Risk Management Externalities in Food Supply Chains *

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Abstract

Private 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. This externality in risk management is particularly relevant for food supply chains that constantly face various shocks and play a primary role in preventing major social losses from food insecurity. We build a theoretical model within the context of US agri-food supply chains, where intermediary firms choose the quantity of output and the investment in reducing operational risk. We show that private firms invest in risk management less than the socially optimal level under perfect competition, but market power introduces competing risk management incentives. Potential welfare gains from policy intervention are considerable, especially under imperfect competition and complementary investments in risk reduction across firms.

JEL Codes: Q13, Q18, L13, D81

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1 Introduction

Supply chain disruptions have become increasingly frequent in recent years (Grossman, Helpman, and Lhuillier, 2023). In response, governments have discussed and implemented a variety of policy interventions to make supply chains more resilient to shocks (Elliott and Golub, 2022). Food markets, in particular, garner attention in these discussions since recent disruptions due to weather, fire, epidemics, and food-borne illness have resulted in stock-outs and elevated prices of staple food products (Hobbs, 2021; Hobbs and Hadachek, 2024). These events affect agents at each stage along the supply chain, including private firms that can endogenously reduce their exposure to various 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, what policy intervention in supply chain resilience is warranted.

To answer this question in the context of the US agricultural sector, we build a theoretical model of a vertical supply chain where intermediary processing/retailing firms are exposed to operational hazards that threaten their ability to source, produce, or deliver the final products to consumers. In our model, firms in the middle of the supply chain anticipate operational hazards and can reduce their exposure to the hazards by choosing a higher level of risk management before the realization of shocks. Each firm also chooses the output level to maximize the expected profit. Firms internalize the benefits of costly risk management through sustained production and profit in expectation of shocks.

We consider the social planner's risk management in a two-stage framework — the social planner chooses the level of risk-reducing investment that maximizes total social welfare (i.e., consumer surplus, firm profits, and producer surplus). In the second stage, given the risk environment set by the social planner, firms choose profit-maximizing outputs. This captures the realistic context where the government imposes policies on supply chain resilience (e.g., requiring vaccines for preventing animal diseases or food safety protocols), but allows the market to dictate equilibrium outputs and prices.

We first show the baseline result that optimal risk management is increasing with respect

to the size of the hazard that firms face. Our model predicts that when firms face a 20% risk of shutdown, for instance, they would invest about 6% of the competitive price into risk management strategies. But when facing a 50% risk of shutdown, they would invest about 16% of the competitive output price. We further demonstrate that the socially efficient level of risk management exceeds the private firm's choice in a competitive market. Intuitively, this gap in risk management reflects an externality that arises from the fact that private firms fail to incorporate the welfare impacts caused by chain disruptions on the greater society and hence invest too little in risk reduction (Baldwin and Freeman, 2022).

Next, our model allows us to further explore the interactions between market power and resilience by imposing flexible assumptions about competition in the style of the Flexible Oligopology/Oligopsony Market (FOOM) model (e.g., Russo, Goodhue, and Sexton, 2011). We show that market power plays an important role in determining the sign and magnitude of the externality in risk management. Specifically, increased market power alters equilibrium risk-management decisions through two mechanisms – a *social welfare* effect and a *coordination* effect. First, as firms gain more influence over market-level quantity, they capture greater shares of the total market welfare. Therefore, firms internalize greater shares of losses due to supply chain disruptions and invest in risk management at a level closer to the social planner. We label this the *social welfare* effect. On the other hand, firm investment may depart from the social optimum depending on how much they coordinate in risk management. Intuitively, this channel arises from firms' incentive to restrict risk management costs, while capturing positive profits in the face of shocks. We decompose these competing channels and show via simulation their implications for social welfare. For example, deadweight loss due to externality in risk management in the perfectly competitive setting is only about 0.2% of the total market welfare. Whereas, the *social welfare* effect can result in deadweight loss of 3.8% in a triopoly scenario. Alternatively, the *coordination* effect can result in a deadweight loss of 6.1% with high degrees of coordination across firms.

Our paper centrally contributes to the discussion of agri-food supply chain resilience in imperfectly competitive settings. The context is particularly relevant because (i) food supply chains

have become increasingly consolidated and specialized over time, deviating from perfect competition. (ii) In such supply chains, even a shock to a single firm may have market-wide impacts and may be exacerbated in the case of simultaneous, correlated shocks (Hadachek, Ma, and Sexton, 2024). (iii) Food supply chains play a primary role in preventing food insecurity (i.e., social losses) following catastrophic shocks (Bellemare, 2015).

Past work has empirically measured how market structure (Gnutzmann, Kowalewski, and Śpiewanowski, 2020) and diversification in production/sourcing (Stevens and Teal, 2024) affected economic outcomes in the presence of historic shocks. Other theoretical work has measured how market structure (Hadachek, Ma, and Sexton, 2024) or flexible marketing options (Chenarides et al., 2023) can potentially make agri-food supply chains more resilient. This paper is one of the first to offer a flexible framework that characterizes firms' risk management decisions, unpack the driving mechanisms, and weigh the equilibrium values against the socially efficient risk management in the context of food supply chains.

More generally, this paper contributes to research on how shocks on firms propagate throughout networks and affect others' welfare along the supply chain (Barrot and Sauvagnat, 2016; Carvalho et al., 2020). A growing body of theoretical work endogenizes risk strategies by firms (e.g., building and strengthening links with input suppliers) and measures the welfare implications of international trade disruptions within the network (Capponi, Du, and Stiglitz, 2024; Grossman, Helpman, and Lhuillier, 2023; Grossman, Helpman, and Redding, 2024; Acemoglu and Tahbaz-Salehi, 2024). Some empirical work has documented that firms adapt to climate risks or natural disasters by adjusting their supply networks (Castro-Vincenzi, 2022; Castro-Vincenzi et al., 2024; Grover and Kahn, 2024). In contrast to past work, we take the links in the supply chain as given. We highlight the firm-level risk management aimed at reducing the firm's exposure to operational hazards and discuss the role of policy intervention in risk management. Importantly, our model is flexible to accommodate a range of market structures and risk scenarios, which allows us to capture novel insights about this potential market inefficiency and the potential for policy to correct it.

Two insights stand out. First, we reinforce findings from Kirwan (2009) and Russo, Good-

hue, and Sexton (2011) who find that market power distorts and complicates the distribution of welfare gains from agricultural policies relative to the competitive case. Second, we show that the degree to which a firm's risk is dependent on others' risk management plays a meaningful role in determining the risk management decisions and welfare outcomes. Each insight is highly relevant to the US agri-food supply chain, where considerable market concentration exists along the chain and the interdependence in risk management widely exists (Wang and Hennessy, 2015).

The remainder of the article is organized as follows. Section 2 describes the nature of risk management that food and agribusiness firms engage in and the risks they protect against. Section 3 builds the base vertical supply chain model and outlines analytical solutions. Section 4 assigns parameter values for market characteristics and structures. Section 5 presents results from simulations over four market and risk parameter values. Section 6 highlights key findings and concludes.

2 Risk Management in Agribusiness

Agribusiness firms are aware of a long list of risk factors that have the potential to affect their business and undertake risk management strategies to limit risk to some extent. To demonstrate this point and to qualitatively investigate risk factors affecting agribusiness supply chains, we document stated risk factors for the top 20 public agribusiness in their 2023 Form 10K reports.[1] We categorize each stated risk and report the summary in Figure 1.

We highlight a few takeaways from this exercise. First, several of these factors — animal diseases, food safety, natural disasters/climate — pose a particularly unique threat to agriculture and food production. On the other hand, agribusinesses face more common threats — macroeconomic, regulatory, and cyber-security — which may impact every industry in the economy.

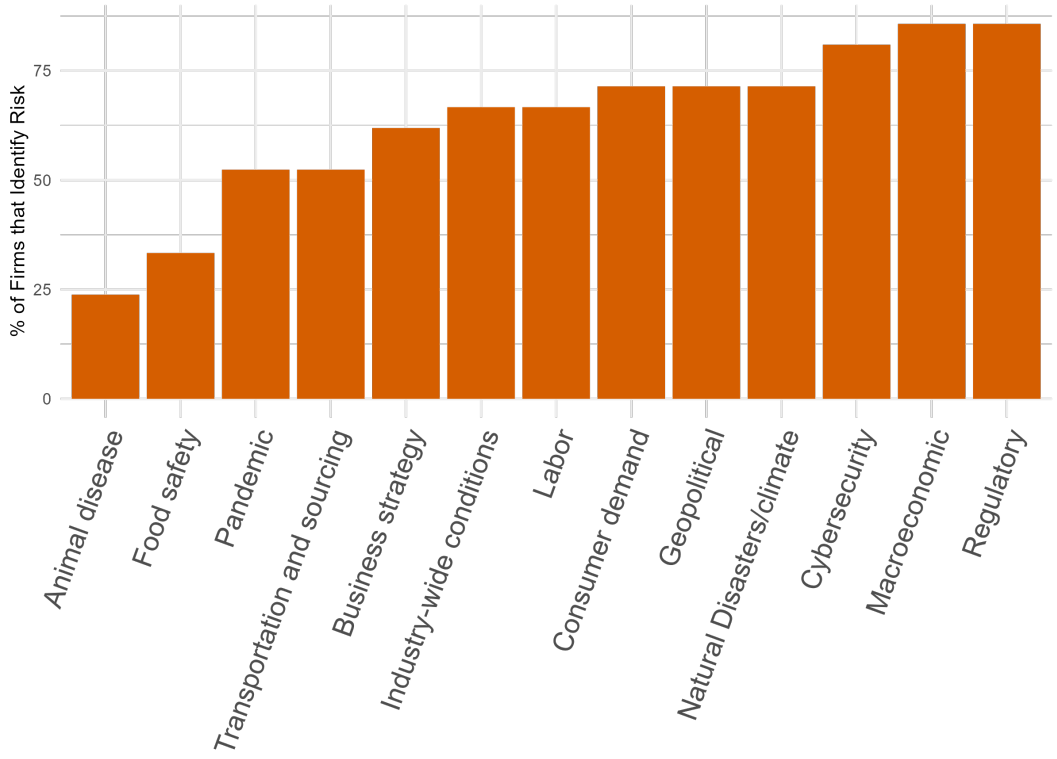
Second, the risks that firms manage are timely based on recent events. In particular, over

[1]Form 10K reports are annual disclosures of financial status, required by the Securities and Exchange Commission. A section of this report requires companies to disclose existing or future risks to their business and the potential impacts of those risks.

60% of the firms identify that geopolitical conflicts in Russia/Ukraine and Israel/Palestine carry potentially devastating effects on their operating capacity, including trade restrictions, property damage, and halts in regular business operations. Many firms also continue to recover from and/or prepare for pandemic events in light of the COVID-19 disruptions. Recent drought, natural disasters, and climate change-related impacts are also front of mind for many of these firms. Many of these risks are predicted to be increasingly frequent in the future.

Lastly, in some cases, firms identify actions taken or programs in place to mitigate the effects of the stated risks. These activities range from simple monitoring and evaluating ongoing situations, diversification of investments or networks, and in some instances, named programs or initiatives that are specific to managing a certain risk. This demonstrates that firms do endogenously reduce some risks, while others may be too costly or impossible to limit exposure.

Figure 1: Risk Factors Identified by Top Agribusiness Firms in their Form 10K



Note: Figure displays the count of agribusiness firms that state a category of risk in their 2023 annual reports. Publicly traded companies are required to disclose any potential risk factor that may disrupt business operations and company valuation. Data was hand-collected and categorized by the authors and is available upon request.

2.1 Examples of Hazards in Agri-Food Processing

To illustrate the probability and magnitude of disruptions that food processing firms in the US may face, below we offer three examples for which data exist: fire, natural disasters, and food-borne contamination.

Fire Facility fires are a common cause of supply disruptions in the US food supply chains. In 2022, more than 13,000 fires occurred in US agricultural and manufacturing plants, and more than 3,000 fires occurred in storage facilities like grain bins and silos (Verzoni, 2022). Because of the high concentration in agricultural processing, a facility fire may interrupt as much as 5-6% of total national production. Given that there are some 41,080 food and beverage processing plants in the US as of 2022 (Bureau of the Census's County Business Patterns, 2022) and some 13,000 fire occurrences, the probability of catching fire in the year is above 30%.

Food processing plants are particularly prone to fire because food is combustible and food processing often involves heat, high pressure, and combustible dust.[2] The plants protect against fire by installing smoke detectors, automatic extinguishing system, dust collection systems like centralized vacuums, and so on. We are unable, however, to find exact statistics on expenditure in fire protection.

Natural disasters Natural disasters like floods and hurricanes are also known to have a meaningful impact on supplier-customer relationships in the supply chain. For example, Barrot and Sauvagnat (2016) notably find that the occurrence of major natural disasters (e.g., hurricanes, blizzards, floods) in the US reduced supplier revenues by 4% in the following quarters. In another context, Carvalho et al. (2020) find that the Great East Japan Earthquake of 2011 reduced overall national GDP by 0.47 percentage points. While these devastating events may have low probabilities, natural disasters present a perennial risk that must factor into management decisions, like

[2]The most obvious sources of combustible dust in food processing facilities include flour, grains, proteins, spices, sugar, and teas (OSHA, 2022).

location, contingency planning, and market diversification.[3] Given that agriculture and food production and processing are generally geographically concentrated within regions, a natural disaster impacting an entire region may be devastating for the total domestic food supply.

Food-borne contamination Another risk associated with food processing is contamination that causes food-borne illness. According to the CDC, 48 million people in the US become ill, 128,000 are hospitalized, and 3,000 die annually due to food-borne diseases (CDC, 2018). One of the most common contamination is caused by Salmonella. There is close inspection on Salmonella contamination, especially regarding meat processing. The Raw Pork Products Exploratory Sampling Program, for instance, was initiated in April 2015 to collect data about Salmonella and other pathogens within pork products. Out of 1,200 plants examined, 200 (i.e., 16.7%) were tested positive for Salmonella in the 2015 survey (FSIS, 2019). The portion of sample tested positive was around 19.0% in 2017 to 2022 (FSIS, 2022). For fresh beef and poultry, the portions of sample tested positive have been lower than 10%.

Firms are conscious of many other hazards that would most impact their business as demonstrated in Figure 1 and invest to mitigate them. The extent to which they invest, although, is ambiguous and may depend on a variety of economic factors, including the probability of the hazard, the cost of risk management, and the size of potential losses. In the next sections, we outline an economic model that incorporates these parameters and show via simulation how the values of these parameters impact optimal risk management.

3 Model

We consider a two-stage supply chain with M farms and $N < M$ homogeneous processors/retailers, providing perishable food to consumers.[4] Consistent with past supply-chain models, e.g., Gardner

[3] Using data from Center for Emergency Management and Homeland Security (2024), we calculate the probabilities that any county is affected by a hurricane, flood, and blizzard as 0.3%, 3.4%, and 4.5%, respectively.

[4] 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 foods, there is a long strand of literature on storage and commodity price-stabilization policies (Wright, 1979; Miranda and Helmberger, 1988; Gouel, 2013).

(1975), Wohlgenant (1989), Sexton (2000), we assume an integrated processing-retailing sector for simplicity. Assume 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 scaling 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 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 Y captures exogenous demand shifters.

Each risk-neutral firm faces a common probability of shutdown and failing to sell its products due to various operational hazards such as fire, product contamination, and animal or human diseases.[5] 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 (e.g., natural disasters), while the actual probability and size of an experienced shock can be reduced by firms that invest in risk technology or risk management (e.g., geographic diversification, biosecurity measures, buffer capacity).

Denote the per-unit investment 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 across firms. Specifically, when the firm investments are complements (substitutes), $\frac{\partial^2 \phi_j}{\partial I_j \partial \bar{I}} < 0$ ($\frac{\partial^2 \phi_j}{\partial I_j \partial \bar{I}} > 0$) with $\bar{I}$ being the average investment by peer firms

[5] Rather than a few firms fully shutting down, an alternative interpretation is that all firms experience a partial shutdown from the same shock and lose a share of their output.

in the industry. Intuitively, this means that the marginal risk reduction from increasing I_j by one unit 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 shuts down, 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 will still incur the costs of procurement and *ex ante* risk management. Thus, 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 Q, $E[Q]$, equals $\sum_{i=1}^{N} E[q_i] = \sum_{i\neq j}^{N}(1-\phi_i)q_i + q_j$. We rewrite the objective function of the firm:

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

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} (C_{I_j}) is the partial derivative of total cost with respect to q_j (I_j), and $\phi_{I_j} = \frac{\partial \phi_j}{\partial I_j} < 0$. The left-hand-side (LHS) of the first equation is the marginal profit from 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 margin cost of producing. In the second equation, similarly, the LHS the marginal return to investing more one unit in reducing risk, 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]

Terms θ and ξ equal $\frac{\partial Q}{\partial q}\frac{q}{Q}$ in the first equation of system (7) and are the conjectural elasticities for buyer and seller power, respectively. When θ (ξ) is equal to 1, the firm has perfect control of market output (i.e., perfect monopsony/monopoly). When equal to 0, the firm has negligible or no influence on 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 any partic-

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

ular form of market competition. Parameter $\eta > 0$ is the absolute 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 new parameter relative to the traditional FOOM model. The term $\varsigma = \frac{\partial I_i / I_i}{\partial I_j / I_j} \; \forall \; i \neq j$ 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 risk management given an increase in investment by a peer firm j. Therefore, this equation captures the Nash equilibrium for risk management.

The conjectural elasticity in risk-reducing investment may take on distinct values from ξ and θ. On the one hand, ς could be smaller because investments by peer companies may be harder to observe than outputs by peers. On the other hand, food processing companies are often conglomerates of many branches, and risk strategies may be easily coordinated across branches within the same company. Furthermore, industry-level coordination in risk management does not violate anti-trust policies, meaning that risk technologies may be easily coordinated or shared among firms.

3.2 Socially Optimal Equilibrium

A social planner who maximizes the expected social welfare has a different objective function. Here, we let the social planner determine the risk-reducing investment, and firms choose output given the planner's risk management. Noticeably, we do not let the social planner set firm-level outputs, because 1) it is unlikely that the government would consider such a policy, and 2) if we did, the social-planner would simply generate the trivial perfect-competition outcomes in expectation (see subsection A3 for details).

The objection function of the social planner is specified as:

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

where $E[CS]$ is the expected total consumer surplus (CS) and $E[PS]$ is the expected total producer

surplus (PS) for the farms. The CS equals $\int_0^Q P^r(x) - P^r(x)dx$ where $Q = Nq$. The market output varies with the realization of ϕ and follows a Binomial distribution of $N \sim \text{Bin}(\bar{N}, 1-\phi)$. Similarly, the PS equals $\int_0^Q P^f(x) - P^f(x)dx$.

Given investment 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^* to 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 to make, the firms only compete in q.

Therefore, the FOCs for investment in solving the private and public problems differ in a critical way, while the FOCs for output are the same. The second equation in system (7) suggests, 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 survives more by reducing the shutdown probability, earning an increment of $\Delta P q \phi_I$. On the other hand, the equilibrium ΔP, or the profit margin, is negatively affected by the additional investment because the investment conjecture (i.e., the $\phi_I \varsigma$ term) and the increased average investment by peers (i.e., the $\phi_{\bar{I}}$ term) imply larger equilibrium output. In the private problem, each firm only cares about the second force to the extent it reduces its own marginal return from investing and ignores the negative impact on peers' profits.

When the government sets the common amount of investment for homogeneous firms in equilibrium, the marginal cost is of the same form, but the marginal return differs from that for firms in two ways. On the one hand, the government incorporates the negative impact of increasing investment, hence increasing $E[Q^*]$, on the equilibrium ΔP and profits on all firms. This effect, thus, implies lower I^* set by the government than the firms in equilibrium. On the other hand, by considering CS and PS in computing the marginal return to investing, 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. The endogenous risk on output adds non-trivial complexity to the model, creating two interdependent trade-offs and an ambiguous public-private wedge in risk-reducing investment. We explore this via simulation and discuss its implications in subsection 5.2.

3.4 Analytical Solutions

To obtain analytical solutions and enable simulation, we assign linear functions to the model. The farm supply and market demand functions are:

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

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

It follows that the CS and PS are measured by triangle areas determined by the equilibrium Q. The firm's profits are captured by the rectangular area set by 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 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] Take, for example, administering vaccines to each live animal (Hennessy, 2007), or instituting food safety protocols for food output Hennessy (1996).

We impose an exponential hazard function that has long been used in a variety of contexts to measure the probability of firm shutdown or 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 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 agricultural supply chains — the interdependence of risk management among agribusiness firms. That is, one firm's risk management can also influence other firms' probability of shutdown, 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 shutdown risk 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 firm outputs and investments would be identical in equilibrium. We rewrite equation (7) as:

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

[7] Some risk management strategies may more closely resemble fixed cost or capital investments (e.g., storage 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.

where $\Phi = \lambda e^{-\gamma(I+\kappa I^2)}$ and I is the symmetric investment by a firm, $X = \frac{(1-\Phi)\xi+\frac{\Phi}{N}}{\eta}$, and $H = \frac{(1-\Phi)\theta+\frac{\Phi}{N}}{\varepsilon}$. Term $E[Q]$ equals $(1-\Phi)Q+\frac{\Phi}{N}Q$. The second condition in system (7) 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, 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 open under shutdown risk and varies in a Binomial distribution of $N \sim \text{Bin}(\bar{N}, 1-\phi)$ and $Q = Nq$.

Given the linear demand and supply functions and solutions found in equation (A2), the

objective function for the government can be rewritten as:[8]

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

Given the symmetry in solution, the FOC is:

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

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 also normalized to 1.0. The corresponding demand elasticity at this equilibrium, η, hence equals $\frac{1}{\alpha}$, and $a = 1 + \alpha = 1 + \frac{1}{\eta}$.

Similarly, the competitive farm equilibrium price 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. Because of 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 farm price elasticity of supply at the

[8] Note that $E[Q(I)^2] = E[q^2N^2] = q(I)^2E[N^2] = q(I)^2N^2\left[(1-\phi)^2 + \frac{(1-\phi)\phi}{N}\right] = Q(I)^2\left[(1-\phi)^2 + \frac{(1-\phi)\phi}{N}\right]$. See subsection A1 for derivation of the formula.

Table 1: Baseline Parameter Values

Parameter	Description	Baseline Value
λ	Impact of shock without risk management	0.2
γ	Semi-elasticity of risk management	10
κ	Interdependence of I between firms	0
ε	Farm supply elasticity	1
η	Demand elasticity for final goods	0.7
f	Competitive farm share	0.3
N	Number of firms	4

competitive equilibrium. Values for ε and η are set based on the literature for staple food markets as described in Table 1. The last market parameters relate to buyer and seller power. We start by studying the perfectly competitive case ($\xi = \theta = 0$) in our baseline specification and build up to the imperfectly competitive case.

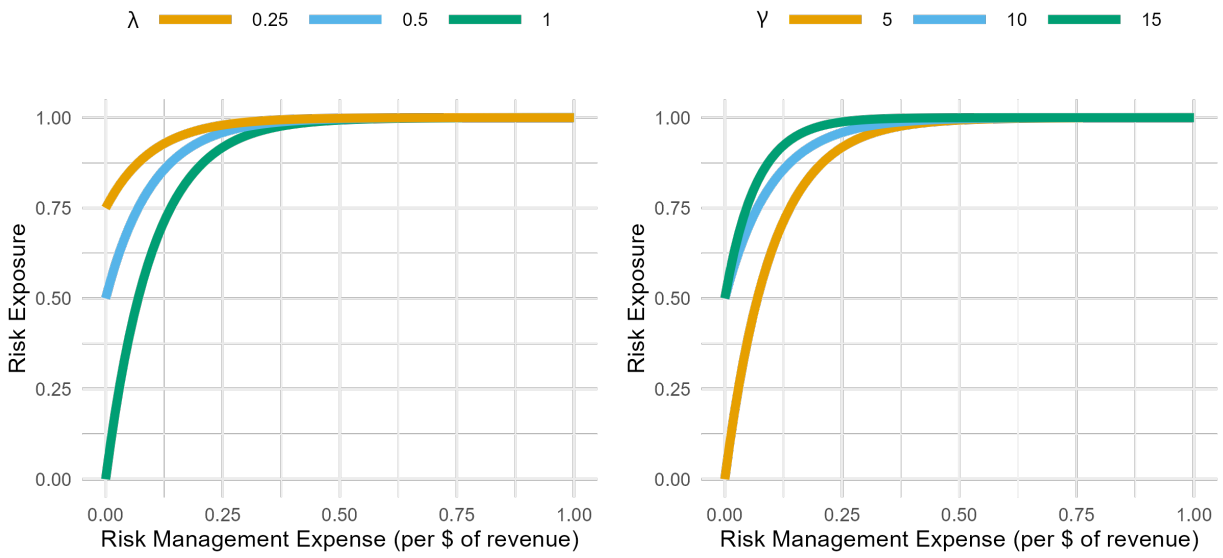
4.1 Risk Parameters

The remaining parameters relate to the nature of the risk function. The risk parameters, of course, vary by context. For example, managing the threat of a food safety risk is distinct from managing the threat of a food manufacturing fire. Hence, we do not claim to identify accurate values of these parameters within a specific context, but rather they should reflect a generalized form of risk that firms uniformly face. We then show how risks of different natures may affect risk management decisions and welfare distribution.

We start by studying risk management strategies that are independent from firm to firm ($\kappa = 0$), but relax this assumption in subsection 5.3. Next, for a given hazard, λ measures the probability of shutdown without any investment in resilience, namely, $\phi = \lambda e^0 = \lambda = \phi(0)$. For example, Figure 2a demonstrates the impact of risk management on $1 - \Phi$ for three values of λ. As a baseline, we set $\lambda = 0.20$ such that the hazards are sufficiently large that firms are conscious

and motivated to protect against them.[9]

Figure 2: Changes in Risk with Respect to Different Parameters



(a) Size of Hazard

(b) Risk Technology

Note: Figure displays the values of the hazard function ϕ plotted against levels of risk management. In panel a, the hazard rate λ, which captures the probability of shutdown absent risk intervention (the y-intercept value). In panel b, the three lines represent different values of risk technology γ. Larger γ values reflect cheaper risk mitigation.

The value of γ captures the effectiveness of strategies or technology in reducing risk exposure (e.g., food safety protocols, diversification, and maintaining contingency plans). 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 previously stated, the value of γ is context and strategy-specific. Some hazards may be more cheaply avoided (higher values of γ), while others may be difficult or impossible to influence (low values of γ).

Figure 2b demonstrates the shape of the risk function for different values of γ. Since there is

[9] Ma and Lusk (2021) offer two examples of the size of shocks to the total market. A fire at a beef processing plant in 2019 reduced total market processing capacity by 5-6%, and worker illness and quarantine mandated from COVID-19 reduced production by about 40%. Given that meat processors likely engaged in some level of risk management pre-COVID-19, the pandemic could have had a more devastating effect in the absence of those strategies. A value of $\lambda = 0.20$ is not unprecedented given recent experiences. The probability of a facility fire is also quite high, as discussed in section 2.

little precedent for this parameter in the literature, we set γ at a moderate value of 10 in the baseline and explore different values via simulation. This baseline value implies that at an initial value of $I = 0.10$ (10% of every dollar of revenue earned), an increase in risk management expenditure by 10% causes risk probability (ϕ) to fall by 1%.

5 Simulation Results

We examine the model solutions and explore the effects of varying the hazard and market structures via simulation. We start with the competitive setting. The magnitude of the public-private risk externality is displayed as well as the difference in welfare for consumers, producers, and firms, respectively under different levels of hazard. Second, we explore how market power affects the equilibrium outcomes for risk management and welfare via the quantity competition channel. Lastly, we focus on coordination through the channel of risk management and how it influences the wedge between the social-planner and private firm solutions.

5.1 Level of Hazard: λ

Our model does not presume the nature nor magnitude of hazard faced by the firm. Instead, it is generalizable to the array of contexts and shocks that agents in the supply chain may face. The only implicit assumption regarding the nature of hazards is that private or public intervention can reduce their exposure to some extent.

We hence start by determining how the level of hazard that firms face impacts their production and risk management behavior. The parameter $\lambda \in [0,1]$ determines the expected size of the hazard that firms face in absence of risk management interventions. Isolated and small threats to output would take a value close to 0, whereas catastrophic and cascading risks would take values closer to 1.

Given our baseline conditions, our first set of results demonstrates that socially optimal risk management exceeds what is achieved in the private equilibrium for most levels of hazard.

Figure 3 illustrates these findings. Panel (a) demonstrates that for sufficiently small hazards ($\lambda <$ 0.12), the firm's optimal strategy is to not invest in risk management (i.e., the corner solution). As the expected magnitude of hazard increases past the corner solution threshold, their optimal risk management strategy is increasing in λ. For moderate hazards ($\lambda = 0.5$), they invest about 16% of the normalized competitive market price into risk management expenses. Wheras, the social planner invests about 18% of the competitive market price when facing the same hazard. For more modest hazards ($\lambda = 0.20$), businesses and the social planner invest about 6% and about 8% of the competitive price, respectively, reflecting the nonlinearity in the hazard rate.

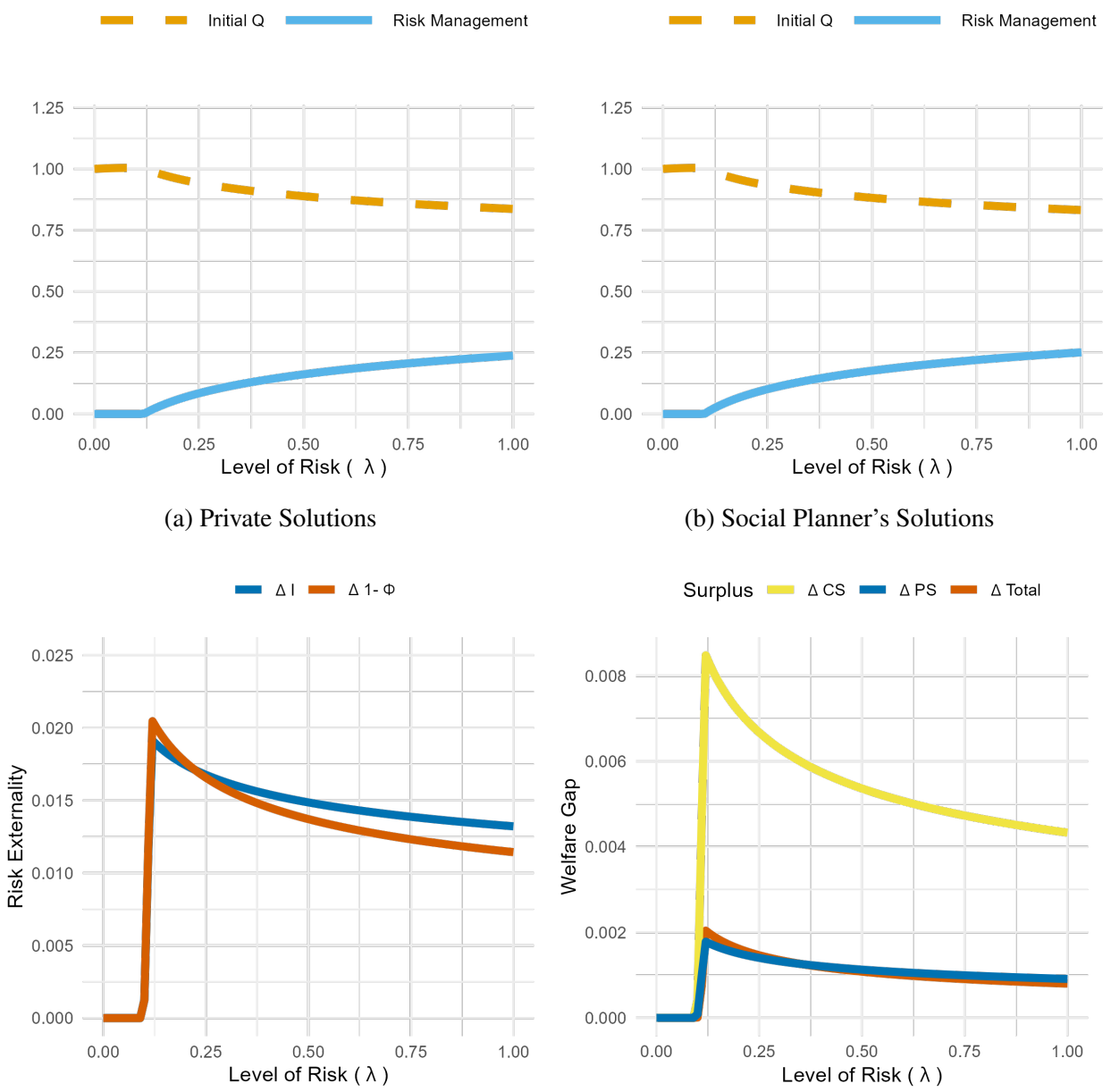
The level of hazard and risk management also carries implications for the optimal production levels for firms. For values of $\lambda < 0.12$ (i.e., before engaging in risk management), the equilibrium quantity is increasing in λ. This is due to the fact that as the magnitude of shock increases, firms produce slightly more to shield against the rising potential losses.[10] As risk management expenses move off the corner and increase, firms produce less (i.e., Q^* falls), because they are decreasing their expected downside loss through investing in risk management and weighing the cost of additional risk management into the marginal cost.

For the social planner, similarly, the optimal investment is zero for sufficiently small hazards ($\lambda <$ 0.10). This threshold, importantly, is slightly lower than that of the competitive firms, indicating a small range of λ where the optimal public investment in risk management would be strictly positive and the optimal private investment remains at zero. Said differently, the social planner engages in risk management for smaller hazards that competitive firms do not on their own accord. This gap reflects an externality in risk, whereby the firms under-invest in risk management and do not consider the risk propagated to consumers and producers.

As λ increases, Figure 3c shows that the size of the risk externality grows quickly at first, and then decreases once firms move away from the corner solution. $\Delta I = I^*_{gov} - I^*_{firm}$ is the difference in risk management investment as a proportion of the competitive output price. At a value

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

Figure 3: 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 results from 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: $\varepsilon = 1$, $\eta = 0.7$, $f = 0.3$, $\kappa = 0$, $\varsigma = 0$, and $\xi = \theta = 0$.

of $\lambda = 0.12$, the risk externality peaks at an approximate \$0.02 gap, and the private equilibrium is

about 2 percentage points more likely to realize the shock than the social planner's solution.[11]

Welfare impacts of risk externality We measure welfare in expectation terms throughout this section. Figure 3d plots the welfare gap between the private firm's and the social planner's optimal levels of risk management, namely, $\Delta W = E[W|I^*_{gov}] - E[W|I^*_{firm}]$. Similarly, ΔCS and ΔPS are computed and plotted in the figure. As the wedge in investment widens, the net welfare gains from potential government intervention increase, too. At $\lambda = 0.12$, the potential gain in CS from policy intervention is worth $\frac{0.008}{CS^c} = 1.1\%$ of the competitive, risk-free social welfare, which is economically significant given the total size of CS in the context of US food market.[12]

Although not plotted in Figure 3d, $\Delta\pi$ is negative. This reflects the basic problem setup, where firms maximize only their own profit, but the social planner maximizes total welfare. The social planner's solutions may result in lower π than the private equilibrium equilibrium if ΔCS and ΔPS sufficiently offset the difference.[13] This is indeed the case in this set of simulations as $\Delta CS + \Delta PS > \Delta W > 0$.

These simulation results offer two important insights into risk management in perfectly competitive markets. First, we show the intuitive result that higher levels of hazard yield more risk management from both a firm and a social welfare perspective. Second, public investment in risk management increases earlier and faster with respect to the size of the hazard, implying a public-private wedge in risk-reducing investment (Baldwin and Freeman, 2022). Under this baseline scenario, increasing risk management by about \$0.02 per unit increases total social welfare (or eliminates deadweight loss) by about 0.2%. Thus, supply chain resilience policies to protect against devastating shocks are economically justified under perfect competition.

We now proceed to show that, perhaps surprisingly, buyer and seller power creates conflicting incentives for risk management investment made by firms. Imperfect competition adds

[11] It is important to note that all agents are risk neutral in this model. If consumers and farmers are more risk-averse than intermediary firms, the externality intuitively would be larger in magnitude since firms would tend to take on riskier behavior than the other supply chain agents.

[12] The competitive, risk-free CS equals $\frac{a}{2} \approx 0.71$ with equilibrium quantity normalized to 1.0.

[13] It is important to note that, although this is the perfectly competitive case, firms may still earn a positive profit due to the nature of risk. When a shock is realized, the total market quantity reduces and the total price increases, creating the possibility of positive profits in both the private equilibrium and the social planner's solutions for $\lambda > 0$.

significant complexity to the wedge between firm and government risk investments and potential welfare gain from policy intervention.

5.2 Quantity Conjecture: ξ and θ

For Figure 3, we impose a value of $\xi = \theta = 0$, meaning that the firm's marginal quantity choices do not influence the market price; firms take prices as given. However, for a concentrated agriculture and food processing sector in the US, this structure is unlikely to hold in practice (Sexton, 2013).

As described in subsection 3.1, we allow for flexible market power assumptions by introducing the conjectural elasticity, ξ and θ, with a range of $[0, 1]$. The parameters 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.

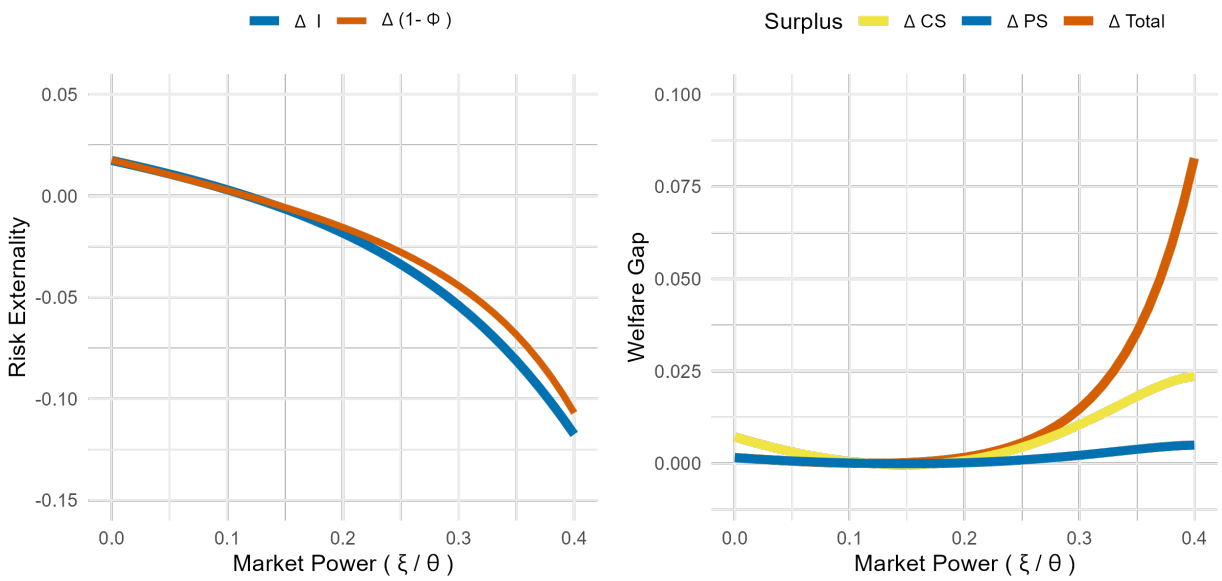
Let $\xi = \theta$ throughout the simulations. Figure 4a suggests that the wedge between private and public optimal risk-reducing investments falls in the conjectural elasticity. This confirms the conflicting forces discussed in subsection 3.3. When competition is near perfect, there is near zero profit to be pursued by firms, and thus, firms only have a small incentive to invest in risk management given their already thin margins. As market power increases, however, the first effect eventually dominates (i.e., $\xi = \theta \geq 0.09$), and the risk externality in I turns negative. That is, oligopolistic firms actually over-invest in risk management relative to the social planner.

The public-private wedge in W is always positive given ξ and θ. Importantly, the welfare wedge increases in market power, indicating more return to policy intervention in less competitive settings. This is the case because, as the share of firm profits rises, the social planner would prefer to lower I and induce larger Q produced by the firms. Two forces are active. Market power reduces CS and PS, everything else the same. Market power implies worse distortion due to over-investing in risk management and hence more gain from correcting it with policy intervention. As a result, ΔCS and ΔPS initially fall in ξ and θ before they eventually rise.

In the meantime, $\Delta\Pi$ rises and falls and eventually stays positive. Again, two forces compete and producing the varying impact of policy intervention on firm profits. On the one hand, the

government maximizes the total welfare instead of profits by imposing I for all firms. Firm profits tend to fall in exchange for increased CS and PS. On the other hand, as market power increases, the share of profits out of total welfare increases, too. The distortion due to over-investing also increases. The government corrects the over-investment and hence may increase firm profits. Importantly, after ξ and θ reach 0.25, CS, PS and profits increase simultaneously and at an increasing speed. This implies Pareto improvement for all players in society thanks to the policy intervention. With ξ and θ equal 0.33 (i.e., a triopoly setting), the total potential gain in welfare is worth $\frac{0.026}{W^c} = 3.8\%$ of the competitive social welfare, which is economically significant.[14]

Figure 4: Wedge in Risk Investment and Welfare under Market Power



(a) Gap in Risk Investment

(b) Gap in Welfare

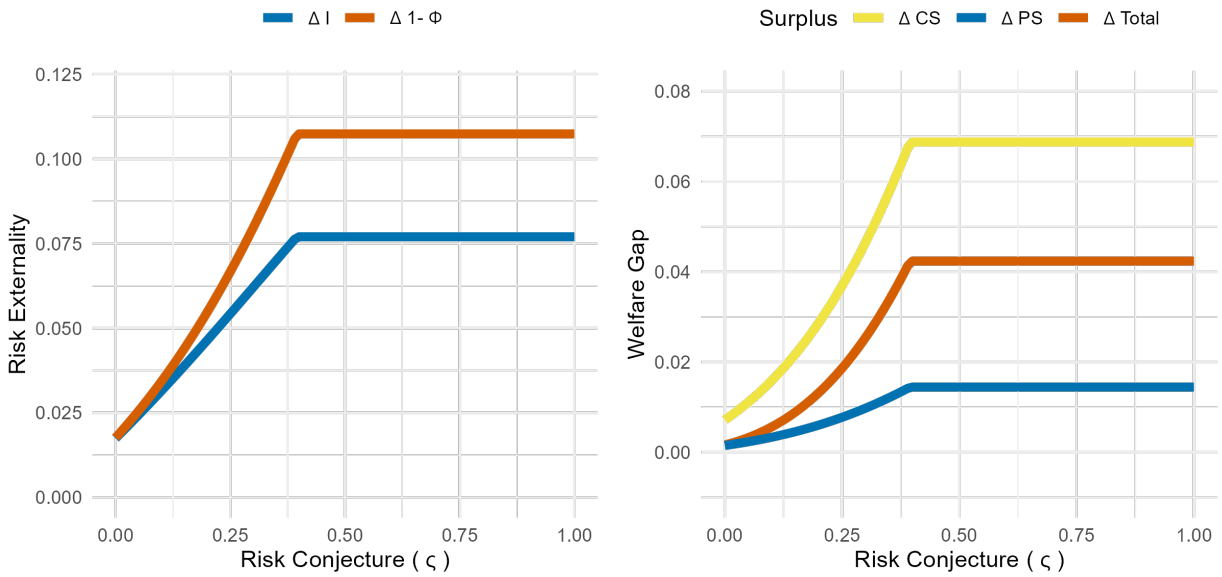
Note: Figure displays results from numerical simulations with respect to market power parameters ξ and θ. Δ indicates the difference between the social planner's solutions and the private firm's. All welfare terms are measured in expectation. All other parameters are set at baseline values: $\lambda = 0.2$, $\varepsilon = 1$, $\eta = 0.7$, $f = 0.3$, $\kappa = 0$, $\varsigma = 0$.

[14]The competitive social welfare is ≈ 0.69 with risk-free equilibrium quantity and retail price normalized to 1.0.

5.3 Risk 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. It captures the firm's conjecture on the change in peers' investment given a change in its own investment. This parameter is set to zero in the baseline simulation. The larger ς is, the bigger a firm thinks the impact of increasing I_j on the market-level risk management is. If a firm produces a significant share of the market, it also dictates aggregate market risk. As detailed in subsection 3.2, the government imposes the same I across firms and effectively ensures $\varsigma = 1$.

Figure 5: Wedge in Risk Investment and Welfare under Risk Conjecture



(a) Gap in Risk Investment

(b) Gap in Welfare

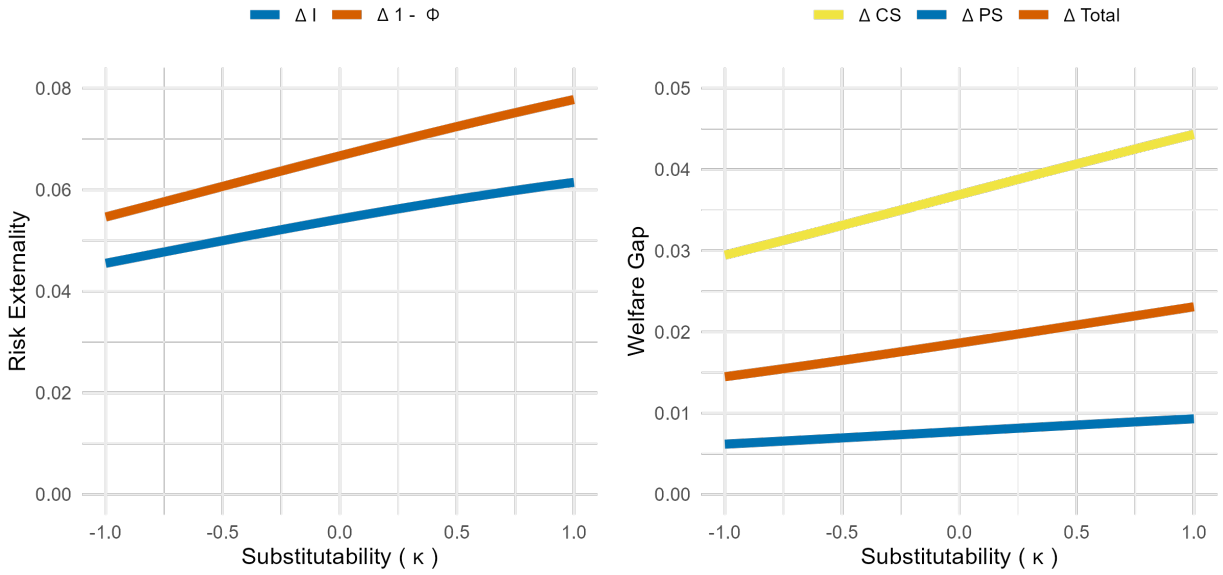
Note: Figure displays results from numerical simulations with respect to risk conjecture parameter ς. Δ indicates the difference between the social planner's solutions and the private firm's. All welfare terms are measured in expectation. All other parameters are set at baseline values: $\lambda = 0.2$, $\varepsilon = 1$, $\eta = 0.7$, $f = 0.3$, $\kappa = 0$, $\xi = \theta = 0$.

As ς increases, the risk-competition effect among firms weakens and firms invest less in risk management because firms can better coordinate their risk in the same way that firms better coordinate in output with larger ξ and θ. The public-private wedge in risk investment, thus, increases as government investment is constant across values of ς. The welfare gain from closing

ΔI^*, as well, increases with CS and PS increasing and profits falling. [15]

A firm's risk management may also affect other firms' risk, not just through the risk conjecture, but physical risk dependence. The animal disease provides a prime example of this risk-dependence among firms, where disease may spread among neighbors (Wang and Hennessy, 2015), and protection by one firm may protect other firms (i.e. creating free-riders). The nature of this dependence may be positive or negative and is captured by κ. Recall that ς affects firm solutions via Φ_{II}, and Φ_{II} depends on κ (see equation (14) for details). The impact of ς hence depends on κ. Varying κ from -1 to 1 characterizes various cases of firm investments being substitutes or complements.

Figure 6: Wedge in Risk Management and Welfare w.r.t to Risk Dependence



(a) Gap in Risk Investment

(b) Gap in Welfare

Note: Figure displays results from 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. All other parameters are set at baseline values: $\lambda = 0.2$, $\varepsilon = 1$, $\eta = 0.7$, $f = 0.3$, $\varsigma = 0.25$, $\xi = \theta = 0$.

Figure 6a suggests that the externality in risk investment increases in κ. When firm investments are complemented, but such interdependence is ignored due to a small ς, the firm tends

[15] The wedge in investment levels off after ς reaches 0.40 because I^*_{firm} stays at the corner solution of zero beyond that point.

to invest even less than the socially optimal level relative to a setting where firm investments are independent. In contrast, if the substitution among firm investments is not fully accounted for due to a small ς, the firm mitigates free-riding and tends to invest more than in a setting of independent investment, narrowing the risk externality.

Figure 6b displays the corresponding welfare gains from policy intervention. The total welfare as well as CS and PS grow in κ with ΔI, intuitively. Note, the change in ΔI and gains in welfare are considerable from $\kappa = +/-1$ to $\kappa = 0$ (i.e., differences of 10-20% relative to values at $\kappa = 0$), indicating the critical role of investment interdependence in measuring the wedge in risk management and return to policy intervention.

6 Concluding Remarks

Increasingly frequent disruptions in the agricultural supply chains inspire various policy interventions in the US and beyond. The interventions may be justified because the socially and privately optimal levels of supply chain resilience differ. Such a public-private wedge exists mainly because the firm does not incorporate the impacts of supply chain disruptions, like food insecurity, on consumer or producer (i.e., farmer) welfare and does not fully incorporate how its risk management affects peer firms.

We are one of the first to model the private and public problems of investing in risk management, specifically, reducing the risk of operational disruptions in the context of agricultural production. Both the private firm and social planner weigh the costs of the risk management behavior with the benefits of more certain market outcomes. Considering the context of agricultural production, the model incorporates inter-firm complementarity and substitution in the investment (e.g., in the case of animal diseases). The model also allows for various degrees of market power in processing/retailing to reflect a key feature of US agricultural markets (Sexton, 2013).

Simulations demonstrate the potential risk externality and the potential welfare gains under a number of plausible market contexts and risk factors. We show that firms may invest less than half

the socially optimal amount in risk management facing high levels of risk, resulting in considerable deadweight loss. The wedge widens as firms form stronger conjectures regarding the risk-reducing investment by peers, effectively obtaining enhanced quantity control in expectation and further distorting the supply. The distribution of welfare returns to policy intervention depends on the structure of the market. Also, contrary to public discourse, a processing/retailing stage with more market power reduces and even flips the risk externality as oligopolistic firms internalize a larger share of the potential losses from disruptions, while the return to policy intervention grows rapidly in market power.

This article conceptualizes the potential risk externality in vertical agri-food supply chains and provides a novel theoretical framework for welfare evaluations of private and public risk management in various market structures. The findings can be generalized to many food markets and reflects a multitude of the operational risks food supply chains may face. Recent studies of agri-food supply chain (Chenarides, Manfredo, and Richards, 2021; Gnutzmann, Kowalewski, and Śpiewanowski, 2020; Hadachek, Ma, and Sexton, 2024; Stevens and Teal, 2024) provide some practical examples of strategies that have the potential to enhance resilience. Future work is needed to empirically measure the potential for risk management activities to generate welfare gains in specific food markets.

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A Mathematical Details

This appendix gives detailed mathematical derivation 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 summation 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 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 is 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 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.

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

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.

Output and investment The other complicated partial derivative is $Q_I=\frac{\partial Q}{\partial I}$ in equation (19). The analytical expression turns out to be:

$$\frac{-\left[AC+BD+E\frac{c+I}{1-\Phi}+F+F\frac{(c+I)\Phi_I}{1-\Phi}\right]Y-\left[a\alpha A^2+(a\beta-\alpha b)AB-b\beta B^2-F(c+I)\right]Y_I}{G^2}, \tag{A9}$$

where $A=1-\frac{X}{\eta}$, $B=1+\frac{H}{\varepsilon}$, $C=\frac{\alpha bH_I}{\varepsilon}+\frac{a\beta H_I}{\varepsilon}$, $D=\frac{\alpha bX_I}{\eta}+\frac{a\beta X_I}{\eta}$, $E=\frac{\alpha X_I}{\eta}-\frac{\beta H_I}{\varepsilon}$, and $F=\frac{\alpha A+\beta B}{1-\Phi}$.

Term $Y = (1-\Phi) + \frac{\Phi}{N}$, $X = (1-\Phi)\xi + \frac{\Phi}{N}$, and $H = (1-\Phi)\theta + \frac{\Phi}{N}$. Accordingly, $Y_I = -\Phi_I\left(1-\frac{1}{N}\right)$, $X_I = -\Phi_I(\xi - \frac{1}{N})$, and $H_I = -\Phi_I(\theta - \frac{1}{N})$. Term $\Phi = \lambda e^{-\gamma(I+\kappa I^2)}$, and $\Phi_I = -\lambda\gamma(1+2\kappa I)e^{-\gamma(I+\kappa I^2)}$. The denominator, G, equals, $Y(\alpha A + \beta B)$.

A3 Public Solution Choosing Investment and Output

If we let the government decide risk-reducing investment as well as firm output, the planner's problem becomes:

$$\max_{I,Q} E[W] = \underbrace{(a-b)(1-\phi(I))Q - (\alpha+\beta)\left[(1-\phi(I))^2 + \frac{(1-\phi(I))\phi(I)}{N}\right]Q^2 - cQ - IQ}_{E[\Pi]} \underbrace{+\frac{\alpha+\beta}{2}\left[(1-\phi(I))^2 + \frac{(1-\phi(I))\phi(I)}{N}\right]Q^2}_{E[CS]+E[PS]}. \tag{A10}$$

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

$$\begin{aligned} (a-b)(1-\Phi) - (\alpha+\beta)\left[(1-\Phi)^2 + \frac{(1-\Phi)\Phi}{N}\right]Q &= c + I; \\ -(a-b)\Phi_I + (\alpha+\beta)\left[(1-\Phi)\Phi_I - \frac{(1-2\Phi)\Phi_I}{2N}\right]Q &= 1. \end{aligned} \tag{A11}$$

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

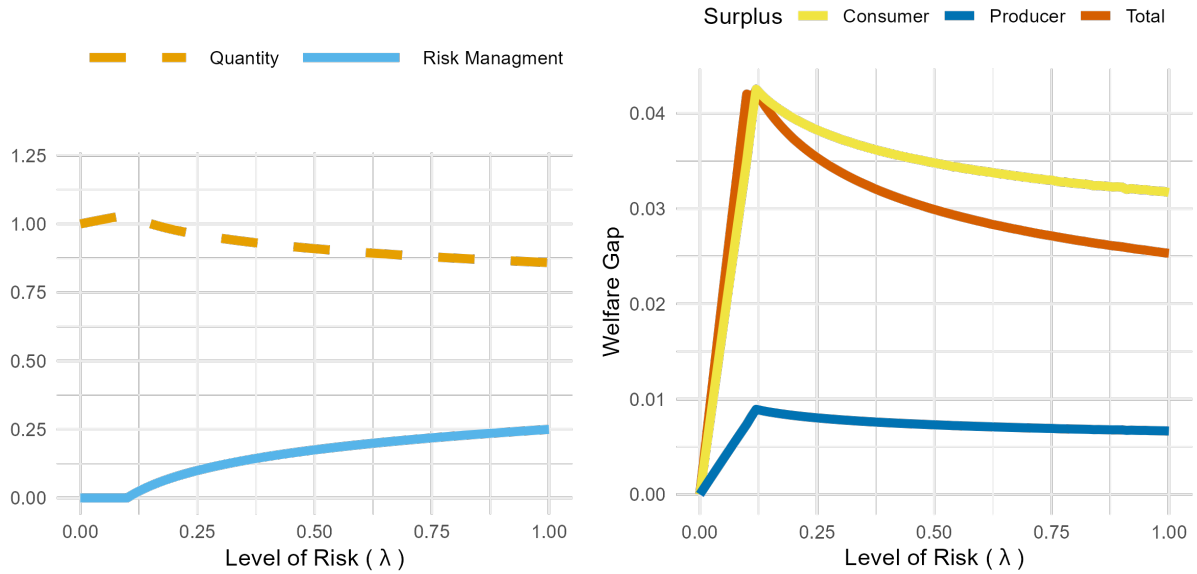
The equilibrium I and Q are displayed in Figure A1. Though the patterns match panel (b) of Figure 3, the equilibrium Q solved from this alternative social planner problem is higher. If there is high market power, the equilibrium Q solved from the alternative setup would be even larger than that from the baseline setup of government decision. This is expected because of eliminating quantity distortion from market power. Thus, the incremental CS and PS would be larger.

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, an increasing social welfare sometimes goes 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.

A4 Risk Technology: γ

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 % reduction in risk for every unit of risk management invested. 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.

Figure A1: Social Planner Solutions: Choosing both I and Q



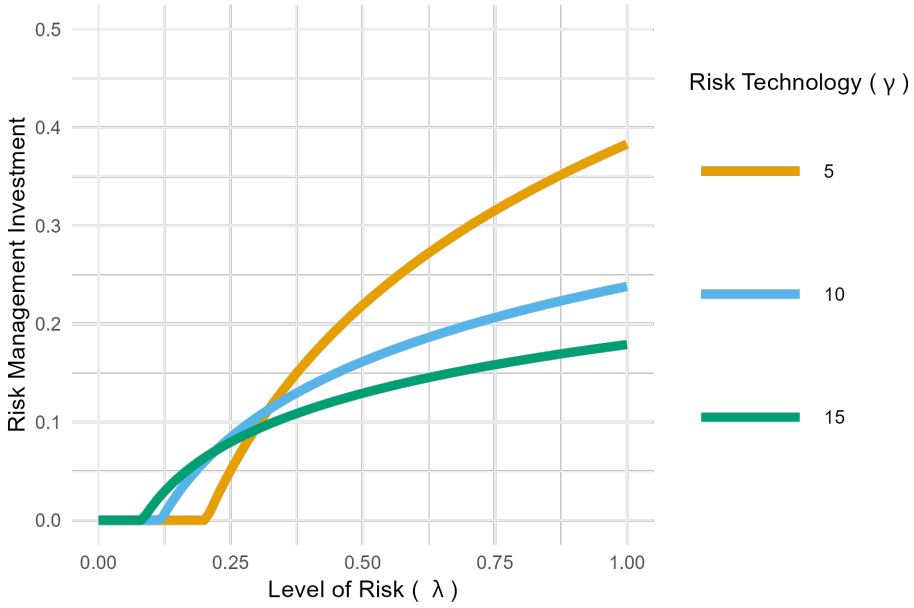
(a) Social Planner's Solutions

(b) Social Planner Welfare Gap

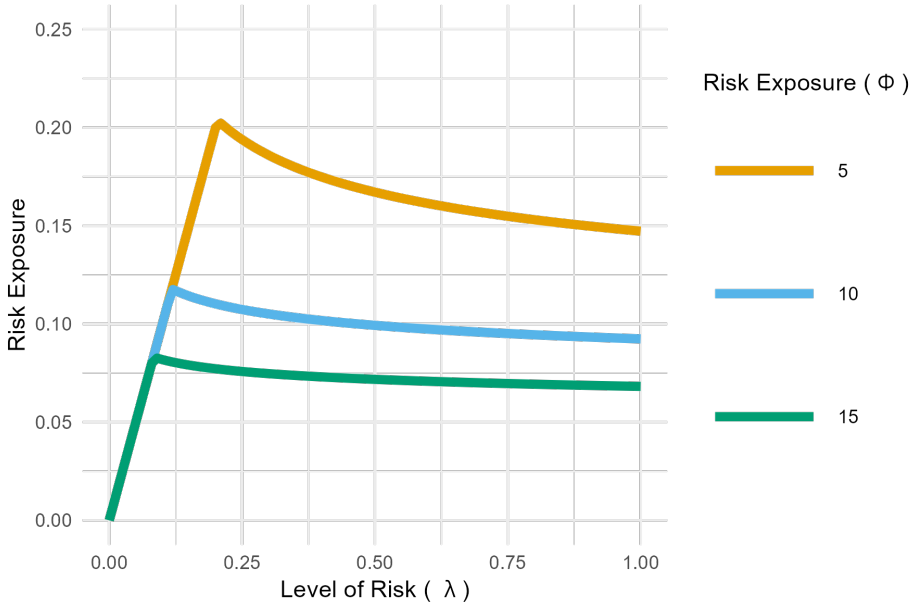
Note: Figure displays results from numerical simulations with respect to the hazard λ. Δ indicates the difference between the social planner's solutions and the private firm's. All welfare terms are measured in expectation. All other parameters are set at baseline values: $\varepsilon = 1$, $\eta = 0.7$, $f = 0.3$, $\varsigma = 0$, $\xi = \theta = 0$.

In practice, γ is difficult to observe and will vary widely with context. At the baseline, we set $\gamma = 10$. However, it is worthwhile noting that different values of γ result in different magnitudes of risk management and risk exposure. As shown in, Figure A2b, risk exposure is proportional for the different values of γ across the spectrum of λ. While the magnitudes may vary in practices from the baseline we choose here, the patterns with respect to the parameters of interest hold for plausible risk technologies.

Figure A2: Firm's Solutions with Different Risk Technologies



(a) Risk Investment



(b) Risk Exposure

Note: Figure displays results from numerical simulations with respect to risk technology parameter γ. 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: $\lambda = 0.2$, $\varepsilon = 1$, $\eta = 0.7$, $f = 0.3$, $\varsigma = 0$, $\xi = \theta = 0$.