Risk Externalities in Vertical Supply Chains

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Abstract

Private firms may under invest in risk management from a social welfare perspective, and this imposes external costs on others linked in the vertical supply chain. We build a theoretical model within the context of agri-food supply chains, where intermediary firms choose quantity of output and the level of costly risk management activities to undertake. The level of risk management is privately determined but affects the welfare of others as shocks propagate throughout the supply chain. We theoretically show that private firms invest in risk management less than the socially optimal level under most plausible market conditions. The findings suggest that policy interventions may be justified to make supply chains more resilient. Simulations further show which types of markets are most vulnerable to the risk externality.

JEL Codes: Q13, Q18, L13, D81

Keywords: agricultural/food supply chain, externality, risk management

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1 Introduction

Supply chain disruptions have become increasingly frequent in recent years. In response, governments have discussed and have implemented a variety of policy interventions to make supply chains more resilient to shocks in the future (Elliott and Golub, 2022). Food markets in particular garner attention in these discussions since recent disruptions have resulted in stock-outs or elevated prices of staple food products (Hobbs, 2021; Hobbs and Hadachek, 2024). These events affect agents at each stage of the supply chain, including private firms that can endogenously reduce their exposure through risk management strategies. A critical open question for policy making, however, is whether private firms arrive at a socially efficient level of risk management or whether there is justification for public intervention.

We model a vertical supply chain in the context of US food supply chains, where intermediary processing firms face operational risks that threaten their ability to produce, deliver, or sell their final product to the retail market. We use this framework to examine the wedge between the private (i.e., *laissez faire*) and the socially optimal equilibria of risk management and the market determinants of the wedge. We also quantify the returns to social welfare from closing the public-private wedge in risk management and discuss the policy implications.

In our model, firms in the middle of the supply chain anticipate disruptions with an endogenous hazard probability. Prior to the realization of the hazard, each firm chooses its expected profit-maximizing level of output and risk management activities that reduce their exposure to disruptions. Firms internalize the benefits of costly risk management through sustained production and profit when shocks occur. We impose flexible assumptions about competition in our context in the style of the Flexible Oligopology/Oligopsony Market (FOOM) model, which allows us to map equilibrium outcomes under a spectrum of market structure parameters.

Next, we turn to the social planner's perspective in a two-stage framework, where the social planner chooses the level of risk management that maximizes social welfare (i.e., consumer surplus, profit of intermediaries, and producer surplus) given firm outputs. In the second stage, given the risk-environment set by the social planner, firms choose profit-maximizing outputs.

We show that the socially efficient level of risk management may deviate from the private firm because the social planner internalizes the benefits of firm-level risk management that accrue to the consumer and raw input supplier (e.g., farmers). Hence, even with a risk-neutral consumer, a wedge may exist between the firm's private solutions and the social planner's.

Intuitively, this wedge 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 (Baldwin and Freeman, 2022). This public-private wedge is particularly relevant to agricultural and food supply chains for several reason: (i) Food supply chains have become increasingly consolidated and specialized over time, and therefore, even a shock to a single firm may have market-level impacts and may be exacerbated in the case of simultaneous, correlated shocks (Hadachek, Ma, and Sexton, 2024). (ii) Many major food products are perishable and have limited shelf life, limiting the storage of products in the case of shuttered production. (iii) Food supply chains play a primary role in preventing food insecurity (i.e., social losses) following catastrophic shocks.

Few studies, however, have conceptualized or measured this externality. Perhaps most similar to our work is the literature on storage and commodity price-stabilization policies (Wright, 1979; Miranda and Helmberger, 1988; Gouel, 2013). A commonality across these early models is the role of storage, either public or private, that could carry inventory from one period to the next, whereby the storer may purchase products during price downswings and sell the product at a future time, smoothing price and quantity across idiosyncratic shocks. These articles generally show that there are societal welfare gains from such stabilization in the short-run, but it lowers surpluses in the long-run as the stored inventory is released to the market. While public buffer stocks have not been a common proposal to today's food supply chain resilience challenges, their goals and rationale are similar to other policies being discussed.

Not all supply chain risks, however, can be quelled by storage infrastructure. Infectious animal and plant diseases also threaten food supply chains, and when present, can impact large shares of the market (Schlenker and Villas-Boas, 2009; Spalding et al., 2023). Shocks of this nature may simultaneously shift supply and demand and market outcomes may be volatile and uncertain. Mitigating these risks involves *ex ante* preventative efforts, like biosecurity measures, to stamp out a threat before it escalates. These efforts may be substitutes, whereby investment from one farm reduces the risk to disease events to all other neighbors (Hennessy and Marsh, 2021). In this case, farms may underinvest in disease prevention due to the free-rider problem.

Given recent global supply chain pressures, economic modellers have given renewed attention to the concept of resilience in vertical supply chains stemming from geopolitical and macroeconomic shocks. Generally, recent articles show that supply chains, when left to operate without government interference, will yield socially inefficient outcomes (Baldwin and Freeman, 2022; Grossman, Helpman, and Lhuillier, 2023; Capponi, Du, and Stiglitz, 2024). These articles focus on new dimensions of resilience, such as, sourcing inputs domestically or internationally (Grossman, Helpman, and Lhuillier, 2023), networks and bargaining between other agents (Grossman, Helpman, and Sabal, 2023; Acemoglu and Tahbaz-Salehi, 2024), capital investments (Capponi, Du, and Stiglitz, 2024), and spatial diversification (Castro-Vincenzi et al., 2024). The key innovation and commonality in these models is the endogenous and costly firm-choice to structure supply chains in alternative ways.

The framework set forth in this article is similarly motivated to uncover social efficient levels of resilience, but we deviate in a few key ways: i) Our framework is presented through the lens and the context of agri-food supply chains. ii) In light of the agri-food supply chain focus, we incorporate flexible assumptions about market power without specifying a particular form of competition. Instead, market-power in our model is determined along a spectrum between perfect competition and monopolistic markets, which is convenient for modelling the differing extents of market power present in modern agri-food markets (Crespi and MacDonald, 2022). iii) We generalize the investment decision made by the firm, making our model applicable to the wide array of risk management decisions a firm may undertake. iv) We study the interactions of these decisions among firms and government intervention and explore the different cases of complements, substitutes, and independent resilience investment decisions.

We simulate over values of four risk and market parameters to match a range of agri-food markets. First, we establish as a baseline, that a risk externality does exist in vertical supply chains for sufficiently large risks. For the highest levels of risks that firms face, we find that firm's optimal strategy is to invest 8.0 cents into risk management for every dollar in revenue earned. Facing the same risks, the social planner, in contrast, would invest 19.5 cents into risk management. The difference between the two reflects the externality borne by consumers and producers along the supply chain, resulting in a lower total market welfare in the private market than the social planner's equilibrium.

The interdependence of firm investments play a critical role, too. In particular, when the investments are substitutes, the free-rider problem adds to the externality of risk management by firms and enlarges the public-private wedge in resilience investment. We further show that as the risk-reducing technology improves sufficiently, firms move closer to the socially optimal levels risk management. This implies that there could be substantial societal returns in the form of risk reduction to government investment in resilience-enhancing technology and mitigation efforts. Lastly, as market power increases, the risk externality actually decreases given that firms internalize a larger share of the market surplus lost from shocks and are more heavily incentivized to protect throughput.

The remainder of the article is organized as follows: Section 2 builds the base vertical supply chain model and outlines analytical solutions. Section 3 assigns parameter values for market characteristics and structures. Section 4 presents results from simulations over four market and risk parameter values. Section 5 discusses key findings and concludes.

2 Model

We consider a two-stage supply chain with M farms and $N < M$ homogeneous processors/retailers, providing food to consumers.[1] The model assumes fixed proportions in production throughout the supply chain, such that a given volume of the farm product is required to produce a unit of the consumer good. Given fixed proportions, the output produced at each stage of the supply chain can be equalized given appropriate measurement units and is denoted by Q.

To allow for the buyer power exercised by the processor/retailer (hereafter, the firm), we specify the inverse supply function of farmers as:

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

where X denotes supply shifters. Similarly, to allow for the exercise of seller power, the inverse consumer demand for the processed product is:

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

where Y contains demand shifters.

Each risk-neutral firm faces a hazard of shutdown, $\phi \in (0, 1)$, due to various operational risks such as fire outbreak, failing to obtain key inputs, and human diseases.[2] The key innovation to the traditional model is that investments to resilience are endogenous to the firms (but are exogenous to other agents in the supply chain), including adding prevention facilities, building slack capacity, and health protection. Denote the per-unit investment by

[1] Consistent with past supply-chain models, e.g., Gardner (1975), Wohlgenant (1989), Sexton (2000), we assume an integrated processing-retailing sector.

[2] Rather than a few firms fully shutting down, it is equivalent to interpret all firms experiencing a partial shutdown from the same shock and losing ϕ share of their product.

I_j for firm j.

We allow for the model flexibility that individual investments can be technical complements or substitutes to each other. When the firm investments are complements (substitutes), we have $\frac{\partial^2 \phi}{\partial I_j \partial I_k} < 0$ ($\frac{\partial^2 \phi}{\partial I_j \partial I_k} > 0$). Intuitively, the marginal reduction in the hazard by increasing I_j by one unit is larger if I_j and I_k reinforce each other or are complements, and *vice versa*.

In practice, investments are complements if, for instance in the livestock supply chain, investments by a feedlot's neighbors may complement the feedlot owner's investment: because it is the weakest link that determines the outbreak of a disease, the owner's marginal return from investing increases in neighbors' investments. Investments may also be substitutes, for example, when investments by neighbors lower ϕ for the owner.

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

$$\max_{q_j, I_j} E[\pi_j | \phi(I)] = E[(P^r(Q) - P^f(Q))q_j | \phi(I)] - cq_j - I_j q_j, \tag{3}$$

where $Q = \sum_{j=1}^{N} q_j$ and c is the constant marginal cost of processing and retailing.[3] The per-unit cost of risk management, I_j, are exclusive to the other marginal production costs.

Depending on whether firm j shuts down, the status-contingent profit changes. When the firm survives the hazard of ϕ, it earns $E[\pi_j] = E[P^r(Q) - P^f(Q)]q_j$, where $Q = qN$ and the probability density function (pdf) of N follows a Binomial distribution of $N \sim \text{Bin}(N, 1-\phi)$. When the firm shuts down, it earns zero profit. Thus, the objective function is rewritten as:

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

[3] Fixed costs are irrelevant to the short-term production decision of interest and hence omitted.

When demand and supply curves are linear, which we assume in this article for simplicity, the expected retail and farm prices essentially depend on the expected Q. The expected Q equals $E[\sum_{j=1}^{N} q_j] = \sum_{j=1}^{N} E[q_j]$. Thus, $E[Q] = (1-\phi)Q$. We rewrite the objective function of the firm:

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

2.1 Private Equilibrium

The equilibrium by letting firms choose q_j and I_j can be found by taking the first-order-conditions with respect to Equation 5, respectively.

$$\begin{gathered}[\frac{\partial P^r}{\partial Q}\frac{\partial Q}{\partial q_j/q_j} - \frac{\partial P^f}{\partial Q}\frac{\partial Q}{\partial q_j/q_j}](1-\phi)^2 + \Delta P(1-\phi) = c + I_j \\ [-\frac{\partial P^r}{\partial Q/Q} + \frac{\partial P^f}{\partial Q/Q}]q_j\phi^{'}(1-\phi) - \Delta P\phi^{'} = q_j,\end{gathered} \tag{6}$$

where $\Delta P = P^r((1-\phi)Q) - P^f((1-\phi)Q)$ and $\phi^{'} = \frac{\partial \phi}{\partial I_j} < 0$. The left-hand-side (LHS) of the first equation here is the marginal profit from producing one more unit of product with $(1-\phi)$ reflecting how much of the additional unit of output is expected to realize under the shutdown risks.

Rewrite the two equations with symmetry in equilibrium, we have:

$$\begin{gathered}(1-\phi)P^r[1 - \frac{(1-\phi)\xi}{\eta}] = (1-\phi)P^f[1 + \frac{(1-\phi)\theta}{\epsilon}] + c + I \\ -\phi^{'}P^r[1 - \frac{1-\phi}{\eta}] + \phi^{'}P^f[1 + \frac{1-\phi}{\epsilon}] = 1.\end{gathered} \tag{7}$$

where θ and ξ are equal to $\frac{\partial Q}{\partial q}\frac{q}{Q}$ 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), and 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 price competition behaviors (e.g. Cournot-Nash or tacit collusion) and does not require us to impose a specific form of market competition. $\eta > 0$ is the absolute demand elasticity evaluated at the market equilibrium, and $\epsilon > 0$ is the farm supply elasticity evaluated at the market equilibrium. Prices are evaluated at $(1-\phi)Q$.

The left-hand-side (LHS) of the first equation in system 7 represents the processor's perceived net marginal revenue (PMR) from selling an additional unit of the final product, while the right-hand-side (RHS) is its perceived marginal cost (PMC) of acquiring an additional unit of the farm product. Similarly, the LHS of the second equation here represents the marginal return from investing one more dollar in improving resilience, while its RHS is the marginal cost of doing so.

2.2 Public Equilibrium

A social planner who maximizes the expected social welfare has a different objective function. Here, we let the social planner determine the optimal level of risk management, and firms choose output given the planner's risk management. 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 $\int_0^Q P^r(q) - P^r(Q)dq$ where the market output, $Q = q * N$, varies with the realization of shutdown hazard ϕ and follows a Binomial distribution of $N \sim \text{Bin}(\bar{N}, 1-\phi)$. Similarly, the PS equals $\int_0^Q P^f(Q) - P^f(q)dq$.

Given the resilience investments, firms choose the outputs:

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

where superscript $*$ indicates the investments and hazard probability determined by the social planner and $\Delta P(\phi^*) = P^r((1-\phi^*)Q) - P^f((1-\phi^*)Q)$. Taking the first-order-condition, we find Q^* as a function of I. Plugging Q^* to Equation 8, the two-stage game is then solved by backward induction.

2.3 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 is captured by a rectangular determined by the equilibrium Q.

We impose an exponential hazard function that has long been used in a variety of context to measure 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 $\lambda \in (0,1)$ sets the maximum hazard rate.

This hazard function 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 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 Appendix A for details). If $\kappa = 0$, the private investments are independent from each other.

For $\kappa \in [-1,1]$, $\frac{\partial \phi}{\partial I_j} \leq 0$ and $\frac{\partial^2 \phi}{\partial^2 I_j} \geq 0$, which implies that the hazard rate is decreasing in own-firm's investment at a decreasing rate. These are both realistic properties within the context of risk management, and the latter ensures that the hazard rate cannot be negative.

Private solutions Due to symmetry among the firms, we know that firm outputs and investments would be identical in equilibrium. We rewrite the first condition in Equation 7 as:

$$\begin{aligned}(1-\Phi)[1-\frac{(1-\Phi)\xi}{\eta}][a-\alpha(1-\phi)Q)]\\ =(1-\Phi)[1+\frac{(1-\Phi)\theta}{\epsilon}][b+\beta(1-\phi)Q]+c+I,\end{aligned} \tag{13}$$

where $\Phi = \lambda e^{-\gamma(I+\kappa I^2)}$ and I is the symmetric investment by a firm. The second condition in Equation 7 becomes:

$$-\Phi^{'}(1-\frac{1-\Phi}{\eta})[a-\alpha(1-\phi)Q)]+\Phi^{'}(1+\frac{1-\Phi}{\epsilon})[b+\beta(1-\phi)Q]=1, \tag{14}$$

where $\Phi^{'} = -\lambda\gamma(1+\kappa I)e^{-\gamma(I+\kappa I^2)}$. Due to the nonlinearity in the hazard probability, there is no easy analytical solution for I and Q to this system of equations. We rely on numerical solutions in section 4.

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

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

We have the equilibrium output:

$$Q^* = \frac{a[1-\frac{(1-\phi^*)\xi}{\eta}] - b[1+\frac{(1-\phi^*)\theta}{\epsilon}] - \frac{c+I^*}{1-\phi^*}}{\alpha(1-\phi^*)[1-\frac{(1-\phi^*)\xi}{\eta}] + \beta(1-\phi^*)[1+\frac{(1-\phi^*)\theta}{\epsilon}]}. \tag{16}$$

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

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

where $E[\Pi(Q(I), I)] = \sum_{j=1}^{N} E[\pi_j]$ 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 $Q = q \times N$.

Given the linear demand and supply functions and solutions found in equation A2, the objective function for the government can be rewritten as:[4]

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

Given the symmetry in solution, the first-order-condition is:

$$\begin{aligned}-(a-b)\Phi' Q + (a-b)(1-\Phi)Q' + 2(\alpha+\beta)Q[\Phi'(1-\Phi) - (1-\Phi)^2 Q'] \\ -(\alpha+\beta)[\Phi'(1-\Phi) - \frac{\Phi'(1-2\Phi)}{2N}]Q^2 + (\alpha+\beta)[(1-\Phi)^2 + \frac{\Phi(1-\Phi)}{N}]QQ' \\ -cQ' - Q - IQ' = 0\end{aligned} \tag{19}$$

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

[4]Note that $E[Q(I)^2] = E[q^2 N^2] = q(I)^2 E[N^2] = q(I)^2 N^2 \left[(1-\phi)^2 + \frac{(1-\phi)\phi}{N}\right]$

3 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 $f = 1 - c$. This farm price is the farm share of the normalized retail value of a unit of the product under perfect competition. The total competitive farm output is also 1.0. Thus, $\beta = \frac{f}{\epsilon}$ and $b = f(1 - \frac{1}{\epsilon})$, where ϵ is the farm price elasticity of supply at the competitive equilibrium. Values for ϵ and η are set based on the literature for the meat and livestock markets as described in Table 1. Since the meat processing sector is approximately a four-firm oligopoly Garrido et al. (2021), we set $N = 4$. Under Cournot price competition, this implies $\xi = \theta = 0.25$.

The remaining parameters relate to the nature of risk and the hazard function. We start by studying risk strategies that are independent from firm to firm ($\kappa = 0$), but later relax this assumption. 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 1a demonstrates the impact of risk management on $1 - \Phi$ for three values of λ. As a baseline, we set $\lambda = 0.5$ such that the risk are sufficiently large that firms are conscious and motivated to protect against them.[5]

Lastly, the value of γ captures the effectiveness of strategies or technology in reducing risk exposure. Equivalently, γ can be interpreted as the "semi-elasticity of risk management" (i.e., percent reduction in risk with respect to a unit change in I with $\kappa = 0$).[6] The value of this parameter in reality will be context and strategy dependent. Some risks may be more

[5] 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 about 40%. Given that meat processors likely engaged in some level of risk management pre-COVID-19, the pandemic could have had a much more devastating effect in absence of those strategies. Therefore, a value of $\lambda = 0.5$ is large, but not unrealistic given recent experiences.

[6] For our hazard function ϕ, the term $\frac{\partial \phi}{\partial I}\frac{1}{\phi}$ is equal to γ if $\kappa = 0$.

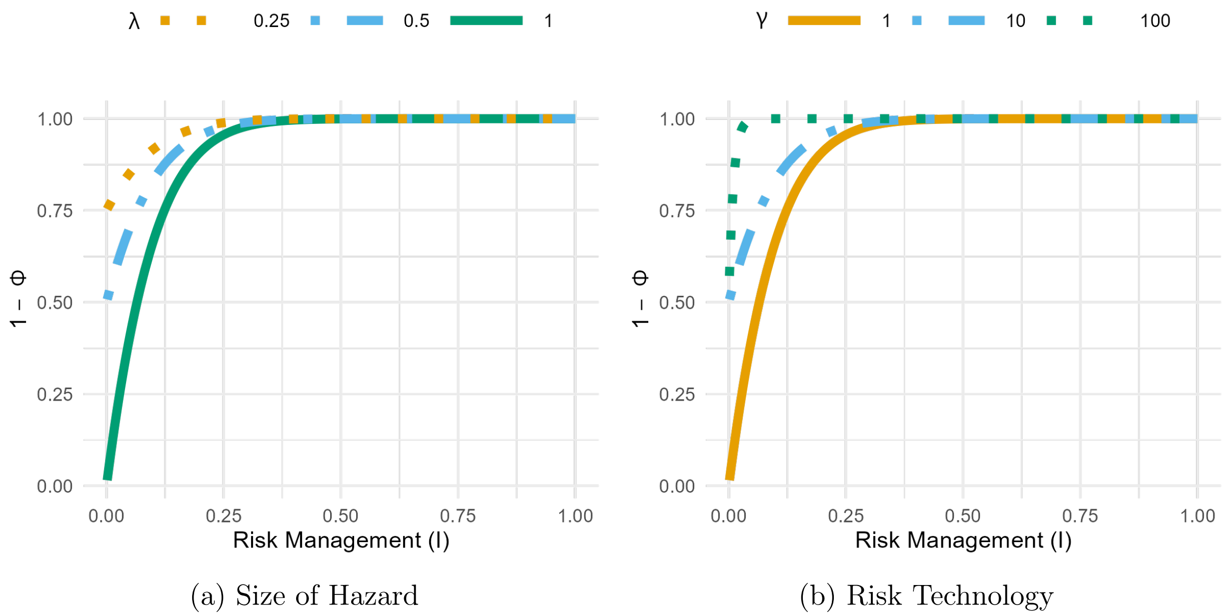


Figure 1: Changes in Hazard Rate with Respect to Different Risk Parameters

cheaply avoided (higher values of γ), while others may be difficult or impossible to influence (low values of γ).

Figure 1b demonstrates the shape of the hazard function for different values of γ. Since there is 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 $I = 0.1$, an increase in risk management expenditure by 1% causes risk exposure (ϕ) to fall by 1%.

4 Simulation Results

We discuss the simulation results in this section. We start with the magnitude of the private-public wedge in investment and how the wedge varies with hazard probability and the interdependence of investments. We also examine the role of resilience technology and market power in determining the private-public wedge. The wedge in investment translates to *foregone* social welfare if relying fully on firm choices and can account for as much as 10-15% of

Parameter	Description	Baseline Value
λ	Impact of shock without risk management	0.5
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
c	Processing and retailing marginal costs	0.7
ξ/θ	Intermediary market power	0.25
N	Number of firms	4

Table 1: Baseline Parameter Values

the total risk-free welfare under perfect competition.

4.1 Level of Risk: λ

Our model does not presume the nature nor magnitude of operational risk faced by the firm, but instead it is generalizable to the array of contexts and risks that supply chains may face. The only implicit assumption regarding the nature of risks is that private or public intervention can reduce risk exposure to some extent. Therefore, we start by determining how the level of risk that firms face impacts their production and risk management behavior.

In our model, the parameter $\lambda \in [0, 1]$ determines the expected size of risk that firms face without risk management interventions. Isolated and small threats to output will take a value close to 0, whereas catastrophic and cascading risks will take values closer to 1. For a given shock, the magnitude of λ depends on long-term public investment in risk management; better infrastructure is the smaller λ tends to be.

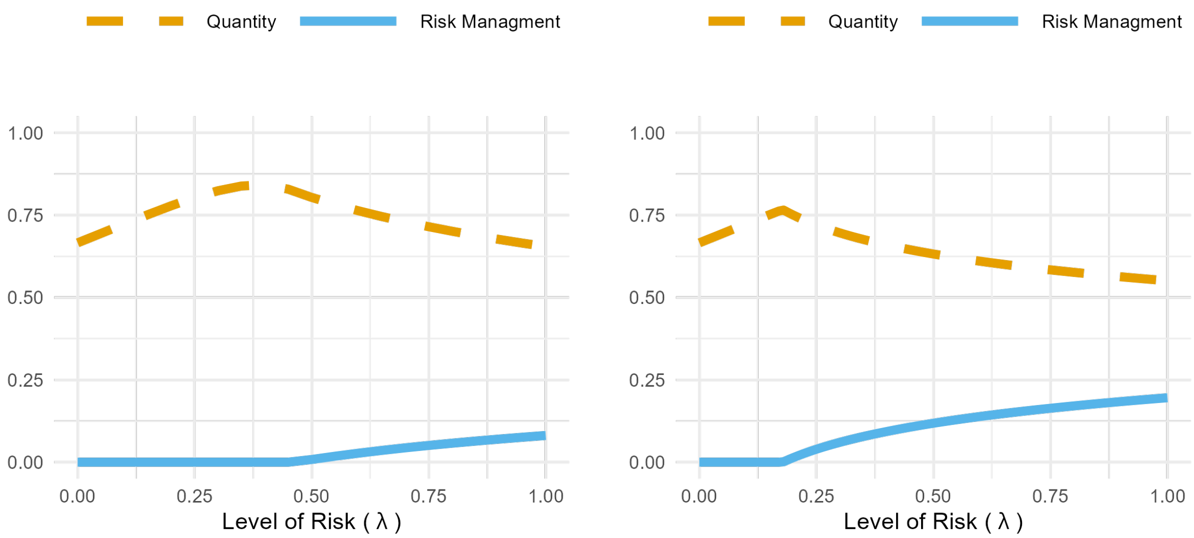
Given our baseline conditions, our first set of results demonstrates that socially optimal risk management exceeds what will be achieved in the private equilibrium for most cases of risks. Figure 2 illustrates these findings. Panel (a) demonstrates that for sufficiently small risks ($\lambda < 0.47$), the firm's optimal strategy is to not invest in risk management (i.e. the corner solution). As the expected magnitude of risk increases past the corner solution threshold, their optimal risk management strategy is increasing in λ. For the very largest risks ($\lambda = 1$), they invest about about 8% of the normalized competitive market price into risk management expenses. For more modest risks ($\lambda = 0.5$), businesses spend much less, about 0.8% of the normalized price, reflecting the nonlinearity in the hazard rate. 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 (Wikinson, 2019). This aligns very closely with our findings when $\lambda \approx 0.5$.

The level of risk and risk management also carries implications for optimal quantity for firms. For small values of λ, equilibrium quantity is increasing in λ. This is due to the fact that as downside risk increases, firms produce more to shield against the rising potential losses.[7] As risk management expenses move off the corner and increases, firms produce less (i.e., Q^* falls), because they are decreasing their expected downside loss through investing in risk management.

For the social planner, similarly, the optimal investment is zero for sufficiently small risks ($\lambda < 0.20$). This threshold, importantly, is lower than that for the firms, indicating a range of λ where the optimal public investment in resilience would be strictly positive and the optimal private investment remains at zero. Said differently, the social planner engages in risk management for more modest risks that firms do not on their own accord. Then, as λ increases, the size of the risk externality grows quickly at first, and then plateaus once firms move from the corner solution but is still slightly increasing with respect to the size of risk. The public-private wedge in resilience investment, $\Delta I^* = I^*_{gov} - I^*_{firm}$, is plotted in Figure 3a.

Figure 3b plots the net welfare gains from moving from private to public levels of

[7] This stands in contrast to the findings of Sandmo (1971), who 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.



(a) Private Solutions

(b) Social Planner's Solutions

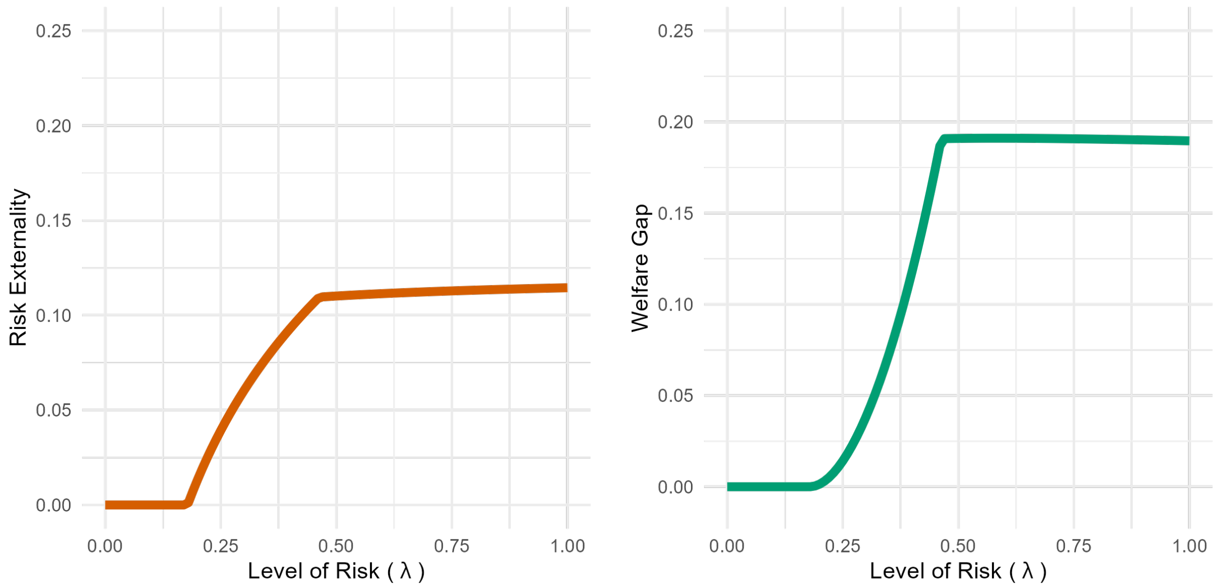
Figure 2: Model solutions across different levels of risk

risk management, namely, $\Delta E[W] = E[W|I^*_{gov}] - E[w|I^*_{firm}]$. As the wedge in investment widens, the potential welfare gains from government intervention increase, too. However, for sufficiently large risks (i.e., $\lambda > 0.47$, $\Delta E[W]$ falls slightly with the widening investment wedge. The potential welfare gains fall because $E[W|I^*_{gov}]$ decreases with a large $\lambda > 0.47$ at a faster rate than ΔI^* rises. The $\Delta E[W]$ is about 0.19 or $\frac{0.19}{(a-b)\times Q^c} = 7.8\%$ of the risk-free and competitive social welfare (hereafter, W^*), which is economically significant.

4.2 Investment Interdependence: κ

The interdependence among firm investment also affects the risk externality. Figure 4a plots ΔI^* against κ in the range of $[-1, 1]$. As shown in Appendix A, when κ is negative (positive), firm investments are substitutes (complements). As κ increases, ΔI^* falls monotonically and slowly. When κ increases from -1 to 1, ΔI^* decreases by some 10%.

The externality is larger, when firm investments are substitutes because of another source of market failure at play; firm j tends to free-ride on other firms' investments and thus under-invest even more in equilibrium. When firm investments are complements, each



(a) Risk Externality

(b) Potential Welfare Gains

Figure 3: The Wedge Between Socially Optimal and Private Risk Management

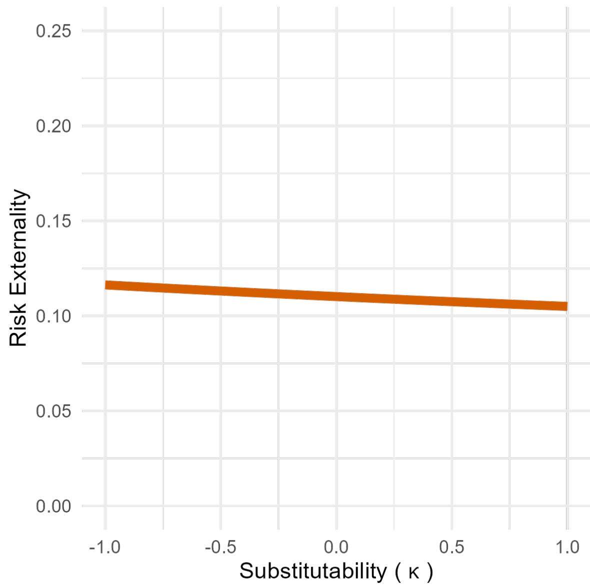
firm is incentivized to increase investment as others increase their investment, resulting in relatively large equilibrium investment by firms.

Figure 4b plots the potential welfare gains, $\Delta E[W]$, against the parameter of interest. Compared against the public-private wedge in investment, $\Delta E[W]$ changes in κ in the opposite direction. This again is because I^*_{gov} and hence $E[W|I^*_{gov}]$ increases as κ goes from negative to positive, which overwhelms the narrowing ΔI^*. The largest potential welfare gains account for as much as 8.6% of W^*.

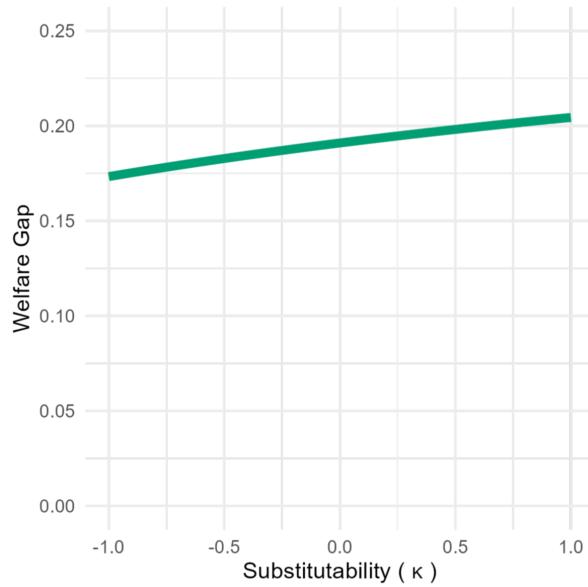
4.3 Resilience Technology: γ

An underlying assumption of section 2 is that firms and governments can have a meaningful influence on their risk exposure. As discussed in section 3, γ measures the "semi-elasticity of risk management" without investment interdependence. Everything else the same, a larger γ suggests a more efficient technology in hazard mitigation.

When γ is smaller than 1.75, the return to investing in resilience is so small that both public and private choose not to invest at all. The wedge hence is also zero. As the



(a) Risk Externality



(b) Potential Welfare Gains

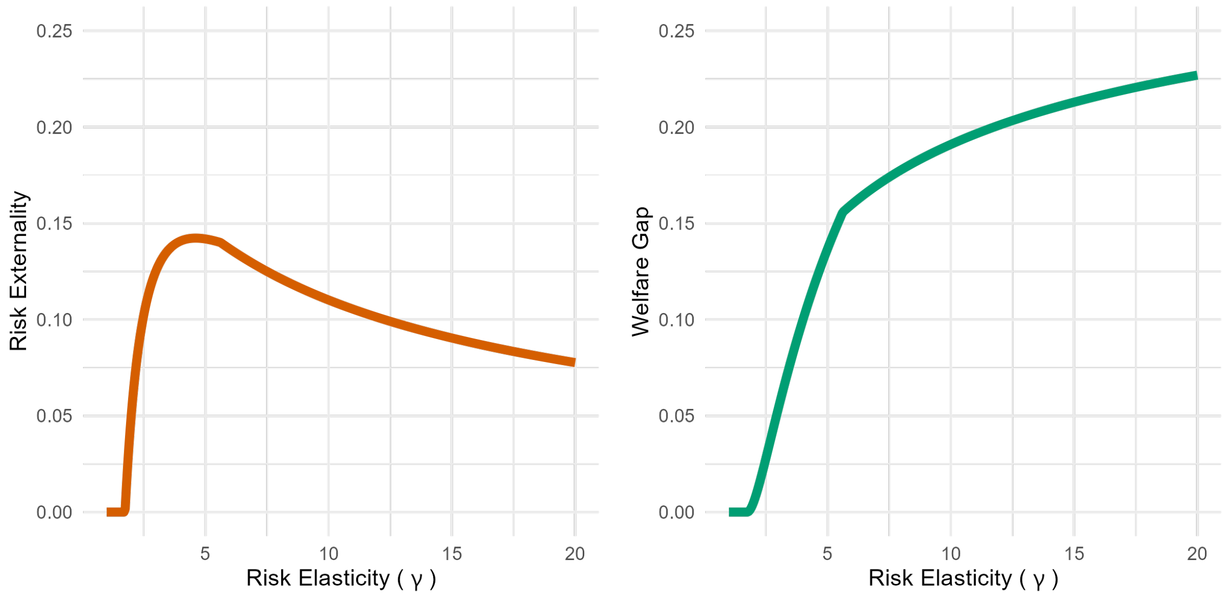
Figure 4: Changes w.r.t Risk Management Interdependence (κ)

technology becomes more efficient, the government begins to invest in resilience before firms do. The wedge grows, therefore, at a decreasing rate and reaches a peak at $\gamma = 3.61$. As γ increases further, the wedge narrows, reflecting the fact that the firm investment grows at a faster speed than the government investment in response to more efficient technology.

Figure 5b shows that $\Delta E[W]$ moves in the same direction with ΔI^* until γ reaches 3.61. After that point, the increase in $E[W|I^*_{gov}]$ due to more efficiently technology outpaces the decrease in ΔI^*, resulting in increasing $\Delta E[W]$. When γ equals 20, the potential welfare gains from government intervention is as large as 9.5% of W^*. From policy perspective, this suggests that the benefit from government intervention tends to be larger when more efficient risk-reducing technology is available, though the degree of intervention is likely smaller.

4.4 Market Power: ξ / θ

Finally, the role of seller and buyer market power in driving the risk externality is illustrated by Figure 6a. The public-private wedge narrows as ξ and θ increases. The decrease accelerates, especially after ξ and θ reach 0.10 or $N = 10$.

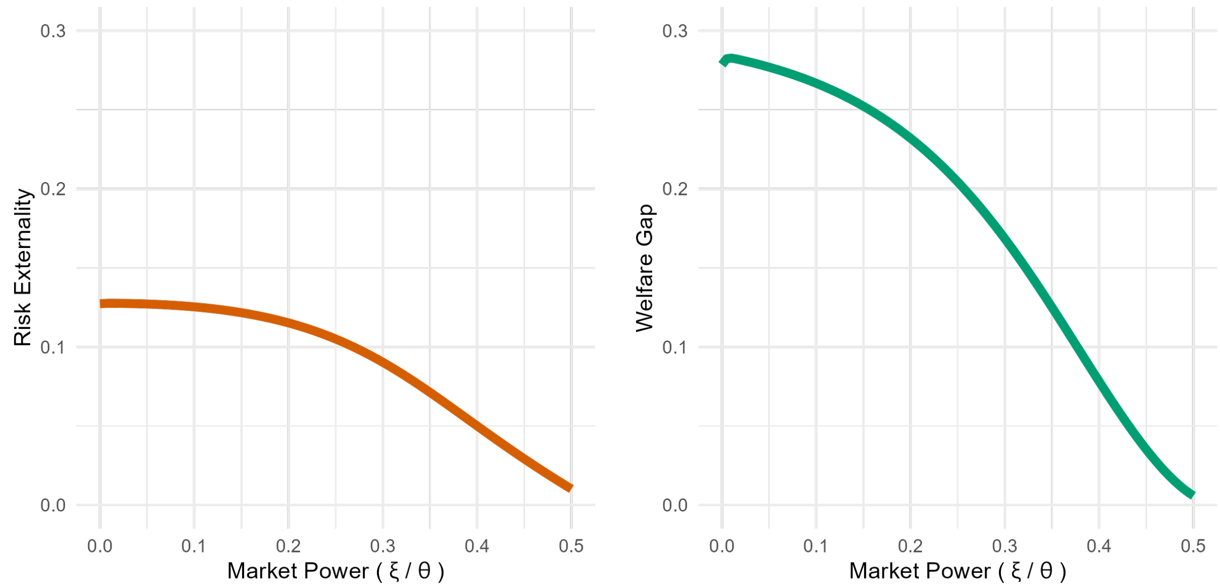


(a) Risk Externality (b) Potential Welfare Gains

Figure 5: Changes w.r.t. Risk Elasticity (γ)

The wedge as well as the potential welfare gains (see Figure 6b) decrease in ξ and θ because firms with greater market power more fully internalize the externality of supply-chain hazard. In fact, the decrease in wedge is merely a consequence of CS and PS that shrink in greater market power exercised by firms. As CS and PS have decreased shares and the total firm profits has a larger share in the social welfare, the government objective function converges with the firm objective function. As a result, the optimal public and private choice of resilience investments converge.

Importantly, this should not be read as evidence against government intervention in markets with dominant firms in general; this is only evidence that potential returns to government intervention in risk management tend to be low in markets with dominant firms. Government intervention that aims at increasing efficiency, CS, and PS in such markets, for instance, may still generate considerable gains (see Hadachek, Ma, and Sexton (2024) for discussion on the role of market power in efficiency of supply chains).



(a) Risk Externality

(b) Potential Welfare Gains

Figure 6: Changes w.r.t Market Power (ξ / θ)

5 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 social and private-firm optimal levels of supply chain resilience differ. Such a public-private wedge exists mainly because firms do not incorporate impacts of supply chain disruptions, like food insecurity, on consumer welfare. The wedge, however, has not been quantified based on up-to-date empirical findings of its key determinants.

Our supply-chain model characterizes private and public problems of investing in enhancing resilience, namely, reducing the hazard of ceasing operation. Considering the context of agricultural production, the model incorporates inter-firm complementarity and substitution in the investment. 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 potential welfare gains under a number of market contexts and risk factors. We show that firms may invest less than half the socially optimal amount in risk management activities high levels of risks, resulting in considerable welfare losses. Also, contrary to public discourse, a processing/retailing stage with more market power reduces the risk externality as oligopolistic firms internalize a larger share of the potential losses from disruptions, though the total welfare falls in the exercise of market power as well.

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 interventions. The policy attention regarding supply chain resilience is economically and socially justified under a wide range of plausible market conditions. This finding can be generalized to all food markets and reflects a multitude of the operational risks supply chains may face. Recent studies of agri-food supply chain (Gnutzmann, Kowalewski, and Śpiewanowski, 2020; Chenarides, Manfredo, and Richards, 2020; Hadachek, Ma, and Sexton, 2024; Stevens and Teal, 2024) provide some practical examples of strategies that have potential to enhance resilience. However, future work is needed to empirically measure the potential for risk management activities to generate welfare gains that match specific strategies and food markets.

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A Mathematical Details

This appendix gives detailed mathematical derivation of 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

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

A2 Partial Derivatives

For the parameterized hazard in subsection 2.3, 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:

$$
\begin{aligned}
&\frac{\partial - \lambda\gamma(1+\kappa\bar{I})e^{-\gamma(I_j+\kappa I_j\bar{I})}}{\partial \bar{I}} \\
&= -\lambda\gamma\kappa(1-\gamma I-\gamma\kappa I^2)e^{-\gamma(I_j+\kappa I_j\bar{I})}
\end{aligned}
\tag{A5}
$$

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.

The other complicated partial derivative is $Q' = \frac{\partial Q}{\partial I}$ in Equation 19. The analytical expression turns out to be:

$$
\frac{-A + C(1-\Phi) + (AB+3CD)\Phi' - 2BC(1-\Phi)\Phi' + E(1-\Phi)^2\Phi' - 2AD\frac{\Phi'}{1-\Phi}}{F^2}, \tag{A6}
$$

where $A = \alpha+\beta$, $B = a-b$, $C = \frac{\alpha\xi}{\eta} - \frac{\beta\theta}{\epsilon}$, $D = c+I$, $E = \frac{a\alpha\xi^2}{\eta^2} - \frac{a\xi\beta\theta}{\eta\epsilon} + \frac{\alpha\xi b\theta}{\eta\epsilon} - \frac{b\beta\theta^2}{\epsilon^2}$, $F =$

$\alpha(1-\Phi)[1-\frac{(1-\Phi)\xi}{\eta}]+\beta(1-\Phi)[1+\frac{(1-\Phi)\theta}{\epsilon}]$, $\Phi=\lambda e^{-\gamma(I+\kappa I^2)}$, and $\Phi'=-\lambda\gamma(1+\kappa I)e^{-\gamma(I+\kappa I^2)}$.