, I_j), \tag{3}$$

where $Q = \sum_{j=1}^{N} q_j$ and C is the total costs of processing and retailing that includes the investment in risk reduction. Fixed costs are inconsequential to the short-term production decisions of interest and are, thus, omitted from the setup.

Each firm faces a probability of shutdown, ϕ_j. Depending on whether firm j is forced to close, the status-contingent profit changes. When the firm survives the hazard, it earns revenue of $E\left[P^r(Q) - P^f(Q)\right] q_j$ in expectation. When it shuts down, it earns zero revenue but still incurs the costs of procurement and *ex ante* risk management. The objective function is rewritten as:

$$\max_{q_j, I_j} E[\pi_j] = E\left[P^r(Q) - P^f(Q)\right](1 - \phi_j)q_j - C(q_j, I_j). \tag{4}$$

When firm j survives, the expected market quantity, $E[Q]$, is equal to $\sum_{i=1}^{N} E[q_i] = \sum_{i \neq j}^{N}(1 -$

$\phi_i)q_i + q_j$. We rewrite the objective function of the firm:

$$\max_{q_j, I_j} E[\pi_j] = \left(P^r(E[Q]) - P^f(E[Q])\right)(1-\phi_j)q_j - C(q_j, I_j). \tag{5}$$

The private Nash equilibrium can be found by taking the first-order conditions (FOCs) with respect to q_j and I_j, respectively.

$$\begin{aligned} \left(\frac{\partial P^r}{\partial Q}\frac{\partial E[Q]}{\partial q_j} - \frac{\partial P^f}{\partial Q}\frac{\partial E[Q]}{\partial q_j}\right)(1-\phi_j)q_j + \Delta P(1-\phi_j) = C_{q_j} \\ \left(\frac{\partial P^r}{\partial Q}\frac{\partial E[Q]}{\partial I_j} - \frac{\partial P^f}{\partial Q}\frac{\partial E[Q]}{\partial I_j}\right)(1-\phi_j)q_j - \Delta P q_j \phi_{I_j} = C_{I_j}, \end{aligned} \tag{6}$$

where $\Delta P = P^r(E[Q]) - P^f(E[Q])$, C_{q_j} and C_{I_j} are the partial derivatives of total cost with respect to q_j and I_j, and $\phi_{I_j} = \frac{\partial \phi_j}{\partial I_j} < 0$ is the marginal risk reduction from one additional unit of I_j. The left-hand side (LHS) of the first equation is the marginal revenue of producing one more unit of q_j with $(1-\phi_j)$ reflecting the expected probability of avoiding shutdown, while the right-hand side (RHS) is the marginal cost of production. In the second equation, similarly, the LHS is the marginal return to investing an additional unit into risk management, while the RHS reflects the marginal cost of investing.

Plugging in $\frac{\partial E[Q]}{\partial q_j}$ and $\frac{\partial E[Q]}{\partial I_j}$ under symmetry in equilibrium (see derivation in subsection A2), the two equations in system (6) are rewritten as:

$$\begin{aligned} (1-\phi)P^r\left[1 - \frac{(1-\phi)\xi + \frac{\phi}{N}}{\eta}\right] = (1-\phi)P^f\left[1 + \frac{(1-\phi)\theta + \frac{\phi}{N}}{\varepsilon}\right] + C_q \\ -P^r q\left[\phi_I - \frac{(1-\phi)\phi_{II}}{\eta}\right] = -P^f q\left[\phi_I + \frac{(1-\phi)\phi_{II}}{\varepsilon}\right] + C_I. \end{aligned} \tag{7}$$

where prices are evaluated at $E[Q] = (1-\phi)Q + \phi\frac{Q}{N}$, $\phi_I = \frac{\partial \phi}{\partial I}$, $\phi_{\bar{I}} = \frac{\partial \phi}{\partial \bar{I}}$, and $\phi_{II} = \frac{(N-1)\phi_I \varsigma}{N} + \frac{[(N-2)\varsigma + 1]\phi_{\bar{I}}}{N}$.[6]

The terms θ and ξ are equal to $\frac{\partial Q}{\partial q}\frac{q}{Q}$ in the first equation of conditions (7) and are the con-

[6] Notably, the first equation collapses to the traditional FOOM condition in the risk-free world (i.e., $\phi = 0$). See the FOC in the traditional FOOM setup in, for instance, Hadachek, Ma, and Sexton (2024).

jectural elasticities for the buyer and seller power, respectively. When θ (ξ) is equal to 1, the firm has perfect control of the market output (i.e., perfect monopsony/monopoly). When equal to 0, the firm has negligible or no influence on the total market output (i.e., perfect competition). Oligopsonies/Oligopolies will take on values between 0 and 1 with varying degrees of intensity. This model can capture the range of anti-competitive behaviors (e.g., Cournot-Nash or tacit collusion) and does not require imposing any particular form of market competition. Parameter $\eta > 0$ is the absolute value of the demand elasticity evaluated at the market equilibrium, and $\varepsilon > 0$ is the farm supply elasticity evaluated at the market equilibrium.

The second equation introduces a third conjectural elasticity, which allows for collusion along the dimension of investing in risk management. The new term captures the fact that firms may form Nash conjectures along a non-price or non-quantity dimension. In this case, $\varsigma = \frac{\partial I_i/I_i}{\partial I_j/I_j}\ \forall\ i \neq j$ reflects a conjectural elasticity of risk management. It takes on an interpretation similar to the output conjectural elasticities (ξ and θ) and ranges in $[0,1]$. Intuitively, it captures the extent to which one firm adjusts its investment given an increase in investment by a peer firm j. Thus, this equation captures the Nash equilibrium for risk management.

The conjectural elasticity of risk management may take values different from ξ and θ. On the one hand, ς could be smaller because investments by peer companies may be harder to observe, and therefore, more difficult to collude in or impose penalty upon, than output by peers. On the other hand, industry-level coordination in risk management does not violate anti-trust policies, which focuses on preventing direct control on output. Hence, coordination along non-output mechanisms, like risk technologies or strategies, may be easily formed among firms. For instance, empirical evidence suggests that car manufacturers collude in input technology (Alé-Chilet et al., 2024), telecommunication firms collude in product offerings (Bourreau, Sun, and Verboven, 2021), and ice cream manufacturers collude in the quality of products (Sullivan, 2020).

3.2 Socially Optimal Equilibrium

A social planner who maximizes the expected social welfare has an objective function different from that of the private firm. Here, we let the social planner determine the risk-reducing investment, and firms choose output given the planner's level of risk management. Noticeably, we do not let the social planner set firm-level outputs, meaning that the social planner would only achieve a second-best solution. We do so because (i) in practice, it would require the government to seize control of outputs produced by the private food processing/retailing firms, which seems unlikely, and (ii) if we did, the social planner would simply generate the trivial perfect-competition outcomes in expectation (see subsection B2 for details of the first-best solution that could be achieved by the social planner).

The objective function of the social planner is specified as:

$$\max_{I_1 \dots I_N} E[W] = \sum_{j=1}^{N} E[\pi_j] + E[CS] + E[PS], \tag{8}$$

where $E[CS]$ is the expected total consumer surplus (CS) and $E[PS]$ is the expected total producer surplus (PS) for the raw input suppliers, or farmers in this case. CS equals $\int_0^Q P^r(x) - P^r(Q)dx$ where $Q = Nq$. The final market output varies with the realization of ϕ. Similarly, PS equals $\int_0^Q P^f(Q) - P^f(x)dx$.

Given the investment solution, I^*, and corresponding $\phi(I^*)$, firms choose the outputs:

$$\max_{q_j} E[\pi_j] = \Delta P(\phi^*)(1-\phi^*)q_j - C(q_j, I_j), \tag{9}$$

where $\Delta P(\phi^*) = P^r\left((1-\phi^*)Q\right) - P^f\left((1-\phi^*)Q\right)$ because $E[Q] = (1-\phi^*)Q$ due to symmetry. Taking the FOC with respect to q_j, we find Q^* as a function of I. Plugging Q^* into the equation (8), the two-stage game is then solved by backward induction.

3.3 Discussion on Theoretical Solutions

As specified in subsection 3.1, firms effectively compete along two dimensions: risk-reducing investment, I, and output, q. In both dimensions, the firm forms conjecture on others' reaction to its choice and makes decisions taking others' actions as given. As subsection 3.2 specifies, in contrast, the government sets I for all firms. Given the equal investment, the firms only compete in q in the social planner's problem.

Therefore, the FOCs for private and public risk management differ in a critical way, while the FOCs for output are the same. The second equation in system (7) suggests that the marginal cost of investing is C_I (i.e., incremental investment given the output), and the marginal return is determined by two forces. On the one hand, the firm marginally increases its probability of surviving the shock by increasing I, earning an increment of $\Delta P q \phi_I$. On the other hand, the equilibrium ΔP (i.e., the profit margin) shrinks with additional investment because the investment conjecture (i.e., $\phi_I \varsigma$) and the increased average investment by peers (i.e., $\phi_{\bar{I}}$) imply larger realized equilibrium output. In the private-firm problem, each firm only internalizes the second force to the extent it reduces its own marginal return from investing and ignores the negative impact on peers' profits.

When the social planner sets the uniform risk-reducing investment for homogeneous firms in equilibrium, the marginal cost is of the same form, but the marginal return for firms differs from that of the private firm's solution in two ways. First, the government incorporates the negative impact of increasing investment on the equilibrium ΔP and the profits of all firms. This effect in isolation, thus, implies a lower I^* set by the government than the firms in equilibrium. Second, by considering CS and PS in computing the marginal return to risk management, I^* chosen by the government tends to elicit a larger $E[Q^*]$ by investing more in risk management. The two effects conflict and produce ambiguous net impacts on the wedge between private and public optimal investments in risk management.

The conflicting effects throw sharp contrast against a standard model of the firm *versus* social planner choosing risk-free output. In the standard model, the social planner would simply set the competitive output, maximizing CS and PS and reducing firm profits to zero. Endogenous risk management adds non-trivial complexity to the model and optimal policy conditions, creating two interdependent trade-offs and an ambiguous public-private wedge in risk-reducing investment. We explore this through simulation and discuss its implications in subsection 5.3.

3.4 Analytical Solutions

To obtain analytical solutions and enable simulation, we assign linear functions to the model. In subsection B1, we show solutions under a nonlinear functional form, supporting that the linear baseline case does not cause a loss of generality. The farm supply and market demand functions are as follows:

$$P^f(Q) = b + \beta Q, \tag{10}$$

$$P^r(Q) = a - \alpha Q, \tag{11}$$

CS and PS are hence measured by triangle areas determined by the equilibrium Q. The profits of firms are captured by the rectangular area set by the equilibrium Q.

We let $C = cq_j + I_j q_j$, implying a constant marginal cost of processing/retailing and a per-output investment in risk. The unit cost of investment implies an increasing cost of risk with the scale of production. Generally, this can be interpreted as production-cost inefficiencies that ensure a more stable production process and output.[7] For example, the cost of administering vaccines to each live animal (Hennessy, 2007) would scale proportionally to output.

We impose an exponential hazard function that has long been used in a variety of contexts to measure the probability of risk exposure or firm closure (Audretsch and Mahmood, 1995; Wang and Hennessy, 2015):

$$\phi(I_j; I_{k\neq j}) = \lambda e^{-\gamma(I_j + \kappa I_j \bar{I})}, \tag{12}$$

where $\lambda \in (0,1)$ indicates the size of the exogenous hazard. The term $e^{-\gamma(I_j + \kappa I_j \bar{I})}$ captures the

[7]Some risk management strategies may more closely resemble fixed cost or capital investments (e.g., infrastructure and mechanical systems). However, evaluating the payoffs of these forms of risk management would require a multiple-period model over the life of those investments. We leave this alternative setup and its implications to future research.

endogenous exposure to the hazard, where firm j can lower its exposure through I_j.

This functional form of ϕ captures a critical feature of managing biohazards: the interdependence of risk management among agribusiness firms. That is, one firm's risk management can also influence other firms' probability of exposure, and *vice versa*. We allow for this possibility captured by the term $\kappa I_j \bar{I}$, where $\bar{I}$ is the average investment by all other firms.

Parameter κ captures the independence (i.e., $\kappa = 0$), the complementarity (i.e., κ is positive and sufficiently small), or the substitutability (i.e., κ is negative or sufficiently large and positive) in investments (see subsection A2 for details). For simulations, we set $\kappa \in [-1, 1]$. In this range, $\frac{\partial \phi}{\partial I_j} \leq 0$ and $\frac{\partial^2 \phi}{\partial^2 I_j} \geq 0$, which implies that risk exposure is decreasing in own-firm's risk management investment at a decreasing rate.

Private solutions Due to the symmetry among the firms, we know that the output and investments of the firms would be identical in equilibrium. We rewrite the first equation in system (7):

$$(1-\Phi)P^r(E[Q])\left(1-\frac{X}{\eta}\right) = (1-\Phi)P^f(E[Q])\left(1+\frac{H}{\varepsilon}\right) + c + I, \tag{13}$$

where $\Phi = \lambda e^{-\gamma(I+\kappa I^2)}$ and I is the symmetric investment by a firm, $X = (1-\Phi)\xi + \frac{\Phi}{N}$, and $H = (1-\Phi)\theta + \frac{\Phi}{N}$. Term $E[Q]$ equals $(1-\Phi)Q + \frac{\Phi}{N}Q$. The second equation becomes:

$$-P^r(E[Q])\left[\Phi_I - \frac{(1-\Phi)\Phi_{II}}{\eta}\right] = -P^f(E[Q])\left[\Phi_I + \frac{(1-\Phi)\Phi_{II}}{\varepsilon}\right] + 1, \tag{14}$$

where $\Phi_I = -\lambda\gamma(1+\kappa I)e^{-\gamma(I+\kappa I^2)}$, $\Phi_{\bar{I}} = -\lambda\frac{\gamma\kappa I}{N-1}e^{-\gamma(I+\kappa I^2)}$, and $\Phi_{II} = \frac{(N-1)\Phi_I\varsigma}{N} + \frac{[(N-2)\varsigma+1]\Phi_{\bar{I}}}{N}$. Because of the nonlinearity in the probability of risk exposure, there is no analytical solution for I and Q to this system of equations. Therefore, we solve this system numerically in section 5.

Public solutions Due to symmetry, denote the equilibrium investment and hazard by $\phi^* = \phi(I^*)$. Given ϕ^* and I^*, the FOC for the firm in the second stage is:

$$\begin{aligned}&(1-\phi^*)\left[1-\frac{(1-\phi^*)\xi+\frac{\phi^*}{N}}{\eta}\right]\left\{a-\alpha\left[(1-\phi^*)+\frac{\phi^*}{N}\right]Q\right\}\\=&(1-\phi^*)\left[1+\frac{(1-\phi^*)\theta+\frac{\phi^*}{N}}{\varepsilon}\right]\left\{b+\beta\left[(1-\phi^*)+\frac{\phi^*}{N}\right]Q\right\}+c+I^*.\end{aligned} \tag{15}$$

Denote $x^* = (1-\phi^*)\xi + \frac{\phi^*}{N}$ and $h^* = (1-\phi^*)\theta + \frac{\phi^*}{N}$, we have the equilibrium output:

$$Q^* = \frac{a\left(1-\frac{x^*}{\eta}\right) - b\left(1+\frac{h^*}{\varepsilon}\right) - \frac{c+I^*}{1-\phi^*}}{\left[(1-\phi^*)+\frac{\phi^*}{N}\right]\left[\alpha(1-\frac{x^*}{\eta})+\beta(1+\frac{h^*}{\varepsilon})\right]}. \tag{16}$$

Denote the equilibrium output by $Q(I)$, the first stage of the social planner's problem becomes:

$$\max_{I_1\ldots I_N} E[W] = E[\Pi(Q(I),I)] + \frac{1}{2}E\left[\alpha Q(I)^2\right] + \frac{1}{2}E\left[\beta Q(I)^2\right], \tag{17}$$

where $E[\Pi(Q(I),I)] = \sum_{j=1}^{N} E\left[\pi_j\right]$ is specified in equation (5). Variable N is the number of firms that are exposed to a hazard, and is drawn from a Binomial distribution of $N \sim \text{Bin}(\bar{N}, 1-\phi)$ and $Q = Nq$. Everything else the same, the equilibrium output Q^* increases in a (i.e., demand shifts out) and decreases in b (i.e., supply shifts in). Similarly, one can show that Q^* falls in the seller and buyer power, ξ and θ. While Q^* decreases in I or $\frac{\partial Q^*}{\partial I} < 0$ in general, suggesting that the two actions are strategic substitutes, under a small set of conditions the sign of $\frac{\partial Q^*}{\partial I}$ could be positive.

Given the linear demand and supply functions and solutions found in equation (A2), the objective function for the social planner can be rewritten as follows (see subsection A1 for derivation of the expression):

$$\max_I E[W] = \underbrace{(a-b)(1-\phi)Q(I) - (\alpha+\beta)\left[(1-\phi)^2 + \frac{(1-\phi)\phi}{N}\right]Q(I)^2 - cQ(I) - IQ(I)}_{E[\Pi]} + \underbrace{\frac{\alpha}{2}\left[(1-\phi)^2 + \frac{(1-\phi)\phi}{N}\right]Q(I)^2}_{E[CS]} + \underbrace{\frac{\beta}{2}\left[(1-\phi)^2 + \frac{(1-\phi)\phi}{N}\right]Q(I)^2}_{E[PS]}. \tag{18}$$

Given the symmetry in solution, the FOC is:

$$-(a-b)\Phi_I Q + (a-b)(1-\Phi)Q_I + (\alpha+\beta)\left[(1-\Phi)\Phi_I - \frac{(1-2\Phi)\Phi_I}{2N}\right]Q^2 - (\alpha+\beta)\left[(1-\Phi)^2 + \frac{(1-\Phi)\Phi}{N}\right]QQ_I - cQ_I - Q - IQ_I = 0 \tag{19}$$

where $Q_I = \frac{\partial Q}{\partial I}$, $\Phi = \lambda e^{-\gamma(I+\kappa I^2)}$, and $\Phi_I = -\lambda\gamma(1+2\kappa I)e^{-\gamma(I+\kappa I^2)}$.

4 Parameterization

We normalize the risk-free, competitive equilibrium industry-level output, Q^c, to 1.0. The corresponding equilibrium retail price on the national market is $a - \alpha Q^c$ and is also normalized to 1.0. The demand elasticity in this equilibrium, η, hence equals $\frac{1}{\alpha}$, and $a = 1 + \alpha = 1 + \frac{1}{\eta}$.

Similarly, the competitive equilibrium price for the farm is $f = 1 - c$. The farm price is the farm share of the normalized retail revenue from a unit of the final food product under perfect competition. Due to the assumption of fixed proportions and the equalization of units across supply chain stages, the competitive farm output is also 1.0. Thus, $\beta = \frac{f}{\varepsilon}$ and $b = f(1 - \frac{1}{\varepsilon})$, where ε is the elasticity of the farm supply in competitive equilibrium.[8] The other market parameters are related to the buyer and the seller power. We start by studying the perfectly competitive case

[8]Importantly, the value of elasticity varies along the linear demand and supply curves by construction. Thus, we only assign $\eta = 0.7$ and $\varepsilon = 1.0$ as the means in the corresponding distributions in the competitive equilibrium and let the elasticity be determined by the corresponding price and output solutions in the simulation. The formulas for prices and output are rewritten in subsection A3.

Table 1: Baseline Parameter Values

Parameter	Description	Baseline Value	Sim. Range	Justification
Risk Parameters:				
λ	Size of the hazard	$\lambda \sim N(0.25, 0.075)$	$[0, 1]$	Depends on the nature of risk. Baseline values discussed in Appendix C.
γ	Semi-elasticity of risk investment	$\gamma \sim N(35, 10)$	NA	
κ	Interdependence of I among firms	0	[-1,1]	
Market Parameters:				
ξ/θ	Market power parameter	0	[0,0.5]	(Saitone and Sexton, 2017)
α	$\frac{\partial P^r}{\partial Q}$, slope of the demand curve	$\eta \sim U(0.46, 0.92)$	NA	(Andreyeva, Long, and Brownell, 2010; Okrent and Alston, 2011)
β	$\frac{\partial P^f}{\partial Q}$, slope of the supply curve	$\varepsilon \sim U(0.81, 1.61)$	NA	(Chavas and Cox, 1995)
f	Competitive farm share	0.3	NA	Retail-farm price spread. See the table note.
N	Number of intermediary firms	4	NA	Set based on a four-firm processing stage (e.g., the US poultry processing), but the value is not consequential to simulation outcomes

Note: The value of competitive farm share out of each retail food dollar is set at 30%, and is set to be a conservative measure calculated from the retail-farm price spread in the meat industry (https://www.ers.usda.gov/data-products/meat-price-spreads/). Setting f at different values imposes no qualitative impacts on the simulation results, but they are available upon request.

($\xi = \theta = \varsigma = 0$) in our baseline specification and build up to the imperfectly competitive case.

4.1 Risk Parameters

The remaining parameters relate to the nature of the risk function, $\Phi(I|\lambda, \gamma)$, and, of course, vary by context. We hence do not claim to identify accurate values of these parameters within a specific context, but draw parameter values from a plausible distribution set based on the management of hog diseases and show via simulation how the nature of risk affects the outcomes.

For a given hazard, λ measures the probability of exposure without any investment in risk management, namely, $\phi = \lambda e^0 = \lambda = \phi(0)$. As a baseline, we draw values for λ from a normal distribution $\lambda \sim N(0.25, 0.075)$ such that the hazards are sufficiently large and firms are aware and motivated to protect against them.

The value of γ captures the effectiveness of strategies or technologies in reducing risk exposure (e.g., processing safety protocols and animal vaccination). Equivalently, γ can be interpreted as the "semi-elasticity of risk management" (i.e., the percent reduction in risk with respect to a unit change in I with $\kappa = 0$). Mathematically, the term $-\frac{\partial \phi}{\partial I}\frac{1}{\phi}$ is equal to γ if $\kappa = 0$. As stated above, the value of γ is context and strategy specific. Some hazards may be avoided more cheaply (higher values of γ), while others may be costly to influence (low values of γ).

To calibrate the value of γ, we rely on relatively abundant information on diseases and vaccines in the context of the US hog industry. In Table C, we list the ranges of γ computed in the context of hog diseases (e.g., PEDv). Detailed computation steps based on vaccination trial data are explained in Appendix C. For simulations, we draw values of γ from a normal distribution, $\gamma \sim N(35, 10)$.

5 Simulation Results

We examine the solution of the model and study the effects of varying the nature of the hazard and market structures via three sets of simulations. For each set of simulations, we vary one parameter at a time, holding all other parameters at their baseline values above. We draw 1,000 values from the distributions specified in Table 1 and generate the mean and standard deviation of the simulation outcomes for each value of the parameter of interest.

First, we consider the competitive setting ($\xi/\theta = 0$) without interdependence in risk management ($\kappa = 0$), and focus on the magnitude of the externality of risk management and welfare implications under different levels of the hazard (λ), ranging from negligible hazards to extreme hazards. Second, in the competitive setting, we examine how the interdependence of risk management among firms influences the externality in risk management. Third, we explore how market power (ξ/θ and ς), from perfectly competitive to a duopoly, affects the equilibrium outcomes for risk management and welfare and how it interacts with the interdependence of risk management.

5.1 Magnitude of the Hazard: λ

We start by evaluating how the level of hazard impacts the production and risk management decisions. The parameter $\lambda \in [0,1]$ is the expected size of the hazard absent risk management. Isolated and small threats to production would take a value close to 0, whereas catastrophic and cascading risks would take values closer to 1.

Risk externality Given baseline conditions listed in Table 1, our first set of results demonstrate that socially optimal risk-reducing investment exceeds what is achieved in the private equilibrium for most levels of hazard, confirming the intuitive argument made in Baldwin and Freeman (2022). Externality in risk investment, though, does not necessarily increase with the magnitude of hazard.

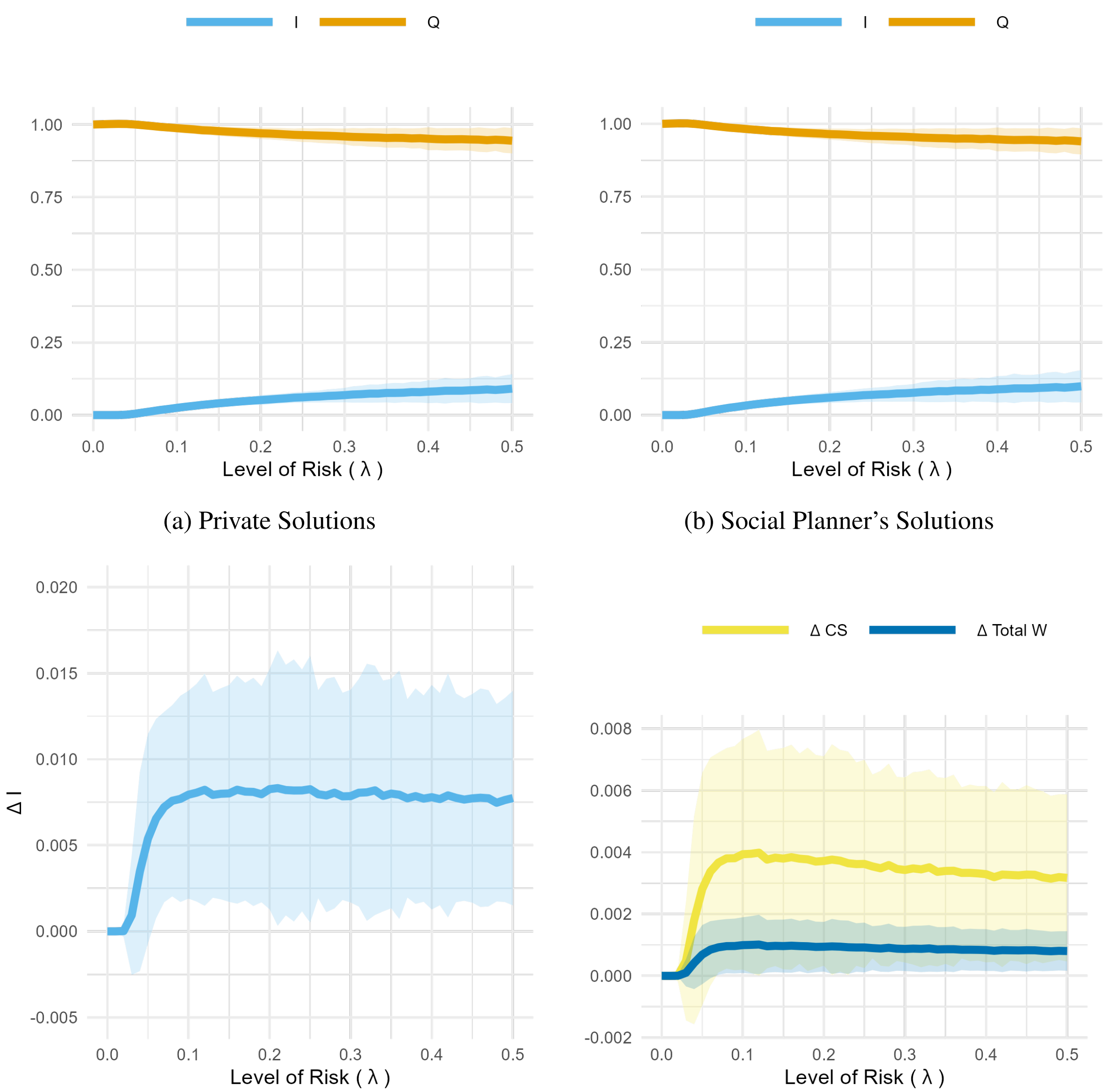
In Figure 1, the solid line represents the mean value of 1,000 simulations at a value of λ with the bands of 1.96 $\times$ the standard deviation. Panels (a) and (b) demonstrate that for sufficiently small hazards ($\lambda < 0.03$), the optimal strategy is not to invest in risk management (i.e., the corner solution) in both equilibria. As the magnitude of the hazard increases, the optimal public investment, I^*_{gov}, increases, followed by the optimal private investment, I^*_{firm}. For large hazards (e.g., $\lambda = 0.30$), firms would invest 6.9% of each normalized, competitive retail dollar into risk management, while the social planner invests about 7.5%. For more modest hazards ($\lambda = 0.10$), private and public optimal investments are about 2.5% and about 3.2% of the normalized dollar, respectively.[9]

Panel (c) plots the wedge in risk investment, ΔI. When ΔI plateaus at a value of $\lambda = 0.12$, the firm would invest about 24% ($\frac{\Delta I}{I^*_{gov}} = \frac{0.008}{0.03}$) less than what the social planner would invest in risk management. Practically, this simulation illustrates that, in the most basic, perfectly competitive market setup, there exists a risk externality with hazards for which $\lambda > 0.02$, and that the size of the externality is relatively consistent after $\lambda > 0.12$.

The level of hazard and risk management also carry implications for the optimal production levels for firms. For values of $\lambda < 0.03$, the equilibrium quantities, Q^*_{firm} and Q^*_{gov}, stay above the

[9] The Risk Management Society's Benchmark Survey, which provides the most detailed record of risk management spending to our knowledge, reports that companies spend about \$9.95 for every \$1,000 of revenue, namely, 1.0% (Wikinson, 2019). This aligns well with the simulation outcomes at $\lambda = 0.07$.

Figure 1: Wedge in Risk Investment and Welfare under Competition



(a) Private Solutions

(b) Social Planner's Solutions

(c) Gap in Risk Investment

(d) Gap in Welfare

Note: Figure displays mean and 1.96-standard-deviation bands from 1,000 numerical simulations with respect to the size of hazard that firms face λ. Δ indicates the difference between the social planner's solutions and the private firm's. All welfare terms are measured in expectation. All other parameters are set at baseline values as described in Table 1.

risk-free level, because firms produce slightly more to shield against the potential losses.[10] As risk

[10]This stands in contrast to the findings of Sandmo (1971), which shows that price uncertainty causes risk-averse managers to produce less. Our finding here differs because the operational risk enters through the endogenous quantity

management expenses move off the corner and increase, firms produce less, suggesting that the two choices form strategic substitutes.

Welfare impacts of risk externality We measure welfare in expectation terms throughout this section. Figure 1d plots the welfare gap between the firm's and the social planner's optimal levels of risk management, namely, $\Delta W = E[W|I^*_{gov}] - E[W|I^*_{firm}]$. At $\lambda = 0.1$, ΔW is worth about 0.1% of the risk-free competitive total welfare. Similarly, ΔCS is computed. At $\lambda = 0.1$, the potential gain in CS from policy intervention is worth $\frac{0.004}{a/2} \times 100 = 0.5\%$ of the competitive, risk-free consumer welfare. Given that the US food industry generates \$1.5 trillion in annual Gross Domestic Product (Zahniser, 2024), even a 0.5% change of CS would be economically significant. Although not plotted in Figure 1d, ΔPS is proportional to ΔCS (see equation (18)). Intuitively, $\Delta\Pi$ is negative since the social planner's objectives deviate from the firm's private profit maximization problem.[11]

5.2 Interdependence in Risk Management: κ

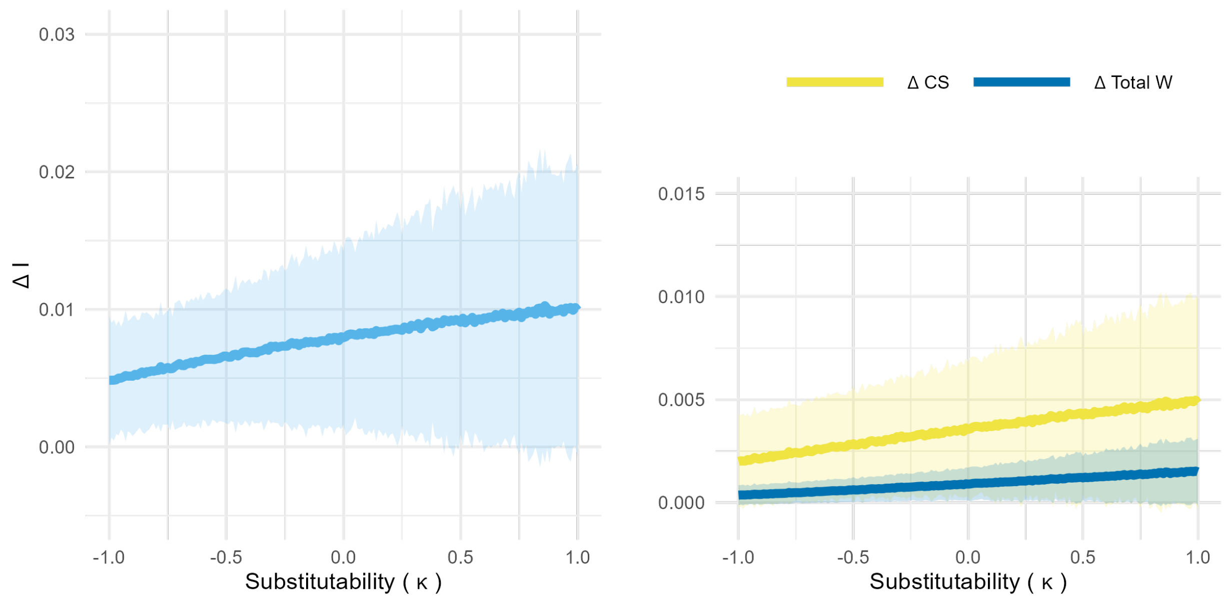
As highlighted in section 2, a firm's risk management of biohazards may be interdependent with other firms. Protective actions taken by one firm may, for instance, help protect other firms (i.e., creating free-riders). The nature of the dependence may be positive or negative and is captured by κ in the formula of $\phi(I)$. Varying κ from -1 to 1 characterizes various cases in which firm investments are substitutes or complements.

Figure 2a suggests that the externality in risk investment increases in κ. When firm investments are complements ($\kappa > 0$), the firm tends to invest even less than the socially optimal level relative to a setting where firm investments are independent. In contrast, if substitution among firm investments ($\kappa < 0$) is not accounted, the firm mitigates free-riding and tends to invest more than in a setting of independent investment, narrowing the externality of risk management.

variable, so firms can directly affect expected revenue by increasing quantity. In Sandmo's model, however, the uncertainty is exogenous.

[11] Although this is the perfectly competitive case, firms may still earn a positive profit. When a shock is realized, the total output falls and the equilibrium retail price increases, creating the possibility of positive profits in both the private equilibrium and the social planner's solutions for $\lambda > 0$.

Figure 2: Wedge in Risk Management and Welfare under Risk Dependence



(a) Gap in Risk Investment

(b) Gap in Welfare

Note: Figure displays mean and 1.96-standard-deviation bands from 1,000 numerical simulations with respect to risk sustainability parameter κ. Δ indicates the difference between the social planner's solutions and the private firm's. All welfare terms are measured in expectation.

Figure 2b displays the corresponding welfare gains from the policy intervention. The welfare improvement from the public intervention increases in κ as the size of deadweight loss from the externality increases. At a value of $\kappa = 1$, the welfare improvements from intervention are about 100% higher than the welfare gain at $\kappa = 0$, which is an economically significant difference. This simulation suggests that the returns to public policy intervention tends to be particularly high in contexts where risk management is complementary among firms.

5.3 Conjectural Variations

So far, we have set $\xi = \theta = \varsigma = 0$, meaning that the firm's quantity and investment choices do not influence the peer firms in the market; firms have no market power. However, for a concentrated agriculture and food processing sector in the US, this assumption is unlikely to hold (Sexton, 2013). We now relax the assumption and consider varying values of the quantity and risk conjectures. As illustrated in subsection 3.3, the conjectures add significant complexity to the public-private wedge in risk investments and potential welfare gains from policy intervention. The interactions of the two types of conjectures are particularly intriguing and discussed carefully in this subsection.

5.3.1 Quantity Conjectures: ξ and θ

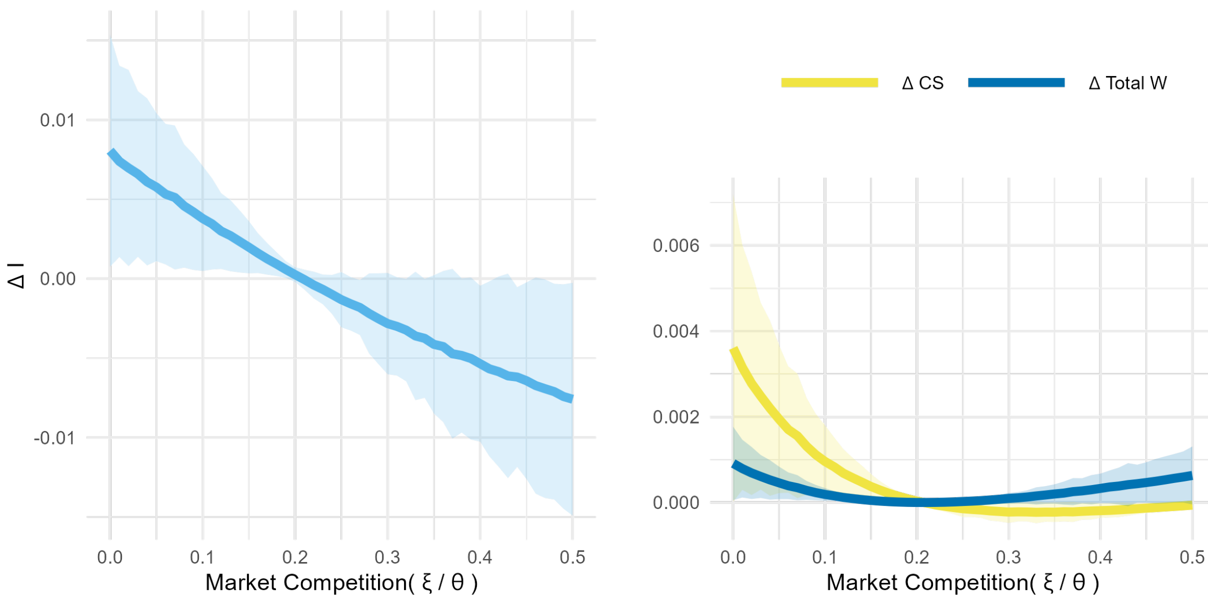
First, we let ξ and θ to vary in a range of $[0, 0.5]$, or from perfect competition to duopoly, while keeping $\varsigma = 0$. Parameters ξ and θ capture the conjecture of the firm on the change in peers' quantity supplied (purchased) given a change in the firm's output (purchase). The larger ξ (θ) is the more seller (buyer) power the firm has.

We keep $\xi = \theta$ throughout the simulations. Figure 3a shows that the wedge between private and public optimal risk-reducing investments decreases in the conjectural elasticity. At a value $\xi/\theta = 0.2$, ΔI drops to 0, implying that the private, imperfectly competitive firm's incentive to invest in risk management matches that of the social planner, and no externality exists. Beyond this threshold, the risk externality becomes negative, implying that firms over-invest in risk management from a social welfare perspective.

At first glance, this result is perhaps counterintuitive to popular belief. However, this reflects the competing incentives that market power introduces to the optimal risk management conditions. As ξ/θ increases, intermediary firms capture greater shares of the total market welfare, and thus, independently have greater incentivize to protect against downside shocks. Without collusion in investment, a firm does not internalize negative profit impacts on peers as it increases I_j. The social planner, in contrast, by setting a common risk investment for all firms in the first stage, effectively implements perfect coordination in risk management. The socially optimal I remains relatively flat for all values of ξ/θ.

The gap in welfare and who benefits from risk management intervention also varies with respect to the quantity conjectures. For $\xi/\theta < 0.2$, consumers and farmers are the primary beneficiaries of the risk management intervention, improving by as much as 0.5% of their total surplus by moving from the private solution to the public one. However, when $\xi/\theta > 0.2$, the firms are the primary beneficiaries of the government-coordinated risk management. Total welfare still improves as the gains in firm profits outweigh the losses in consumer and producer surplus.[12]

Figure 3: Wedge in Risk Investment and Welfare under Market Power



(a) Gap in Risk Investment

(b) Gap in Welfare

Note: Figure displays mean and 1.96-standard-deviation bands from 1,000 numerical simulations with respect to market power parameters ξ and θ with $\varsigma = 0$. Δ indicates the difference between the social planner's solutions and the private firm's. All welfare terms are measured in expectation. All other parameters are set at baseline values described in Table 1.

The results contribute importantly to public discourse about the role of market power and supply chain resilience. We show that firms with more market power may actually contribute positively to resilience because of their increased incentive to protect profits than in the perfectly competitive case. The baseline total welfare still decreases as firms extract surplus from input suppliers and their customers, but at least after a certain threshold, more highly concentrated markets would provide more protection from hazards than would the social planner's solutions. This opposes the findings by Hadachek, Ma, and Sexton (2024) who assume exogenous risks and show that that market power harms the resilience of agrifood supply chains. Endogenous risk manage-

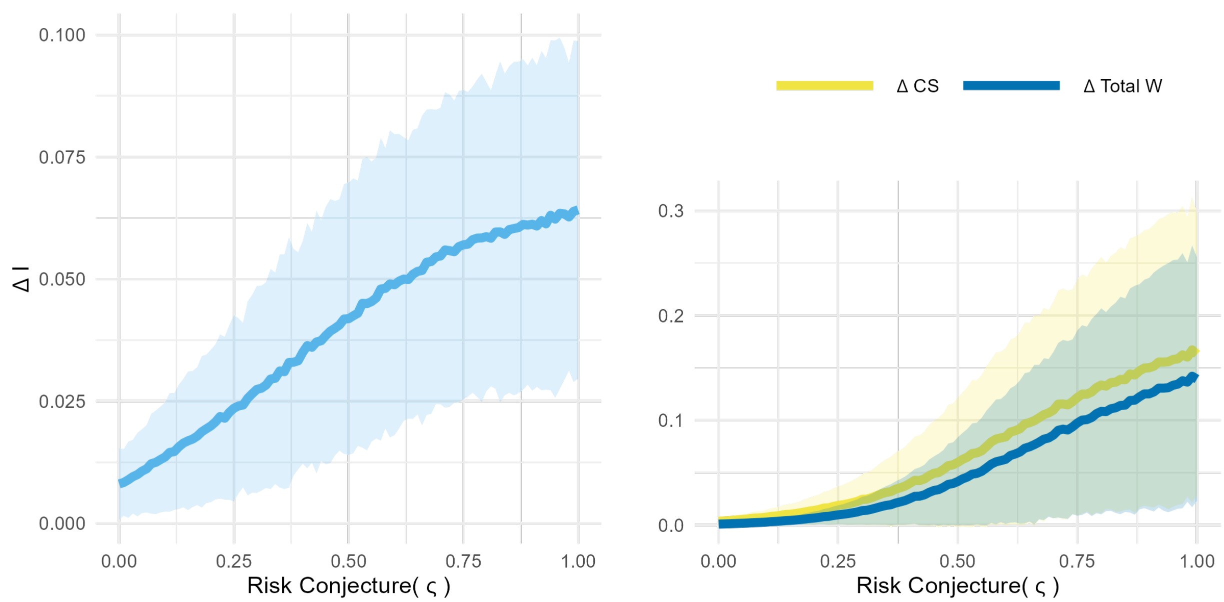
[12] An alternative social planner objective function that more highly values the economic rents of consumers and producers over the imperfectly competitive firms would yield different simulation results in this exercise. This, however, would require an entirely different setup and conditions than the objective function outlined above.

ment by firms may be the underlying theoretical reason why empirical studies on supply chain resilience, such as Gnutzmann, Kowalewski, and Śpiewanowski (2020) and Richards, Polyviou, and Ubilava (2024), find that more concentrated markets tend to be more resilient to shocks.

5.3.2 Investment Conjecture: ς

Coordination among intermediary firms may also enter through the channel of risk management as discussed in subsection 3.1. The degree of risk management coordination is captured by ς and reflects the firm's conjecture on the change in peers' investment given a change in its own investment. The larger ς, the firm has greater control over market-level risk exposure through their own choice of I_j. As detailed in subsection 3.2, the government imposes the same I across firms and effectively ensures $\varsigma = 1$ among firms.

Figure 4: Wedge in Risk Investment and Welfare under Risk Conjecture



(a) Gap in Risk Investment

(b) Gap in Welfare

Note: Figure displays mean and 1.96-standard-deviation bands from 1,000 numerical simulations with respect to risk conjecture parameter ς with ξ and θ equal zero. Δ indicates the difference between the social planner's solutions and the private firm's. All welfare terms are measured in expectation. All other parameters are set at baseline values described in Table 1.

Figure 4a shows that as ς increases given $\xi = \theta = 0$, ΔI widens as firms invest less relative to the social optimum because they can better coordinate risk-reducing investment in the same way that firms better coordinate in output with larger ξ and θ. The welfare gains for farmers and consumers from closing ΔI^* also increase, while firm profits fall.

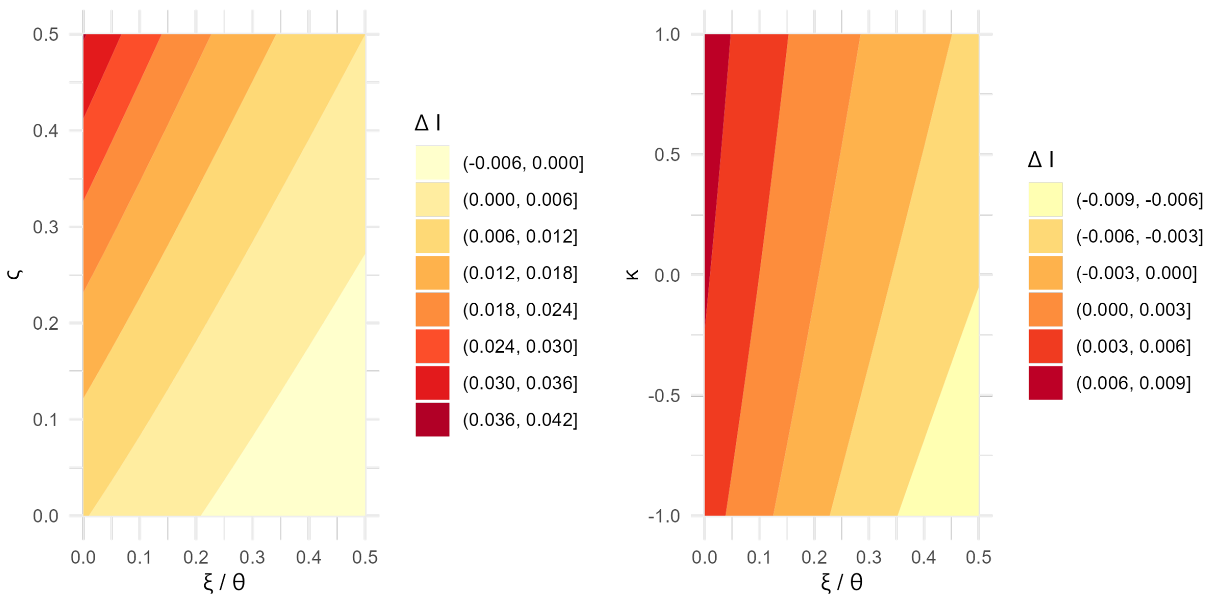
When ς is large, the magnitudes of the risk externality and welfare wedges are large relative to the simulations where ς is small. For instance, when $\varsigma = 0.4$, firms under-invest in risk management by 54% of the social optimum. In this case, the total deadweight loss from letting firms dictate risk management is about 3.6% of total welfare achieved by the social planner at the same value of ς. Consumers would stand to benefit the most from government intervention, gaining as much as 7.0% of the baseline consumer surplus.

5.4 Interactions of Risk and Market Characteristics

When varied independently, simulations so far have shown that the quantity conjectures (ξ/θ) and the investment conjecture (ς) draw different implications for policy justification and welfare impacts. When varied jointly, the implications of conjectures on risk externality and welfare are particularly complex.

For any given value of the risk conjecture (ς), higher buyer and seller power (ξ/θ) affect the externality in risk management through two effects. First, firm profits represent a greater share of social welfare as ξ/θ increase, all else the same. Firms hence internalize a greater share of total welfare losses from a given hazard and invest more in risk management, and the externality narrows (i.e., the *social welfare* effect). Second, as long as firms do not perfectly collude in risk management, they tend to over-invest relative to socially optimum because firms fail to incorporate the negative impacts of investing on peers' profits. Firms invest more when ξ/θ is larger, or when there are larger profits to potentially capture. The social planner imposes an equal risk investment among firms and effectively improves investment coordination, which may result in a lower level of socially optimal investment (the *investment collusion* effect). The collusion effect is weak if firms already coordinate well in risk management (i.e., large ς), while the social welfare effect dominates, and *vice versa*.

Figure 5: Interaction of Risk Interdependence and Market Structure



(a) Market Power and Risk Coordination (b) Market Power and Risk Interdependence

Note: Figure displays the wedge in risk investment ΔI plotted over differing values of conventional buyer/seller power ξ/θ and the risk conjecture ς.

Figure 5a displays the interaction of quantity and risk conjectures in a contour plot. When ς is small, both the social welfare and the investment coordination effects are strong. The externality in investment falls from positive to negative as the conventional ξ/θ rises. In contrast, with a large ς, the externality falls faster (i.e., $\frac{\partial^2 \Delta I}{\partial \xi \partial \varsigma} < 0$), but stays positive because the collusion effect is trivial and the social welfare effect dominates. In summary, the nature of imperfect competition — whether in quantity or in risk management practices — plays a vital role in the underlying justification for policies aimed at increasing supply chain resilience.

Furthermore, Figure 5b shows the interaction between quantity conjecture and interdependence in risk management, with ξ/θ varying along the horizontal axis and $\varsigma = 0$. Given κ, increasing market concentration reduces the externality in risk management. Like in Figure 3a, the externality turns negative, meaning that the firms invest more than the social planner does, when ξ/θ is large. The externality widens if the firm investments are complements instead of substitutes, and it widens at a faster rate with smaller ξ/θ (i.e., $\frac{\partial^2 \Delta I}{\partial \kappa \partial \xi} < 0$).

6 Concluding Remarks

Increasingly frequent disruptions in agrifood supply chains have inspired various policy interventions in the US and beyond. Interventions may be justified because the socially and privately optimal levels of supply chain resilience differ. A public-private wedge in risk management exists mainly because the firm does not incorporate the impacts of supply chain disruptions, like food insecurity, on consumer or producer welfare, nor does it fully incorporate how its risk management affects peer firms.

We propose a new model to characterize the private and public problems of investing in risk management, specifically, reducing the risk of biohazards in the context of the US agrifood sector. Both the private firm and social planner weigh the costs of the risk management against the benefits of more stable market outcomes. The model incorporates inter-firm complementarity and substitution in risk management, a key feature of agricultural production and a novel feature relative to existing models on supply chain resilience. The model also allows for various degrees of market power in processing/retailing to reflect the reality of US agricultural markets (Sexton, 2013).

Simulations demonstrate the potential risk externality and welfare gains from policy intervention under a number of plausible market and hazard contexts. Contrary to popular discourse, a processing/retailing stage with more collaboration in output reduces and may even flip the risk externality as oligopolistic firms internalize a larger share of the potential losses from disruptions, but do not coordinate well in risk management. If firms coordinate closely in risk management, there is considerable justification for policy intervention that would provide large social gains. The gains depend, critically, on inter-firm complementarity and substitution in risk management.

In summary, the nature of coordination among firms in an imperfectly competitive market determines the direction and magnitude of risk externality in a nonlinear way. The role of interdependence in risk management is also critical. All else the same, the more complementary and cooperative risk investments are among firms, the higher potential welfare gains are from policy intervention. Future work is needed to empirically estimate the degree of risk coordination and interdependence in specific markets and measure the effectiveness of protective activities to generate welfare gains.

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Appendix: For online publication

A Mathematical Details

This appendix gives detailed mathematical derivations of the key equations and other expressions in the article.

A1 Expectation of Variables

When variable X follows the Binomial distribution of $(N, 1-\phi)$, the pdf of $X = n$ is $C_N^n(1-\phi)^n\phi^{N-n}$. The sum of the probabilities, $\sum_{n=0}^{N} C_N^n(1-\phi)^n\phi^{N-n} = 1$ by definition.

The expectation of X equals

$$
\begin{aligned}
E[X] &= \sum_{n=0}^{N} nC_N^n(1-\phi)^n\phi^{N-n} \\
&= \sum_{n=1}^{N} nC_N^n(1-\phi)^n\phi^{N-n} \\
&= \sum_{n=1}^{N} NC_{N-1}^{n-1}(1-\phi)^n\phi^{N-n} \\
&= N(1-\phi)\sum_{n=1}^{N} C_{N-1}^{n-1}(1-\phi)^{n-1}\phi^{(N-1)-(n-1)} \\
&= N(1-\phi)\sum_{m=0}^{M} C_M^m(1-\phi)^m\phi^{M-m} \\
&= N(1-\phi),
\end{aligned}
\tag{A1}
$$

where $m = n-1$ and $M = N-1$ and $\sum_{m=0}^{M} C_M^m(1-\phi)^m\phi^{M-m} = 1$ by the property of Binomial distribution.

Similarly, we can derive the expectation of X^2 using the same technique

$$
\begin{aligned}
E[X^2] &= \sum_{n=0}^{N} n^2C_N^n(1-\phi)^n\phi^{N-n} \\
&= \sum_{n=1}^{N} nC_N^n(1-\phi)^n\phi^{N-n} + \sum_{n=1}^{N} n(n-1)C_N^n(1-\phi)^n\phi^{N-n},
\end{aligned}
\tag{A2}
$$

where the first term is computed in equation (A1). We focus on finding the value of the second term.

The second term can be rewritten as

$$
\begin{aligned}
&\sum_{n=2}^{N} n(n-1)C_N^n(1-\phi)^n\phi^{N-n} \\
&= \sum_{n=2}^{N}(n-1)NC_{N-1}^{n-1}(1-\phi)^n\phi^{N-n} \\
&= N(1-\phi)\sum_{n=2}^{N}(n-1)C_{N-1}^{n-1}(1-\phi)^{n-1}\phi^{(N-1)-(n-1)} \\
&= N(1-\phi)\sum_{n=2}^{N}(N-1)(1-\phi)C_{N-2}^{n-2}(1-\phi)^{n-2}\phi^{(N-2)-(n-2)} \\
&= N(N-1)(1-\phi)^2\sum_{l=0}^{L}C_L^l(1-\phi)^l\phi^{L-l} \\
&= N(N-1)(1-\phi)^2,
\end{aligned}
\tag{A3}
$$

where $l=n-2$ and $L=N-2$ and $\sum_{l=0}^{L}C_L^l(1-\phi)^l\phi^{L-l}=1$ by the property of Binomial distribution. Adding up the values of the first and second terms in equation (A2), we have

$$
\begin{aligned}
E[X^2] &= N(1-\phi)+N(N-1)(1-\phi)^2 \\
&= N^2(1-\phi)^2+N(1-\phi)\phi \\
&= N^2\left[(1-\phi)^2+\frac{(1-\phi)\phi}{N}\right].
\end{aligned}
\tag{A4}
$$

A2 Partial Derivatives

We give a detailed derivation for a few complicated partial derivatives below.

First order conditions In subsection 3.1, $E[Q]=\sum_{i\neq j}^{N}(1-\phi_i)q_i+q_j$. Thus, we have $\frac{\partial E[Q]}{\partial q_j}=\phi_j+(1-\phi_j)+\sum_{i\neq j}^{N}(1-\phi_i)\frac{\partial q_i}{\partial q_j}$. Due to symmetry, the equilibrium q_i is equal across firms, and so is the equilibrium ϕ_i. Thus, we have $\frac{\partial E[Q]}{\partial q_j}=\phi+(1-\phi)\frac{\partial Q}{\partial q}$. The term $\frac{\partial Q}{\partial q}$ captures the conjectural that a firm has regarding how its competitors react to its output decision. In the case of perfect competition, the market output is not affected by any firm, and $\frac{\partial Q}{\partial q}$ is hence zero. The term is positive for imperfect competition cases. The larger the term, the closer the market is to a monopoly scenario.

The term $\frac{\partial E[Q]}{\partial I_j}$ equals $-\sum_{i\neq j}^{N}\frac{\partial\phi_i}{\partial I_j}q_i=-\sum_{i\neq j}^{N}\left(\frac{\partial\phi_i}{\partial I_i}\frac{\partial I_i}{\partial I_j}+\frac{\partial\phi_i}{\partial\bar{I}}\frac{\partial\bar{I}}{\partial I_j}\right)q_i$. Let $\frac{\partial\phi_i}{\partial I_i}\frac{\partial I_i}{\partial I_j}=\frac{\partial\phi_i}{\partial I_i}\varsigma$, with ς reflecting the common conjecture in risk management and ranges in $[0,1]$. The term $\frac{\partial E[Q]}{\partial I_j}$ hence equals $-\sum_{i\neq j}^{N}\left(\frac{\partial\phi_i}{\partial I_i}\varsigma+\frac{\partial\phi_i}{\partial\bar{I}}\frac{\partial\bar{I}}{\partial I_j}\right)q_i$. For symmetry and because $\bar{I}=\frac{\sum_{i\neq j}I_i}{N-1}$ for firm j, $\frac{\partial E[Q]}{\partial I_j}$ generates $-(N-1)\left(\frac{\partial\phi}{\partial I}\varsigma+\frac{\partial\phi}{\partial\bar{I}}\frac{(N-2)\varsigma+1}{N-1}\right)q=-\left\{(N-1)\phi_I\varsigma+[(N-2)\varsigma+1]\phi_{\bar{I}}\right\}q$.

For easier notation, denote $(N-1)\phi_I\varsigma+[(N-2)\varsigma+1]\phi_{\bar{I}}$ by L. Given the symmetry of firms, the FOCs (5) with respect to q_j and I_j, respectively, are rewritten below.

$$\begin{aligned}\frac{\partial P^r}{\partial Q}\left[\phi+(1-\phi)\frac{\partial Q}{\partial q}\right](1-\phi)q-\frac{\partial P^f}{\partial Q}\left[\phi+(1-\phi)\frac{\partial Q}{\partial q}\right](1-\phi)q+\Delta P(1-\phi)&=C_q\\ -\left(\frac{\partial P^r}{\partial Q}Lq-\frac{\partial P^f}{\partial Q}Lq\right)(1-\phi)q-\Delta Pq\phi_I&=C_I\end{aligned} \tag{A5}$$

In each equation above, we factor out the price evaluated at $E[Q]$ and write terms in the form of elasticity. The system of equations become

$$\begin{aligned}&(1-\phi)P^r\left[1+\frac{\partial P^r/P^r}{\partial Q/Q}\phi\frac{q}{Q}+\frac{\partial P^r/P^r}{\partial Q/Q}(1-\phi)\frac{\partial Q/Q}{\partial q/q}\right]\\ &=(1-\phi)P^f\left[1+\frac{\partial P^f/P^f}{\partial Q/Q}\phi\frac{q}{Q}+\frac{\partial P^f/P^f}{\partial Q/Q}(1-\phi)\frac{\partial Q/Q}{\partial q/q}\right]+C_q,\end{aligned} \tag{A6}$$

where $\frac{\partial P^r/P^r}{\partial Q/Q}=-\frac{1}{\eta}$ and $\frac{\partial P^f/P^f}{\partial Q/Q}=\frac{1}{\varepsilon}$. The term $\frac{q}{Q}=\frac{1}{N}$ in equilibrium.

$$\begin{aligned}&-P^r q\left[\phi_I+\frac{\partial P^r/P^r}{\partial Q/Q}(1-\phi)L\frac{q}{Q}\right]\\ &=-P^f q\left[\phi_I+\frac{\partial P^f/P^f}{\partial Q/Q}(1-\phi)L\frac{q}{Q}\right]+C_I,\end{aligned} \tag{A7}$$

where $\phi_I=\frac{\partial\phi}{\partial I}$ and $\phi_{\bar I}=\frac{\partial\phi}{\partial\bar I}$.

Investment interdependence For the parameterized hazard in subsection 3.4, the second-order, cross derivative of ϕ is $\frac{\partial^2\phi}{\partial I_j\partial\bar I}$. Due to symmetry in equilibrium, the derivative equals:

$$\begin{aligned}&\frac{\partial-\lambda\gamma(1+\kappa\bar I)e^{-\gamma(I_j+\kappa I_j\bar I)}}{\partial\bar I}\\ &=-\lambda\gamma\kappa(1-\gamma I-\gamma\kappa I^2)e^{-\gamma(I_j+\kappa I_j\bar I)}\end{aligned} \tag{A8}$$

The sign of this derivative is determined by the term, $\kappa(1-\gamma I-\gamma\kappa I^2)$. When κ is positive and larger (smaller) than $\frac{1-\gamma I}{\gamma I^2}$, the derivative is positive (negative). Alternatively, when κ is negative, the derivative is positive.

A3 Analytical Solutions for Simulations

For simulations, we assume linear demand and supply functions. Because elasticity varies with the equilibrium output, we need to rewrite FOCs, Q^*, and I^* as functions without elasticity.

Specifically, we rewrite Equation (13) as

$$P^r+\frac{\partial P^r}{\partial Q}\Phi\frac{q}{Q}Q+\frac{\partial P^r}{\partial Q}(1-\Phi)\frac{\partial Q/Q}{\partial q/q}Q=P^f+\frac{\partial P^f}{\partial Q}\Phi\frac{q}{Q}Q+\frac{\partial P^f}{\partial Q}(1-\Phi)\frac{\partial Q/Q}{\partial q/q}Q+\frac{c+I}{1-\Phi},$$

where $\frac{\partial P^r}{\partial Q} = -\alpha$ and $\frac{\partial P^f}{\partial Q} = \beta$. Thus, this condition translates to

$$a - b - \frac{c+I}{1-\Phi} - \left\{ \alpha \left[(1-\Phi)(1+\xi) + \frac{2\Phi}{N} \right] + \beta \left[(1-\Phi)(1+\theta) + \frac{2\Phi}{N} \right] \right\} Q = 0. \tag{A9}$$

Other notation follows subsection 3.4.

Similarly, we rewrite condition (14) as

$$(a-b)\Phi_I - (\alpha+\beta) \left[(1-\Phi)(\Phi_I + \Phi_{II}) + \frac{\Phi\Phi_I}{N} \right] Q + 1 = 0, \tag{A10}$$

where, again, Other notation follows subsection 3.4.

The equilibrium output for the social planner becomes

$$Q^* = \frac{a - b - \frac{c+I}{1-\Phi}}{\alpha \left[(1-\Phi)(1+\xi) + \frac{2\Phi}{N} \right] + \beta \left[(1-\Phi)(1+\theta) + \frac{2\Phi}{N} \right]}. \tag{A11}$$

The partial derivative, $Q_I = \frac{\partial Q}{\partial I}$, in equation (19) becomes

$$\frac{AD - BC}{D^2}, \tag{A12}$$

where $A = -\frac{1}{1-\Phi} - \frac{(c+I)\Phi_I}{(1-\Phi)^2}$, $B = -\left[\alpha(1+\xi) + \beta(1+\theta) - \frac{2(\alpha+\beta)}{N} \right] \Phi_I$, $C = a - b - \frac{c+I}{1-\Phi}$, and $D = \alpha \left[(1-\Phi)(1+\xi) + \frac{2\Phi}{N} \right] + \beta \left[(1-\Phi)(1+\theta) + \frac{2\Phi}{N} \right]$.

B Alternative Model Setups

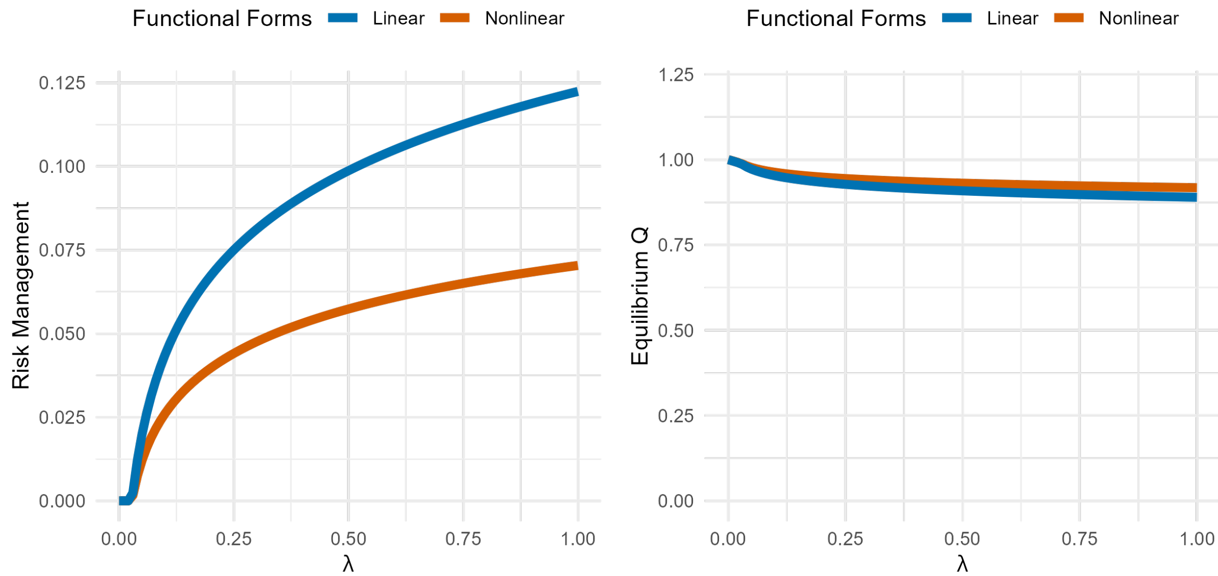
In this appendix section, we discuss alternative modeling settings and the sensitivity of the baseline simulation outcomes.

B1 Constant Elasticities

One implication of assuming linear demand and supply functions is that the elasticity varies with the equilibrium aggregate output, Q^*. Though this assumption is commonly made in the literature (Saitone and Sexton, 2017), one might worry that the changed elasticity could drive simulation outcomes.

To examine the sensitivity of our results to the assumption of linearity, we consider an alternative, weakly inelastic demand function, $P^r = Q^{-\eta}$, and an alternative, weakly inelastic supply function, $P^f = Q^{\varepsilon}$. Notation here follows subsection 3.1. For the private equilibrium, the FOCs remain unchanged as specified in Equation 13 and Equation 14, except that the expressions of retail and farm prices become exponential and the elasticities remain unchanged in simulations.

The welfare measures change accordingly. Specifically, CS equals $\int_0^Q P^r(x) - P^r(Q)dx = \frac{Q^{-\eta+1}\eta}{-\eta+1}$. The final market output varies with the realization of ϕ. Similarly, PS equals $\int_0^Q P^f(Q) - P^f(x)dx = \frac{Q^{\varepsilon+1}\varepsilon}{\varepsilon+1}$.



(a) Investment in Risk Management

(b) Market Quantity

Note: Figure displays results from numerical simulations, assuming linear and nonlinear functional forms. All parameters used for the linear setup are the average values from the distributions specified in Table 1. For the nonlinear setup, the parameters are re-calibrated, such that, given the competitive, risk-free equilibrium Q, the farm price f is worth 30% of the competitive equilibrium price (i.e., c is 70% of P^r). The expression is $0.3\, Q^{-\eta} = Q^{\varepsilon}$, which implies that $Q = 0.49$ and $P^r = 1.64$. Simulated quantities and prices are measured against these two benchmark values.

However, nonlinearity in the demand and supply functions makes it impossible to analytically solve the second stage FOC in subsection 3.2. Equation 15 becomes

$$\begin{aligned}(1-\phi^*)\left[1-\frac{(1-\phi^*)\xi+\frac{\phi^*}{N}}{\eta}\right]\left[(1-\phi^*)+\frac{\phi^*}{N}\right]^{-\eta}Q^{-\eta}\\ =(1-\phi^*)\left[1+\frac{(1-\phi^*)\theta+\frac{\phi^*}{N}}{\varepsilon}\right]\left[(1-\phi^*)+\frac{\phi^*}{N}\right]^{\varepsilon}Q^{\varepsilon}+c+I^*.\end{aligned} \tag{B1}$$

This equation implies that Q^* would be a complex function of I^*, limiting our ability to derive economic insights using the Implicit Function Theorem (see subsection 3.4 for discussion on comparative statics based on the baseline setup). Furthermore,

Figures B1a and B1b plot the optimal risk management and optimal outputs, respectively, under both linear and nonlinear supply and demand functional forms. As shown, the qualitative features of the optimal risk management and output decisions are not sensitive to the functional form that we impose, and the magnitude of the nonlinear specification only slightly deviates from the baseline linear case.

B2 Public Solution Choosing Investment and Output

If we let the government decide risk-reducing investment as well as firm output, the planner achieves the first-best solution. The planner's problem becomes:

$$\max_{I,Q} E[W] = \underbrace{(a-b)(1-\phi(I))Q - (\alpha+\beta)\left[(1-\phi(I))^2 + \frac{(1-\phi(I))\phi(I)}{N}\right]Q^2 - cQ - IQ}_{E[\Pi]} \\ + \underbrace{\frac{\alpha+\beta}{2}\left[(1-\phi(I))^2 + \frac{(1-\phi(I))\phi(I)}{N}\right]Q^2}_{E[CS]+E[PS]}. \tag{B2}$$

Given the specification of ϕ for analytical solutions, the two FOCs follow:

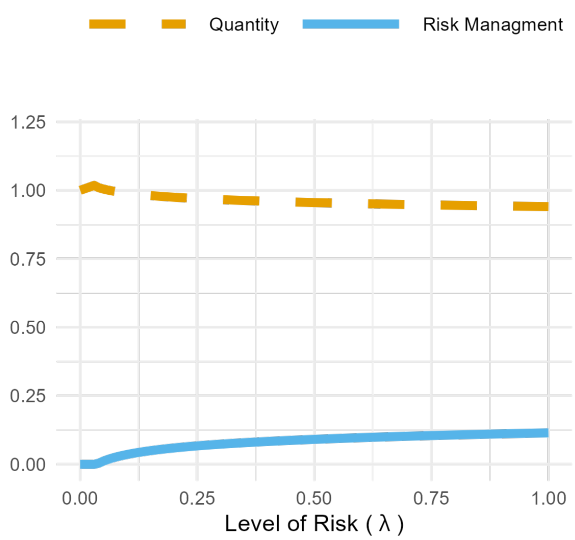
$$\begin{aligned} &(a-b)(1-\Phi) - (\alpha+\beta)\left[(1-\Phi)^2 + \frac{(1-\Phi)\Phi}{N}\right]Q = c + I; \\ &-(a-b)\Phi_I + (\alpha+\beta)\left[(1-\Phi)\Phi_I - \frac{(1-2\Phi)\Phi_I}{2N}\right]Q = 1. \end{aligned} \tag{B3}$$

Here $\Phi = \lambda e^{-\gamma(I+\kappa I^2)}$, and $\Phi_I = -\lambda\gamma(1+2\kappa I)e^{-\gamma(I+\kappa I^2)}$.

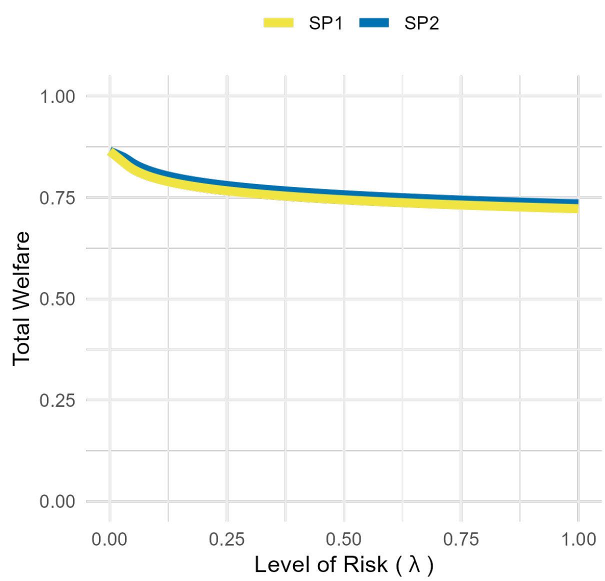
The equilibrium I and Q are displayed in Figure B2. Although the patterns match panel (b) of Figure 1, the equilibrium Q solved from this alternative social planner problem is weakly higher throughout the range of λ. If there is high market power, the equilibrium Q solved from the alternative setup would be even larger than that from the baseline setup of government decision because the social planner who controls output would further eliminate quantity distortion due to market power. Thus, the incremental CS and PS would be larger in this alternative setup, and so is the incremental social welfare. The difference in ΔW under the two alternative setups is displayed in panel (b) of Figure B2.

In this alternative setup, however, the profits earned by agribusiness firms could be negative, when the CS-plus-PS increment rises faster than the decrease in firm profits. Thus, increasing social welfare sometimes comes with decreasing and negative firm profits. While this combination of welfare changes is theoretically sound, it is not practical because negative variable profits could imply firm shutdown or even exit. Our two-stage setup in the baseline, which ensures firm profit-maximizing, rules out negative profits and hence makes better realistic sense.

Figure B2: Social Planner Solutions: Choosing Both I and Q



(a) Alternative Social Planner's Solutions



(b) Social Welfare

Note: Figure displays results numerical simulations with respect to the hazard λ. The yellow curve in panel (b) represents the total welfare under the baseline setup in Section 3, and the blue curve represents the total welfare under the alternative setup of social planner problem described in the appendix. The welfare terms are measured in expectation. All other parameters are set at average values from the distributions described in Table 1.

C Parameterizing the Risk Technology

The effectiveness of risk technology in mitigating risk exposure and the size of shocks is an important determinant of the magnitude that firms invest in equilibrium. In our model, this technology is captured by the term γ. It can be interpreted as a *semi-elasticity of risk management* or the percentage reduction in risk for every unit of risk management invested, mathematically, $-\frac{d\phi}{dI}\frac{1}{\phi}$ is equal to γ if $\kappa = 0$. For example, a value of γ equals 10, implies that from moving from \$0.01 to \$0.02 in risk expenditure per dollar of revenue yields a 10% reduction in risk.

We pin down the plausible range of γ by referring to statistics of hog diseases and the corresponding vaccines. We choose this context because it is one of the most valuable livestock industry and also because it is where the richest information on diseases and treatments is available. The values of γ lie in the range of 15 to 55 in most cases (i.e., between the upper and lower quartiles). We, therefore, make (15, 55) the baseline range for γ in the simulations.

Table C1: Parameter Values and Disease Information

ϕ_0	ϕ_1	dI	c_{vaccine}	V^r	γ	Disease	Animal	Source
0.91	0.69	0.011	3.90	346.67	15.1	PEDV	piglet	vaccine price: `https://www.jrgsupply.com/products/pedv-porcine-epidemic-diarrhea-virus-vaccine-50-dose`
0.91	0.69	0.012	4.20	346.67	14.0	PEDV	piglet	vaccine price: `https://www.fbn.com/direct/product/porcine-epidemic-diarrhea-vaccine`
0.91	0.69	0.013	4.50	346.67	13.0	PEDV	piglet	disease: (Gerdts and Zakhartchouk, 2017)
0.59	0.45	0.011	3.90	346.67	14.8	PEDV	piglet	vaccine price: `https://www.jrgsupply.com/products/pedv-porcine-epidemic-diarrhea-virus-vaccine-50-dose`
0.59	0.45	0.012	4.20	346.67	13.7	PEDV	piglet	vaccine price: `https://www.fbn.com/direct/product/porcine-epidemic-diarrhea-vaccine`
0.59	0.45	0.013	4.50	346.67	12.8	PEDV	piglet	disease: (Gerdts and Zakhartchouk, 2017)
0.057	0.0397	0.005	1.56	346.67	47.2	PRRSV	wean-to-finish	vaccine price: `https://www.fbn.com/direct/product/ingelvac-prrs-mlv`
0.057	0.0397	0.006	2.06	346.67	35.8	PRRSV	wean-to-finish	disease: (Angulo et al., 2023)
0.057	0.0397	0.007	2.56	346.67	28.8	PRRSV	wean-to-finish	
0.065	0.050	0.005	1.56	346.67	35.9	PRRSV	wean-to-finish	vaccine price: `https://www.fbn.com/direct/product/ingelvac-prrs-mlv`
0.065	0.050	0.006	2.06	346.67	27.2	PRRSV	wean-to-finish	disease: (Angulo et al., 2023)
0.065	0.050	0.007	2.56	346.67	21.9	PRRSV	wean-to-finish	
0.061	0.030	0.005	2.06	346.67	57.9	PRRSV	finishing	`https://www.fbn.com/direct/product/ingelvac-prrs-mlv`
0.061	0.030	0.005	2.56	346.67	46.6	PRRSV	finishing	disease: (Renken et al., 2021)

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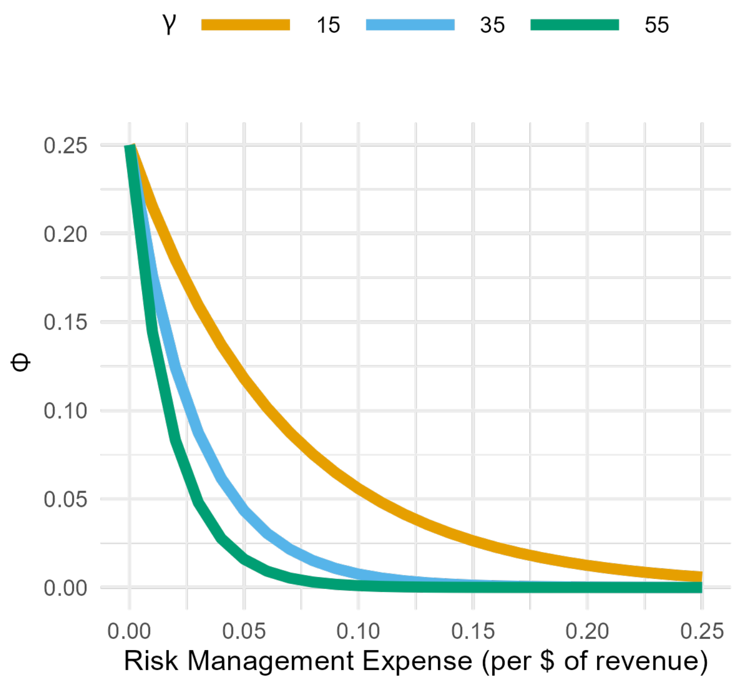
Table C1 – Continued

ϕ_0	ϕ_1	dI	c_{vaccine}	V^r	γ	Disease	Animal	Source
0.061	0.030	0.005	3.06	346.67	39.0	PRRSV	finishing	
0.070	0.029	0.004	1.56	346.67	90.76	PCV2	finishing	vaccine price: https://www.merck-animal-health-usa.com/species/swine/products/circumvent-cml
0.070	0.029	0.006	2.06	346.67	68.72	PCV2	finishing	vaccine price: https://www.scahealth.com/p/ingelvac-circoflex
0.070	0.029	0.007	2.56	346.67	55.29	PCV2	finishing	disease: (Kristensen, Baadsgaard, and Toft, 2011)
0.104	0.050	0.004	1.56	346.67	80.4	PCV2	finishing	vaccine price: https://www.merck-animal-health-usa.com/species/swine/products/circumvent-cml
0.104	0.050	0.006	2.06	346.67	60.9	PCV2	finishing	vaccine price: https://www.scahealth.com/p/ingelvac-circoflex
0.104	0.050	0.007	2.56	346.67	49.0	PCV2	finishing	disease: (Neumann et al., 2009)
0.056	0.030	0.004	1.44	346.67	78.3	PCV2	finishing	vaccine price: https://www.valleyvet.com/ct_detail.html?pgguid=e0b04305-0569-4f04-a233-5e7f1c72705b
0.056	0.030	0.006	1.94	346.67	58.1	PCV2	finishing	
0.056	0.030	0.007	2.44	346.67	46.2	PCV2	finishing	disease: (Jacela et al., 2007)

Note: Authors' creation. Average weight of retail pork per head, q^r, and the retail price of pork, P^r, are obtained from USDA ERS: https://www.ers.usda.gov/data-products/meat-price-spreads. The retail value of a hog is $V^r = q^r \times P^r$. The cost of vaccine, c_{vaccine}, is computed by the price of vaccine (e.g., \$100 for 50 doses) and the number of doses needed per head. The normalized cost of vaccine, dI, equals c_{vaccine} divided by v^r. The mortality rate of hogs without vaccine is ϕ_0 and becomes ϕ_1 with vaccine. Because of imperfect implementation, the reduction of mortality rate is always lower in practice than in laboratory. We use the scaler, $\chi_{\text{lab-farm}} =$ 70%, to capture the loss of vaccine effectiveness based on experts' opinion. We compute $\gamma = -\frac{d\phi}{dI}\frac{1}{\phi_0}$ where $d\phi = -(\phi_1 - \phi_0)$.

Figure C1: Risk Exposure with Different Risk Technologies (γ)



Note: Figure displays $\Phi(I|\gamma,\lambda)$ against I for $\lambda = 0.25$ and different values of γ.

Figure C1 demonstrates the effectiveness of investing in risk management at different values of γ, 15 (lower end of the range), 35 (mean of the range), and 55 (upper end of the range). Higher values of γ lead to steeper declines in $\Phi(I)$ as investment increases, reflecting greater effectiveness of the investment (i.e., higher semi-elasticity of risk management).