

Climate Risk and Supply-Chain Resilience: How Environmental Disruptions Affect SME Performance and International Trade

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Abstract

Heat, floods, cyclones, droughts, and port disruptions increasingly threaten the supply chains on which small and medium-sized enterprises (SMEs) depend, affecting firm performance and international trade. This study synthesizes peer-reviewed evidence published before 1 January 2025 on climate and weather shocks, production networks, trade costs, and SME disaster recovery. It develops a framework tracing disruptions from hazards, exposure, and vulnerability through supply-chain propagation to SME performance and trade outcomes. The analysis highlights how disruptions at suppliers can affect customer firms, how indirect losses may spread through production networks, how delays increase trade costs, and how rising temperatures can constrain export growth in vulnerable economies. Evidence specifically focused on SMEs remains comparatively limited and is often case-based. The paper contributes illustrative analytical models of resilience loss, regional supplier diversification, input specificity and cost pass-through, cost-minimizing inventory buffers, survival under cash and inventory constraints, the trade-equivalent cost of delays, buyer retention, and the benefits and costs of adaptation. These models illustrate how SMEs with higher costs of capital may hold smaller inventory buffers and face lower survival probabilities. They also demonstrate that supplier diversification reduces joint disruption risk most effectively when suppliers operate across different hazard regions. In addition, the paper proposes an SME Supply-Chain Resilience Index (SCRI), five research propositions, and an empirical design for firm-level testing. All numerical illustrations use assumed parameters and should not be interpreted as empirical estimates. The central implication is that SME trade resilience depends not only on avoiding hazards but also on maintaining adequate operational buffers, diversifying suppliers across hazard regions, and improving access to finance.

1. Introduction

Small and medium enterprises (SMEs) are embedded in supply chains that run through farms, factories, roads, ports, and power grids, all of which are exposed to weather. The Intergovernmental Panel on Climate Change frames climate risk as arising from the interaction of hazards with the exposure and vulnerability of people, assets, and systems (IPCC, 2022). A systematic review of 90 studies by Ghadge et al. (2020) concludes that climate change driven extreme weather affects food production, natural resources, and transportation worldwide and that these impacts cascade into interlinked global supply chains. For an SME that buys inputs from a few suppliers and ships to a few buyers, a flood at one supplier or a cyclone at one port can therefore matter more than any change in average climate.

Firm level evidence shows how such shocks travel. Barrot and Sauvagnat (2016) use natural disasters in the United States to show that affected suppliers impose substantial output losses on their customers, especially when the inputs they produce are specific. Carvalho et al. (2021) trace the effects of the Great East Japan Earthquake through the supplier networks of roughly one million firms and find propagation both upstream and downstream, which extends beyond direct links. Inoue and Todo (2019) estimate that, for a predicted mega earthquake, indirect production losses transmitted through supply chains would equal 10.6% of gross domestic product, far above the 0.5% direct effect. Pankratz and Schiller (2024) show that heat at supplier locations reduces the operating income of suppliers and of their customers, and that customers become 7% more likely to terminate a relationship when a supplier’s realized exposure exceeds what was expected.

Trade evidence points the same way. Jones and Olken (2010) find that a poor country that is 1°C warmer in a given year experiences 2.0 to 5.7 percentage points lower export growth, with no detectable effect in rich countries. Osberghaus (2019) reviews the empirical literature and concludes that higher temperatures harm export values, that the effects of disasters are more ambiguous but usually negative for exports of the affected country, and that small, poor, and hot countries with weak institutions suffer most. Time is a trade barrier: Djankov et al. (2010) find that each extra day of delay before shipment reduces trade by more

than 1%, and Hummels and Schaur (2013) estimate that each day in transit is equivalent to an ad valorem tariff of 0.6 to 2.1%. Climate disruptions lengthen and randomize exactly these delays.

Yet the SME dimension remains thinly studied. Several of the strongest network studies rely on data on publicly listed firms (Barrot and Sauvagnat, 2016) or on credit reporting records for large populations of firms (Carvalho et al., 2021), and evidence on small businesses comes largely from post-disaster surveys, such as the study of small businesses after the 2010 flood in Pakistan by Asgary et al. (2012), in which most businesses had reopened after six months but the majority were operating at a loss. In Bangladesh, studies of the ready-made garment sector rank cyclones, flooding, and heavy rain among the leading causes of supply-chain disruption (Ali et al., 2021), but SME specific, trade linked evidence remains scarce.

This paper asks: *How do climate and other environmental disruptions affect the performance and international trade of SMEs, and what makes SME supply chains more resilient?* It pursues four research questions.

- RQ1** How do climate disruptions propagate through supply chains to SME performance?
- RQ2** How do they affect SME participation and performance in international trade?
- RQ3** Which resilience capacities reduce losses at the lowest cost, and how do SME specific constraints change the answer?
- RQ4** How can SME supply-chain resilience be measured?

The paper makes five contributions. First, it integrates climate risk, supply-chain propagation, SME performance, and trade outcomes in one framework (Figure 1). Second, it derives closed form illustrative models that link resilience choices to outcomes and show how SME specific constraints change optimal choices. Third, it organizes the pre 2025 evidence by level of analysis and by type of finding. Fourth, it proposes an SME Supply-Chain Resilience Index (SCRI). Fifth, it states testable propositions and an empirical design. The evidence

boundary is 31 December 2024. Section 2 reviews the literature, Section 3 develops the framework, Section 4 sets out the method, Section 5 synthesizes the evidence and illustrates the models, Section 6 discusses implications, Section 7 sets out limitations and an agenda, and Section 8 concludes.

## 2. Literature Review

### 2.1 Climate Hazards and Economic Activity

A large literature links weather to economic outcomes. Dell et al. (2012) find that higher temperatures reduce growth in poor countries but not in rich ones, and Burke et al. (2015) document a non-linear relationship between temperature and economic production in which output declines at high temperatures. Somanathan et al. (2021) study Indian manufacturing and show that temperature affects labor productivity and labor supply, which is directly relevant to labor-intensive plants in South Asia. Felbermayr and Gröschl (2014) examine the growth effects of natural disasters using geophysical measures of disaster intensity, and Botzen et al. (2019) review the models and empirical studies on the economic impacts of natural disasters. These studies establish that weather matters for output but say less about how shocks move between firms and across borders, which is the focus of the network and trade literatures reviewed below.

### 2.2 Supply-Chain Disruption and Propagation

Production networks amplify and redistribute shocks. Acemoglu et al. (2012) show theoretically how microeconomic shocks can generate aggregate fluctuations in the presence of input-output linkages, and Baqaee and Farhi (2019) extend the analysis to the macroeconomic impact of microeconomic shocks. Empirical work shows the mechanism at the firm level. Barrot and Sauvagnat (2016) find that sales growth of suppliers hit directly by a natural disaster falls by around five percentage points and that customers of disrupted suppliers see sales growth fall by about two percentage points. Carvalho et al. (2021) report that propagation is stronger downstream than upstream and attenuates as it moves away from the source. Boehm et al. (2019) show that input linkages transmit the 2011 Tohoku earthquake to affiliates of Japanese multinationals abroad, so that disruptions cross borders through trade in inputs. Inoue and Todo (2019) find that indirect effects are larger and more persistent when networks have hubs, when intermediate products are hard to substitute, and when cycles are present. Haraguchi and Lall (2015) study the 2011 Thailand floods as a case for supply-chain decision making. Climate-specific evidence comes from Pankratz and Schiller (2024), who show that supplier heat exposure lowers operating income for suppliers and customers and that customers adapt by terminating relationships and choosing less exposed replacement suppliers.

### 2.3 Resilience Concepts

Supply-chain resilience has been defined as the ability to return to the original or a better state after a disruption (Ponomarev and Holcomb, 2009). Christopher and Peck (2004) stress agility, visibility, and collaboration, and Sheffi and Rice (2005) stress redundancy and flexibility in the resilient enterprise. Kleindorfer and Saad (2005) and Tang (2006) classify disruption risks and mitigation strategies, and Ivanov et al. (2014) analyze the ripple effect and the trade-off among efficiency, flexibility, and resilience. In the engineering tradition, Bruneau et al. (2003) introduced the resilience triangle, in which resilience loss is the area between normal performance and the recovery path, and Hallett (2014) distinguishes resilience from vulnerability and discusses its measurement. Linnenluecke and Griffiths (2010) argue that businesses need anticipatory adaptation in addition to post-event recovery. These concepts guide the capacity typology in Section 3.

### 2.4 Diversification and Reshoring

Whether to diversify suppliers or bring production home is a central policy question. Baldwin and Freeman (2022) review what is known about risks in global supply chains. Grossman et al. (2023) ask whether policy should promote international diversification or reshoring, and Bonadio et al. (2021) study how global supply-chain linkages transmitted pandemic shocks. For climate risk, the geography of hazards adds

a further consideration: diversification reduces exposure only when the alternative sources do not share the same hazard, a point formalized in Section 3.

### 2.5 Trade Costs, Time, and Exports

Gravity models relate trade to trade costs (Anderson and van Wincoop, 2003), and the Poisson pseudo maximum likelihood estimator handles zeros and heteroskedasticity (Santos Silva and Tenreiro, 2006). Firm heterogeneity models show that exporting requires fixed and variable costs that only more productive firms cover (Melitz, 2003; Bernard et al., 2007), so cost shocks can push marginal exporters out. Time costs matter: Djankov et al. (2010) use data for 98 countries on the days needed to move cargo from the factory gate to the ship and find that each day of delay reduces trade by more than 1%, with larger effects for time-sensitive goods, and Hummels and Schaur (2013) find that each day in transit is equivalent to an ad valorem tariff of 0.6 to 2.1%, with parts and components trade the most time-sensitive. Climate-related disruptions of roads, ports, and power extend these delays.

### 2.6 SMEs and Disasters

Small firms face barriers to recovery that differ from those of large firms (Runyan, 2006). Asgary et al. (2012) surveyed small businesses in nine severely affected districts six months after the 2010 Pakistan flood and found that about 90% had reopened, most operating at a loss, and that recovery time was associated with average monthly sales, past disaster experience, personal savings, damage to facilities and inventory, disruption of the supply chain, and damage to lifelines. Ates and Bititci (2011) discuss the change process as a key enabler for resilient SMEs. These results suggest that liquidity, savings, and supply-chain continuity are central to SME recovery, which motivates the buffer and survival models in Section 3.

### 2.7 Bangladesh and South Asia

For Bangladesh, Ali et al. (2021) combine a Delphi method with fuzzy analytic hierarchy process for the ready-made garment industry and identify political and regulatory instability, cyclones, labor strikes, flooding, heavy rain, and factory fires as the top six disruption drivers. Chowdhury and Quaddus (2015) propose an optimization-based quality function deployment approach to select resilience strategies in the Bangladesh garment industry. Regional and firm-level identification of climate effects on SME trade remains rare.

### 2.8 Research Gap

Four gaps are identified. First, network studies rarely focus on SMEs, whose resilience capacities are constrained by finance. Second, trade studies typically use country aggregates and cannot separate production shocks from logistics shocks. Third, resilience is often described qualitatively, without models that show how optimal resilience choices differ between SMEs and large firms. Fourth, there is no simple measurement framework that combines diversification, buffers, liquidity, visibility, flexibility, and access to finance for SMEs. Table 1 summarizes the evidence base.

## 3. Theoretical Framework

### 3.1 Climate Risk as Hazard, Exposure, and Vulnerability

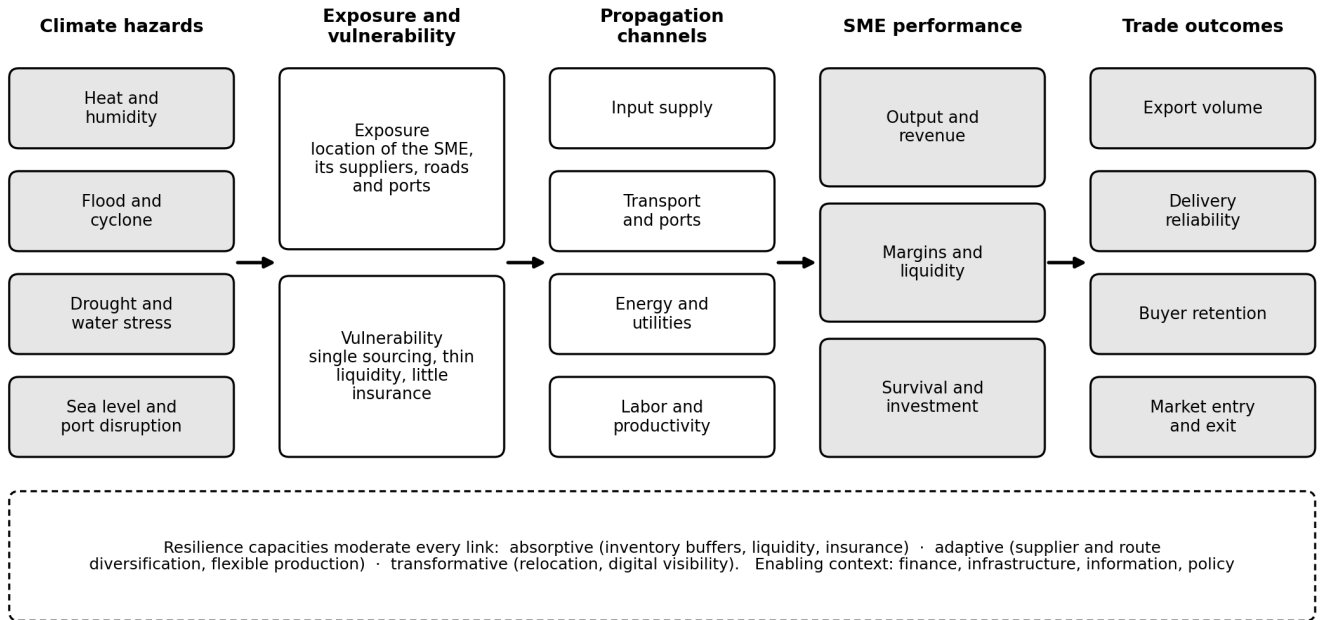
Following the risk framing of IPCC (2022), the risk faced by SME  $i$  is a function of the hazard  $H_i$  at its location and along its supply routes, its exposure  $E_i$ , and its vulnerability  $V_i$ ,

$$R_i = f(H_i, E_i, V_i). \quad (1)$$

Hazards include heat, flood, cyclone, drought, and sea level related port disruption. Exposure is the presence of the SME, its suppliers, and its transport routes in hazard zones. Vulnerability is determined by single sourcing, input specificity, thin liquidity, buyer concentration, and lack of insurance. Table 2 maps hazards to the channels through which they reach SME performance.

### 3.2 Why SMEs Differ

SMEs face constraints that alter the cost and feasibility of resilience (Table 3). They pay more for capital, so holding inventory or cash



**Figure 1. Conceptual framework: climate hazards act through exposure and vulnerability and propagate.**

**Table 1. Selected Pre 2025 Evidence on Climate Shocks, Supply Chains, SMEs, and Trade**

| Study                        | Context and data                      | Main evidence                                                                                                                                                   | Interpretation                        |
|------------------------------|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|
| Jones and Olken (2010)       | Country exports, product level        | A poor country 1°C warmer has 2.0–5.7 percentage points lower export growth; no effect in rich countries; agricultural and light manufacturing exports affected | Climate shock to export capacity      |
| Osberghaus (2019)            | Review of 19–21 studies               | Higher temperature harms export values; disasters often reduce exports of the affected country; small, poor, hot countries most affected                        | Trade channel synthesis               |
| Djankov et al. (2010)        | 98 countries                          | Each day of delay before shipment reduces trade by more than 1%; larger for time-sensitive goods                                                                | Delay as trade barrier                |
| Hummels and Schaur (2013)    | US imports                            | Each day in transit equals a 0.6–2.1% ad valorem tariff; parts and components most time-sensitive                                                               | Time cost of transport                |
| Barrot and Sauvagnat (2016)  | US listed firms, disasters            | Disasters at suppliers reduce sales of hit suppliers and cause output losses for customers, especially for specific inputs                                      | Input specificity                     |
| Carvalho et al. (2021)       | Japan, about 1 million firms          | Earthquake effects propagate upstream and downstream, stronger downstream, and attenuate with distance                                                          | Network propagation                   |
| Boehm et al. (2019)          | US affiliates of Japanese firms       | Input linkages transmit the 2011 earthquake across borders                                                                                                      | Cross-border transmission             |
| Inoue and Todo (2019)        | Japan, agent-based model              | Indirect effects (10.6% of GDP) exceed direct (0.5%) for a predicted mega earthquake; larger with hubs, low substitutability, cycles                            | Indirect losses dominate              |
| Pankratz and Schiller (2024) | Global supplier-customer links        | Heat at suppliers lowers operating income of suppliers and customers; customers 7% more likely to terminate relationships when exposure exceeds expectations    | Climate-driven adaptation of networks |
| Somanathan et al. (2021)     | Indian manufacturing                  | Temperature affects productivity and labor supply                                                                                                               | Labor productivity channel            |
| Ghadge et al. (2020)         | Review of 90 articles                 | Extreme weather affects food, resources, and transport, with cascading effects                                                                                  | Systematic synthesis                  |
| Asgary et al. (2012)         | Small businesses, Pakistan 2010 flood | About 90% reopened after six months but most operated at a loss; recovery linked to sales, savings, supply-chain and lifeline disruption                        | SME recovery determinants             |
| Runyan (2006)                | Small businesses, disasters           | Identifies barriers to recovery for small firms                                                                                                                 | SME recovery barriers                 |
| Ali et al. (2021)            | Bangladesh garment industry           | Cyclones, flooding, and heavy rain among top six disruption drivers                                                                                             | Local hazard ranking                  |
| Chowdhury and Quaddus (2015) | Bangladesh garment industry           | Optimization-based selection of resilience strategies                                                                                                           | Strategy design                       |

**Table 2. Hazard, Channel, and SME Impact Matrix**

| Hazard                        | Input supply                                   | Transport and ports                      | Labor and energy                            | Trade consequence                                    |
|-------------------------------|------------------------------------------------|------------------------------------------|---------------------------------------------|------------------------------------------------------|
| Heat and humidity             | Lower output of heat exposed suppliers         | Slower handling; rail and road stress    | Lower labor productivity; peak power demand | Longer lead times; lower export capacity             |
| Flood                         | Supplier plants and stocks damaged             | Road and rail closures; port access lost | Utility outages; absenteeism                | Missed shipment windows; buyer switching             |
| Cyclone and surge             | Coastal suppliers shut down                    | Port closure; vessel delays              | Power and telecom loss                      | Delivery failure; higher freight and insurance costs |
| Drought and water stress      | Agricultural and water dependent inputs scarce | River and inland transport limits        | Hydropower and cooling limits               | Input price spikes; product quality risk             |
| Sea level and coastal erosion | Gradual loss of coastal sites                  | Chronic port and road exposure           | Coastal utilities at risk                   | Permanent rise in trade costs                        |

is dearer. They have fewer suppliers and buyers, so a single failure is larger relative to their business. They have less insurance, less information about hazards, and less bargaining power to shift costs to partners. These differences enter the models below through the holding cost  $c$ , the number of independent sources, and the cash cover  $K$ . These constraints also reduce SMEs' ability to absorb prolonged disruptions, making recovery more dependent on timely access to external finance, alternative suppliers, and targeted institutional support.

**Table 3. SME Constraints and Their Consequences**

| Constraint               | Consequence for resilience                |
|--------------------------|-------------------------------------------|
| Higher cost of capital   | Costlier buffers; lower optimal inventory |
| Few suppliers and routes | Higher probability of joint disruption    |
| Thin cash reserves       | Short cover; higher exit risk             |
| Concentrated buyers      | Fast buyer loss after stoppages           |
| Limited insurance access | Losses retained on the balance sheet      |
| Limited information      | Late recognition of exposure              |

### 3.3 Resilience Loss and the Capacity Typology

Following ?, let performance drop by a fraction  $\delta$  at the event, remain at that level for  $S$  days, and then recover linearly over  $T$  days. The resilience loss, measured in days of normal output, is the area between normal performance and the recovery path,

$$\Psi = \delta \left( S + \frac{T}{2} \right). \quad (2)$$

Resilience capacities work through the three terms: absorptive capacity (buffers, liquidity, insurance) lowers  $\delta$  and  $S$ , adaptive capacity (diversification, flexible production) shortens  $T$  and lowers  $\delta$ , and transformative capacity (relocation, digital visibility) changes exposure itself. Figure 2 summarizes the typology and Figure 3 illustrates Equation (2).

### 3.4 Propagation Through the Supply Network

Figure 4 shows how a hazard at one supplier, a heat stressed supplier, or a cyclone at a port can disrupt an SME and its buyers. Two properties govern how much of a shock reaches the SME: whether alternative sources share the same hazard, and how substitutable the disrupted input is.

**Diversification across hazard regions.** Suppose an SME has  $k$  suppliers located in  $r$  distinct hazard regions, each region being hit independently with probability  $h$  per period and all suppliers in a region failing together. The probability that all suppliers are disrupted at once is

$$P_{\text{all}} = h^r, \quad r \leq k. \quad (3)$$

Adding suppliers in the same region leaves  $r$  unchanged and does not reduce joint risk, whereas placing each supplier in a new region reduces it geometrically (Figure 5). With  $h = 0.10$ , one region gives  $P_{\text{all}} = 0.10$ , three regions give 0.001, and eight regions give  $10^{-8}$ .

**Input specificity and pass-through.** Let output be a constant elasticity of substitution (CES) combination of the disrupted input, with cost share  $\alpha$ , and all other inputs held fixed. If a share  $s$  of the disrupted input is lost, relative output is

$$\frac{Y}{Y_0} = \left[ \alpha(1-s)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\alpha) \right]^{\frac{\varepsilon}{\varepsilon-1}}, \quad (4)$$

where  $\varepsilon$  is the elasticity of substitution, with limits  $Y/Y_0 = (1-s)^\alpha$  at  $\varepsilon = 1$  and  $Y/Y_0 = 1-s$  as  $\varepsilon \rightarrow 0$  (specific, Leontief type inputs). Applying Equation (4) tier by tier gives the attenuation of a shock along the chain. Figure 6 shows that with  $\alpha = 0.4$  and a 50% input loss, output falls by 50% under Leontief technology but by 28.6%, 24.2%, and 21.4% for  $\varepsilon = 0.5, 1$ , and 3, and that the loss shrinks quickly with each downstream tier unless inputs are specific. This mirrors the empirical finding that input specificity is a key determinant of propagation (?).

### 3.5 The Cost of Resilience and the Optimal Buffer

Consider an SME that faces hazard events at frequency  $h$  per year. A disruption lasts  $D$  days, with  $D$  exponentially distributed with mean  $\mu$ . During a stoppage the SME loses a contribution margin  $m$  per day, and an inventory buffer of  $B$  days of input cover postpones the stoppage. Holding one day of cover costs  $c$  per year, where  $c = (i+s)v$  with  $i$  the interest rate,  $s$  a storage rate, and  $v$  the value of one day of inputs. Expected stoppage days per event are  $E[(D-B)^+] = \mu e^{-B/\mu}$ , so expected annual cost is

$$TC(B) = hm\mu e^{-B/\mu} + cB. \quad (5)$$

The first order condition  $-hme^{-B/\mu} + c = 0$  gives the cost minimizing buffer

$$B^* = \mu \ln \left( \frac{hm}{c} \right)^+, \quad (6)$$

where  $(x)^+ = \max(x, 0)$ . At an interior optimum  $e^{-B^*/\mu} = c/(hm)$ , so the residual expected stoppage loss equals  $\mu c$  and total cost is  $TC^* = \mu c [1 + \ln(hm/c)]$ . Three comparative statics follow:  $B^*$  rises with hazard frequency, with the margin at stake, and with disruption duration, and it falls with the holding cost  $c$ . Because SMEs pay more for capital, their  $c$  is higher and their optimal buffer is smaller, even when they face the same hazards. Figure 7 illustrates the result and Section 5 gives numbers.

### 3.6 Survival Under Cash and Inventory Cover

A firm survives a disruption if it can cover fixed costs until operations resume. Let  $K$  be the days of fixed cost covered by cash and credit and  $C = B + K$  the total cover. With exponential disruption duration, the probability of surviving one event is

$$\Pr(\text{survive} \mid \text{event}) = 1 - e^{-C/\mu}, \quad (7)$$

and the probability of surviving  $T$  years with annual event probability  $\min(h, 1)$  is

$$S_T = (1 - \min(h, 1) e^{-C/\mu})^T. \quad (8)$$

If climate change raises hazard frequency by a multiplier  $\kappa$  so that  $h = \kappa h_0$ , survival falls fastest for firms with thin cover (Figure 8). The ignored recovery period and the assumption of independence over years make the model a stylized benchmark.

### 3.7 The Trade Channel: Delay and Buyer Retention

Disruptions affect trade through the cost of time and through the loss of buyers. In a gravity setting, exports vary with the trade cost factor  $\tau$  raised to the power  $-\theta$ , where  $\theta$  is the trade elasticity. If each day of delay adds an ad valorem equivalent  $a$ , then a delay of  $d$  days changes exports by

$$\frac{X^A}{X^B} - 1 = (1 + ad)^{-\theta} - 1. \quad (9)$$

With  $\theta = 5$  assumed, a per day tariff equivalent of 0.2% reproduces a reduction of about 1% per day, matching the lower bound of ?, while the range of 0.6 to 2.1% estimated by ? implies larger effects for time sensitive products. Delays also risk the buyer relationship. If a buyer's tolerance is  $\tau_b$  days and a stoppage lasts  $D$  days, the share of buyers retained is

$$\rho(D) = e^{-D/\tau_b}. \quad (10)$$

This retention function is an assumed reduced form, motivated by the finding that customers terminate relationships after repeated realized climate shocks (Pankratz and Schiller, 2024). Smaller suppliers with concentrated buyers and low bargaining power are expected to have a smaller  $\tau_b$  (Figure 9).

### 3.8 Adaptation Decisions

Expected annual loss with a buffer  $B$  when hazard frequency is  $\kappa h_0$  is

$$EAL(\kappa, B) = \kappa h_0 m \mu e^{-B/\mu}, \quad (11)$$

so that intensifying hazards raise losses proportionally and buffers scale the loss down exponentially. Consider an adaptation investment (for example flood proofing or backup power) that reduces the loss per event by a fraction  $a$  at an annualized cost  $k$ . With loss per event  $L_e = m\mu$ , the benefit-cost ratio and the break even hazard frequency are

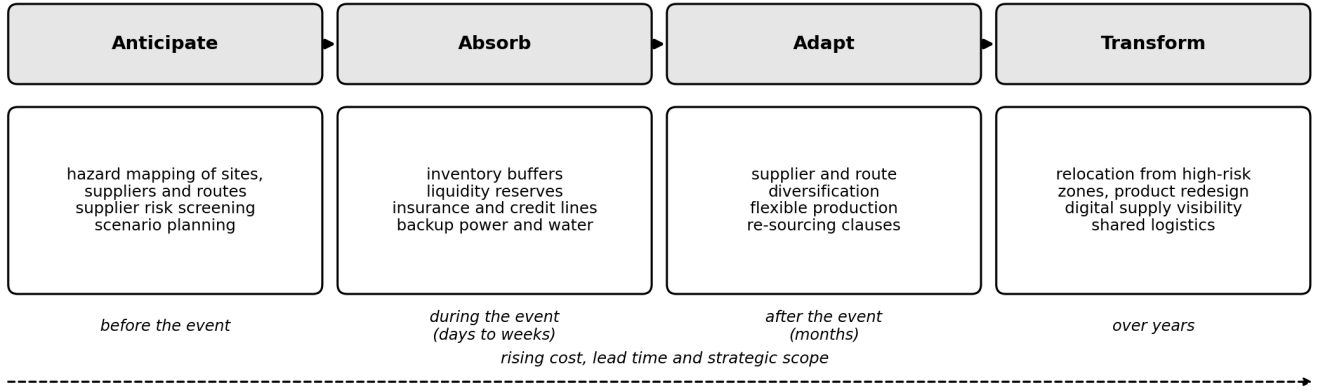
$$BCR = \frac{haL_e}{k}, \quad h^* = \frac{k}{aL_e}. \quad (12)$$

Adaptation pays only for SMEs whose hazard frequency exceeds  $h^*$ , which implies that targeting support at high exposure firms raises returns (Figure 10).

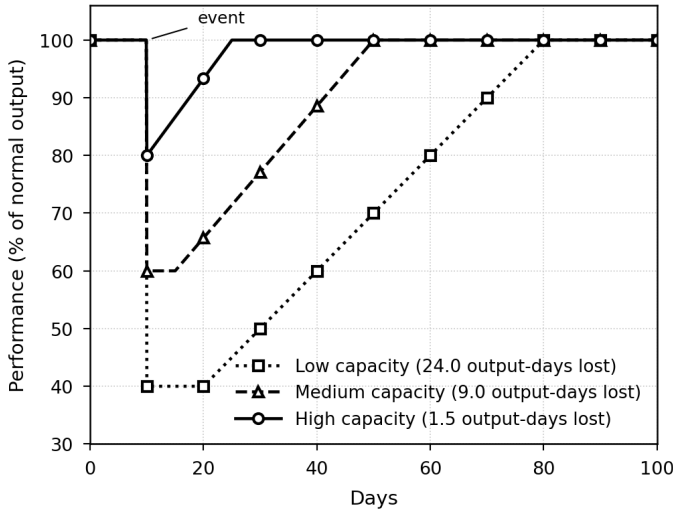
## 4. Methodology

### 4.1 Research Design

The study is a structured secondary evidence synthesis complemented by analytic models. The evidence boundary is 31 December 2024. Peer reviewed journal articles, established working paper series and academic databases, and authoritative institutional reports are prioritized. Each study was coded by level of analysis (country and trade, firm and network, SME), by the type of finding (loss from hazards, propagation, trade impact, time cost, adaptation, small firm focus), and by the reported direction. The models in Section 3 are closed form and illustrate mechanisms with assumed parameters. They do not provide new estimates. Table 4 states the selection framework.



**Figure 2. Resilience capacities across the disruption cycle, from anticipation to transformation, with rising cost and strategic scope.**



**Figure 3. Illustrative performance paths after an event at day 10 for three levels of resilience capacity.**

**Table 4. Evidence Selection Framework**

| Criterion | Included                                                     | Excluded                             |
|-----------|--------------------------------------------------------------|--------------------------------------|
| Date      | Published before 2025                                        | Published in 2025 or later           |
| Quality   | Peer reviewed research and authoritative evidence            | Unsupported commentary               |
| Topic     | Climate and weather shocks, supply chains, SMEs, trade costs | Unrelated disruptions                |
| Outcome   | Output, income, exports, delays, recovery, survival          | Outcomes without economic relevance  |
| Unit      | Firm, network, sector, country                               | Purely technical engineering studies |

#### 4.2 Measurement Variables

Table 5 lists the constructs, indicators, and candidate data sources for empirical work. Hazard exposure should be measured at the location of the firm, of its suppliers, and of the ports and routes it uses, since the network literature shows that supplier location matters (Pankratz and Schiller, 2024). Vulnerability includes input specificity and the share of inputs from a single source. Resilience capacities include days of inventory, days of cash cover, number of supplier regions, and insurance coverage.

#### 4.3 SME Supply-Chain Resilience Index

The SME Supply-Chain Resilience Index (SCRI) combines six components: supplier diversification across hazard regions ( $DV$ ), inventory buffer ( $IB$ ), liquidity and cash cover ( $LQ$ ), supply visibility ( $VS$ ), production flexibility ( $FL$ ), and access to finance and insurance ( $FA$ ). Each raw indicator is rescaled to  $[0, 100]$  as

$$\tilde{z}_{jh} = 100 \frac{z_{jh} - z_j^{\min}}{z_j^{\max} - z_j^{\min}}, \quad (13)$$

and the index is the weighted sum

$$\begin{aligned} SCRI_h = & w_1 DV_h + w_2 IB_h + w_3 LQ_h \\ & + w_4 VS_h + w_5 FL_h + w_6 FA_h, \end{aligned} \quad (14)$$

with  $\sum_{j=1}^6 w_j = 1$ .

Equal weights suit exploratory work, while weights based on hazard type (for example greater weight on stocks and cash for flood prone firms) or on factor analysis may suit applied studies. Rankings can be sensitive to weights, as Figure 11 shows for three hypothetical SMEs. The SCRI measures capacity, not outcomes, and should be reported alongside realized losses. Table 6 lists the components.

#### 4.4 Empirical Models for Future Testing

Four families of models can test the framework. First, a firm panel relates outcomes to hazards and to resilience capacity,

$$\begin{aligned} \ln Y_{it} = & \beta_0 + \beta_1 Haz_{it} + \beta_2 (Haz_{it} \times Res_{i,t-1}) \\ & + \beta_3 SupHaz_{it} + \beta_4 Z_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \end{aligned} \quad (15)$$

where  $SupHaz_{it}$  is the exposure-weighted hazard at the firm's suppliers,  $\mu_i$  are firm effects and  $\lambda_t$  are time effects. The interaction  $\beta_2$  measures whether resilience capacity dampens hazard losses. Event study versions replace  $Haz_{it}$  with indicators for years relative to an event. Legend values give the SCRI under equal weights and under stock-and-cash weights ( $w = 0.10, 0.30, 0.30, 0.05, 0.10, 0.15$ ). The profiles are illustrative and show that weights can reverse rankings.

Second, exports at the firm-destination level are estimated with the Poisson pseudo maximum likelihood estimator,

$$\begin{aligned} X_{ijt} = & \exp(\delta_1 Haz_{it} + \delta_2 Delay_{it} + \delta_3 SME_i \times Delay_{it} \\ & + \alpha_{jt} + \mu_{ij}) \varepsilon_{ijt}, \end{aligned} \quad (16)$$

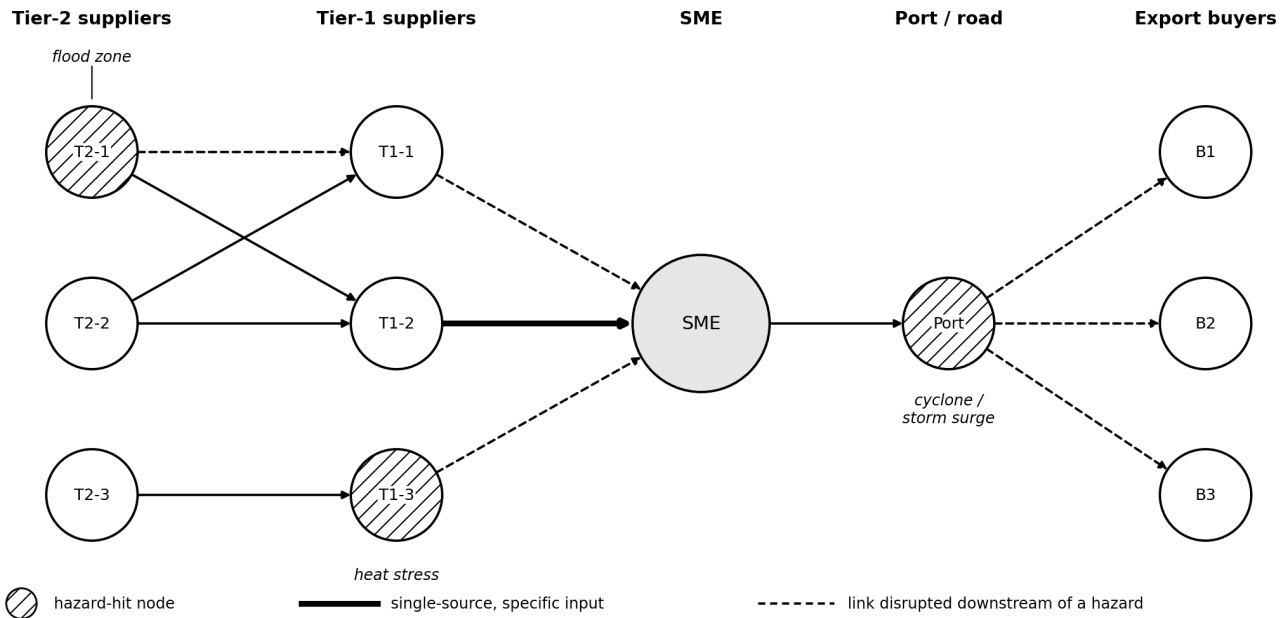
with destination-year effects  $\alpha_{jt}$  and firm-destination effects  $\mu_{ij}$ , so that  $\delta_3$  tests whether delay hurts SMEs more (Santos Silva and Tenreiro, 2006).

Third, network propagation is tested with the supplier hazard specification in Equation (15), interacting  $SupHaz_{it}$  with input specificity, in the spirit of ? and Pankratz and Schiller (2024). Fourth, survival is modeled with a discrete-time model,

$$\begin{aligned} \Pr(Exit_{it} = 1) = & \Lambda(\theta_0 + \theta_1 Haz_{it} + \theta_2 Cover_{i,t-1} \\ & + \theta_3 Haz_{it} \times Cover_{i,t-1} + \theta_4 Z_{it}), \end{aligned} \quad (17)$$

where  $\Lambda$  is the logistic function and  $Cover$  is inventory plus cash days;  $\theta_1 > 0$  indicates that hazards raise exit risk and  $\theta_3 < 0$  indicates that greater cover dampens that effect. Because hazard occurrence is exogenous conditional on location, identification rests on within-firm variation in hazard timing, while adaptation choices and location choices remain endogenous and call for instruments or quasi-experimental designs.

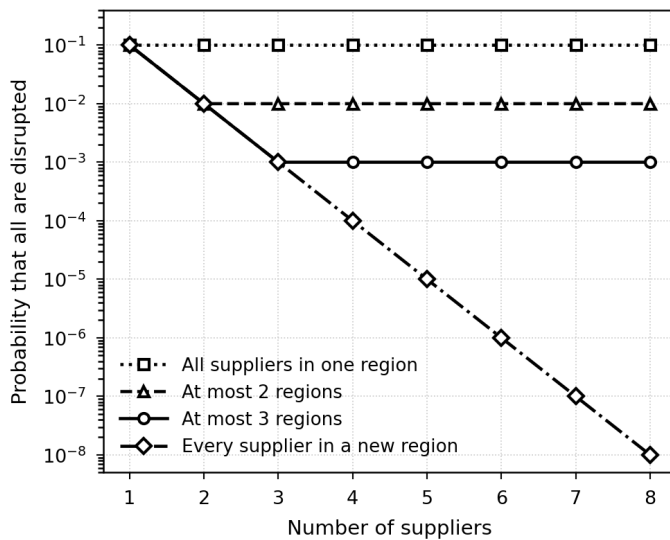
Figure 12 presents the measurement and estimation architecture.



**Figure 4. Illustrative SME supply network with hazard-hit nodes (hatched), a single-source specific input (thick line), and links disrupted downstream of a hazard (dashed).**

**Table 5. Constructs, Indicators, and Candidate Data for Firm Level Research**

| Construct            | Symbol       | Example indicators                                                                                               | Unit                | Candidate data source                                                    |
|----------------------|--------------|------------------------------------------------------------------------------------------------------------------|---------------------|--------------------------------------------------------------------------|
| Hazard exposure      | <i>Haz</i>   | Temperature anomalies; heavy rainfall days; flood extent; cyclone landfall at firm, supplier, and port locations | Index; days; area   | Weather reanalysis; flood extent from satellites; meteorological records |
| Vulnerability        | <i>Vul</i>   | Input specificity; share of inputs from one supplier; buyer concentration; leverage                              | Share; index        | Enterprise survey; customs records                                       |
| Resilience capacity  | <i>Res</i>   | Inventory days; cash cover days; number of supplier regions; insurance; backup power                             | Days; count; 0/1    | Enterprise survey; firm records                                          |
| SME outcome          | <i>Y</i>     | Sales growth; margin; stoppage days; investment; exit                                                            | Percent; days; 0/1  | Enterprise or tax records                                                |
| Trade outcome        | <i>X</i>     | Export value by destination; shipment delay; buyer retention; entry and exit from export markets                 | Currency; days; 0/1 | Customs and shipment data                                                |
| Logistics disruption | <i>Delay</i> | Port dwell time; road closure days; power outage hours                                                           | Days; hours         | Port and utility records                                                 |
| Controls             | <i>Z</i>     | Size; age; sector; location; ownership; credit access                                                            | Various             | Enterprise survey                                                        |



**Figure 5. Probability that all suppliers are disrupted,  $P_{all} = h^r$  with  $h = 0.10$ .**

**Table 6. SCRI Components and Example Indicators**

| Component                 | Example indicators                                  | Scoring |
|---------------------------|-----------------------------------------------------|---------|
| DV: diversification       | Number of hazard regions among suppliers and routes | Min–max |
| IB: inventory buffer      | Days of critical input cover                        | Min–max |
| LQ: liquidity             | Days of fixed cost covered by cash and credit lines | Min–max |
| VS: visibility            | Tier-2 supplier mapping; shipment tracking          | Min–max |
| FL: flexibility           | Alternative inputs qualified; multi-site production | Min–max |
| FA: finance and insurance | Insurance cover; access to contingent credit        | Min–max |

#### 4.5 Data for a Bangladesh Application

A study of Bangladeshi SME exporters could combine an enterprise survey module on inventories, cash cover, supplier locations, and losses; customs and shipment records by destination; weather and flood-extent data for firm, supplier, and port locations; and records on port dwell times, road closures, and outages. The principal seaport and the main export corridors are natural focal points because delays there affect many exporters at once. Access, sampling, and consent conditions must be confirmed before fieldwork, and hazard data should be matched at the level of upazila or firm location where available.

#### 4.6 Validation Plan

The SCRI should be validated by expert review of content, confirmatory factor analysis of dimensionality, tests of measurement invariance across sectors and size classes, and predictive validity against realized losses in held-out hazard events. The illustrative models should be tested by comparing predicted and observed buffers, survival, and buyer retention, and calibrating  $h$ ,  $\mu$ ,  $m$ , and  $c$  from data. Sensitivity to the exponential duration assumption should be checked with heavier tailed distributions.

### 5. Analysis and Results

#### 5.1 Evidence Synthesis

Figure 13 classifies the reported findings of the reviewed studies. Four patterns emerge. First, loss from climate or weather hazards is documented at the firm and plant level for suppliers and customers (Pankratz and Schiller, 2024; Somanathan et al., 2021). Second, propagation through supply links is consistently found, and it is stronger where inputs are specific, where networks have hubs, and where substitution is difficult (?). Third, trade evidence links temperature and delay to lower exports (Jones and Olken, 2010; Osberghaus, 2019; ?; ?). Fourth, adaptation responses are documented for customer-supplier re-

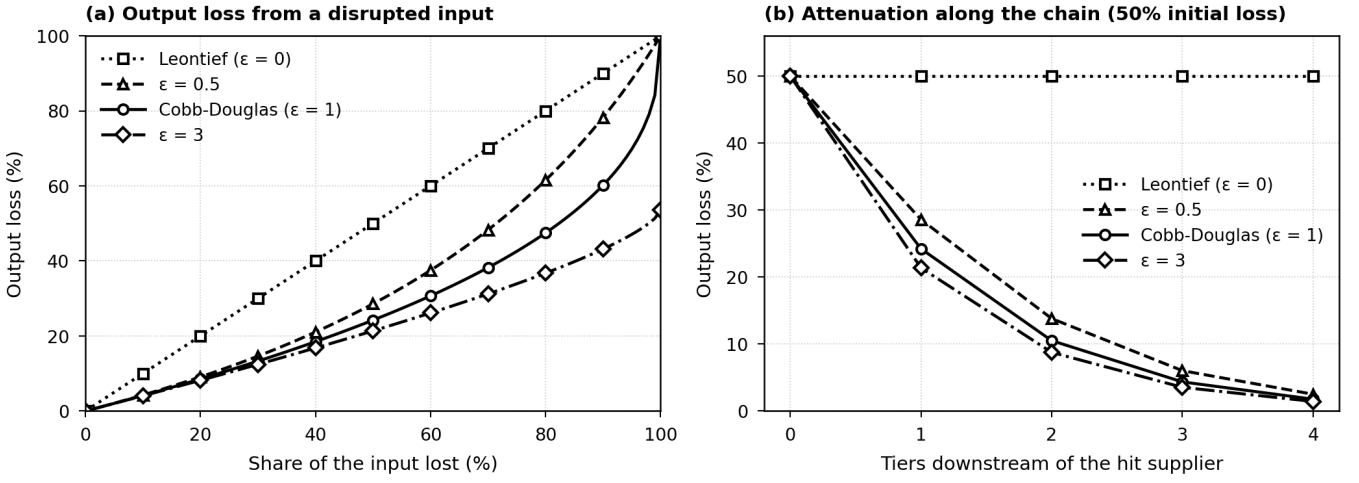


Figure 6. (a) Output loss from a disrupted input for four elasticities of substitution ( $\alpha = 0.4$ ). (b) Attenuation of a 50% initial loss along the chain. Computed from Equation (4); parameters are assumed.

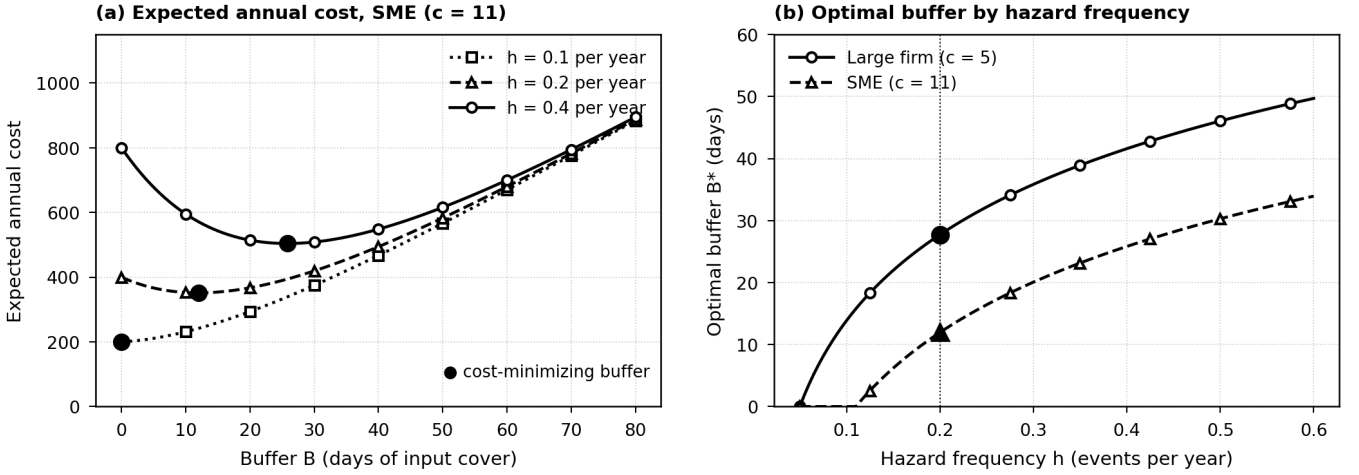


Figure 7. (a) Expected annual cost of an inventory buffer for an SME at three hazard frequencies, with the cost minimizing buffer marked. (b) Optimal buffer as a function of hazard frequency for an SME ( $c = 11$ ) and a large firm ( $c = 5$ ). Assumed parameters:  $m = 100$ ,  $\mu = 20$ .

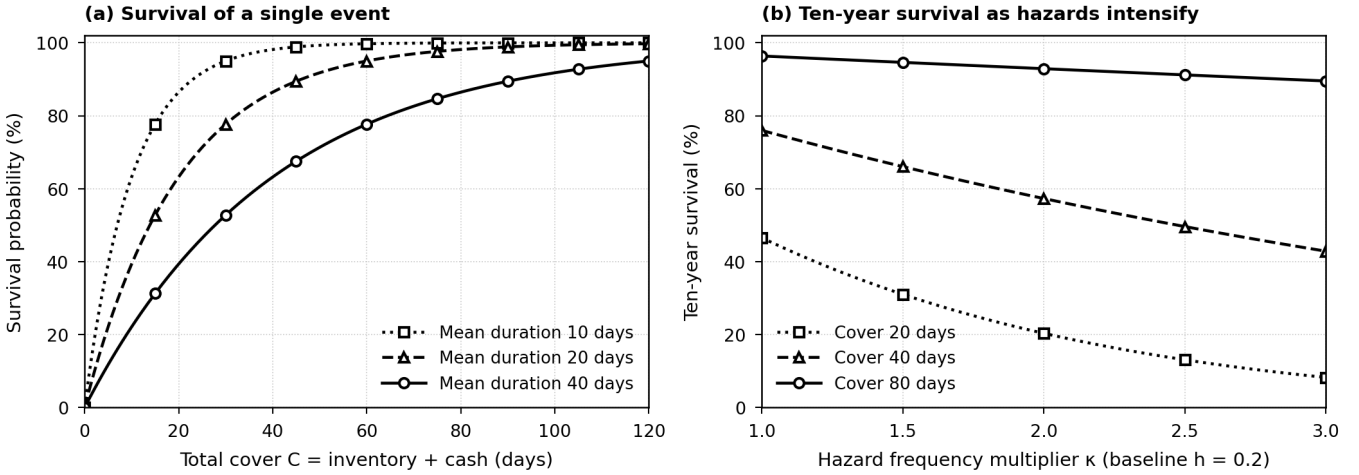


Figure 8. (a) Probability of surviving a single event as total cover rises, for three mean disruption durations. (b) Ten-year survival as the hazard frequency multiplier  $\kappa$  rises from 1 to 3 (baseline  $h_0 = 0.2$ ,  $\mu = 20$ ), for three levels of cover. Computed from Equations (7) and (8).

relationships (Pankratz and Schiller, 2024) and for Bangladesh garment resilience strategies (?), but very few studies combine a small firm focus with a trade outcome. Only the SME recovery studies carry a small firm focus (?Runyan, 2006), and none in the set links an SME recovery outcome to export performance. This is the space the framework and the empirical design are meant to fill.

## 5.2 Numerical Illustrations

The models in Section 3 are evaluated with the assumed parameters in Table 7. The base case is a firm that faces a hazard event every five years on average ( $h_0 = 0.2$ ), loses 100 units of margin per day of stoppage, and experiences disruptions lasting 20 days on average. The parameters are chosen for exposition, not calibrated to any sector.

Table 7. Assumed Parameters for the Numerical Illustrations

| Parameter         | Value       | Meaning                         |
|-------------------|-------------|---------------------------------|
| $h_0$             | 0.20        | Hazard events per year          |
| $m$               | 100         | Margin lost per stoppage day    |
| $\mu$             | 20          | Mean disruption duration (days) |
| $v$               | 50          | Value of one day of inputs      |
| $i$ (SME / large) | 0.18 / 0.06 | Interest rate                   |
| $s$               | 0.04        | Storage rate                    |
| $c$ (SME / large) | 11 / 5      | Holding cost per buffer day     |
| $\alpha$          | 0.4         | Cost share of disrupted input   |
| $\theta$          | 5           | Trade elasticity                |
| $L_e, k$          | 2000, 150   | Loss per event; adaptation cost |

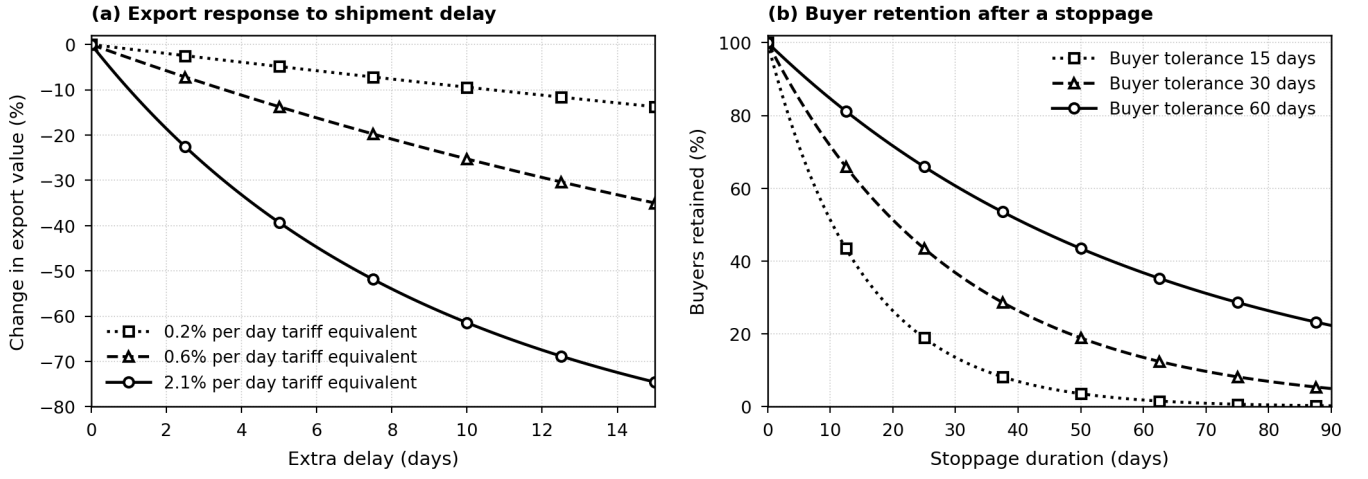


Figure 9. (a) Export response to extra shipment delay for three per day tariff equivalents, with  $\theta = 5$  (Equation 9). (b) Share of buyers retained after a stoppage for three buyer tolerances (Equation 10). Parameters are assumed.

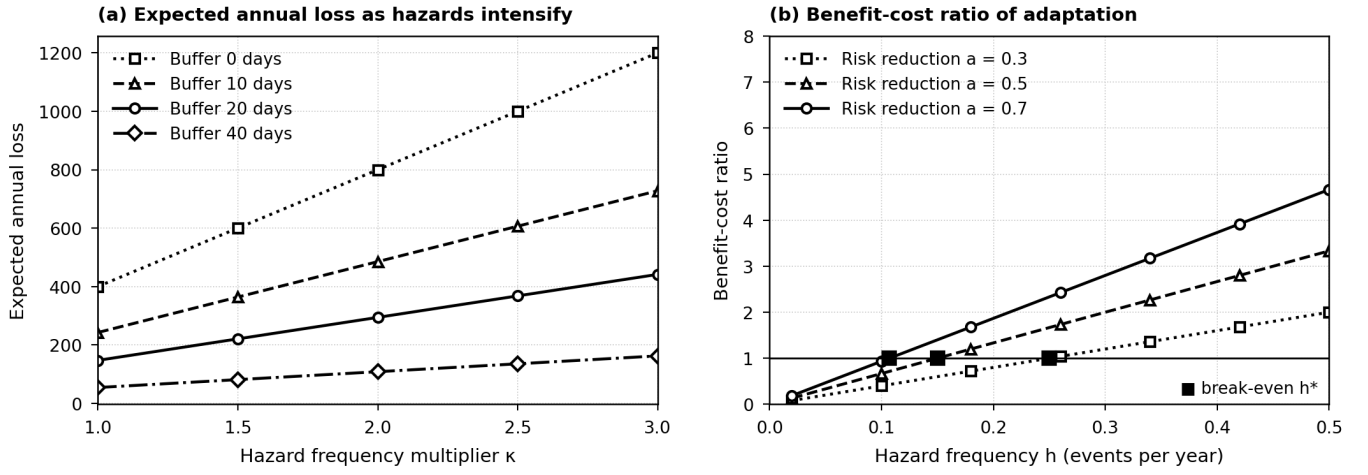


Figure 10. (a) Expected annual loss as hazards intensify, for four buffer sizes (Equation 11). (b) Benefit-cost ratio of an adaptation investment by hazard frequency for three levels of risk reduction, with break even frequency  $h^*$  marked (Equation 12). Assumed parameters:  $L_e = 2000$ ,  $k = 150$ .

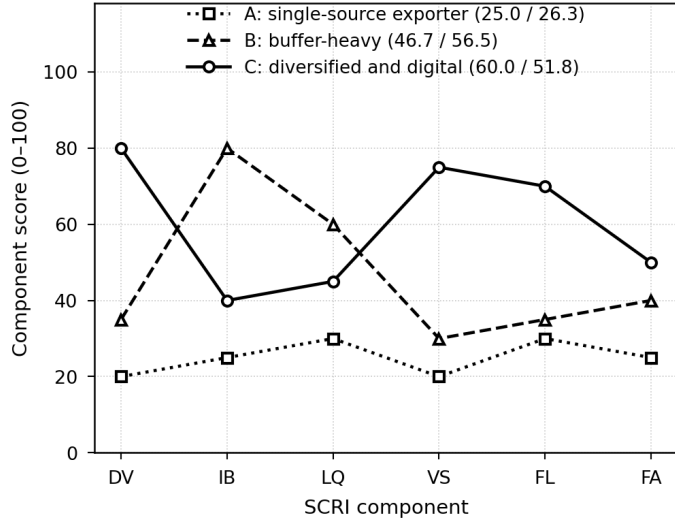


Figure 11. Component profiles of three hypothetical SMEs.

**Resilience loss.** Equation (2) gives 24.0 output-days lost for the low capacity SME, 9.0 for the medium capacity SME, and 1.5 for the high capacity SME (Figure 3), so a 16-fold difference in loss arises from differences in depth, stoppage, and recovery time alone.

**Buffers.** With  $c = 11$  for an SME and  $c = 5$  for a large firm, the cost minimizing buffer at  $h = 0.2$  is 12.0 days for the SME and 27.7 days for the large firm (Table 8). At the optimum, the residual expected stoppage loss is  $\mu c$ , that is 220 for the SME and 100 for the large firm, and total expected cost is 351.5 and 238.6 respectively, against 400 with no buffer. At a lower hazard frequency,  $h = 0.1$ , the SME's optimal

buffer is zero because  $hm = 10$  is below its holding cost of 11, whereas the large firm still holds 13.9 days. In other words, the same hazard justifies resilience for a large firm that an SME cannot afford, which suggests a role for cheaper finance, shared inventory, or insurance.

Table 8. Optimal Buffer and Costs at  $h = 0.2$

|                                    | SME ( $c = 11$ ) | Large firm ( $c = 5$ ) |
|------------------------------------|------------------|------------------------|
| Optimal buffer $B^*$ (days)        | 12.0             | 27.7                   |
| Residual expected loss ( $\mu c$ ) | 220.0            | 100.0                  |
| Total cost at optimum $TC^*$       | 351.5            | 238.6                  |
| Total cost with no buffer          | 400.0            | 400.0                  |

**Survival.** With  $\mu = 20$ , total cover of 20, 40, and 80 days gives single-event survival of 63.2%, 86.5%, and 98.2%. Over ten years at the baseline frequency, the corresponding survival probabilities are 46.6%, 76.0%, and 96.4%. If hazards double, they fall to 20.4%, 57.3%, and 92.9%, and if they triple, to 8.3%, 42.9%, and 89.5% (Table 9, Figure 8). Thin cover is thus far more fragile to intensifying hazards than long cover.

Table 9. Ten-Year Survival by Cover and Hazard Multiplier ( $\mu = 20$ ,  $h_0 = 0.2$ ; percent)

| Total cover $C$ | $\kappa = 1$ | $\kappa = 2$ | $\kappa = 3$ |
|-----------------|--------------|--------------|--------------|
| 20 days         | 46.6         | 20.4         | 8.3          |
| 40 days         | 76.0         | 57.3         | 42.9         |
| 80 days         | 96.4         | 92.9         | 89.5         |

**Trade and buyers.** With  $\theta = 5$ , a 10 day delay lowers exports by 9.4% at a tariff equivalent of 0.2% per day, by 25.3% at 0.6%, and by 61.4% at 2.1% (Figure 9a), so results depend strongly on how time sensitive the product is. A 30 day stoppage retains 13.5%, 36.8%, and

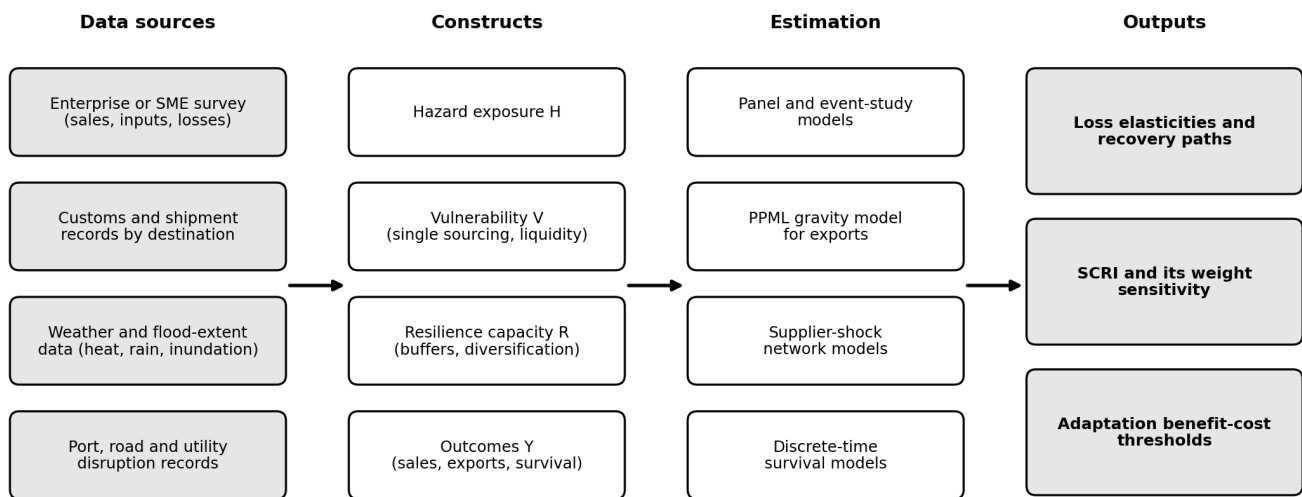


Figure 12. Measurement and estimation architecture for firm level research on climate risk, SME performance, and trade.

| Theme              | Study                        | Loss from climate or weather hazards | Propagation through supply links | Trade or export impact | Time or delay cost | Adaptive or resilience response | Small firm focus |
|--------------------|------------------------------|--------------------------------------|----------------------------------|------------------------|--------------------|---------------------------------|------------------|
| Country and trade  | Jones and Olken (2010)       | ●                                    |                                  | ●                      | ○                  |                                 |                  |
|                    | Osberghaus (2019)            | ●                                    |                                  | ●                      | ○                  |                                 |                  |
|                    | Djankov et al. (2010)        | ○                                    | ●                                | ●                      | ○                  |                                 |                  |
|                    | Hummels and Schaur (2013)    |                                      | ○                                |                        | ●                  |                                 |                  |
| Firm and network   | Barrot and Sauvagnat (2016)  | ●                                    | ●                                |                        |                    |                                 |                  |
|                    | Carvalho et al. (2021)       | ●                                    | ●                                |                        |                    |                                 |                  |
|                    | Boehm et al. (2019)          |                                      | ●                                | ●                      |                    |                                 |                  |
|                    | Inoue and Todo (2019)        | ●                                    | ●                                |                        |                    |                                 |                  |
|                    | Pankratz and Schiller (2024) | ●                                    | ●                                |                        |                    | ●                               |                  |
|                    | Somanathan et al. (2021)     | ●                                    |                                  |                        |                    |                                 |                  |
|                    | Ghadge et al. (2020)         | ●                                    | ●                                |                        |                    | ●                               |                  |
| SME and Bangladesh | Asgary et al. (2012)         | ●                                    |                                  |                        |                    |                                 |                  |
|                    | Runyan (2006)                | ○                                    | ○                                |                        | ●                  |                                 |                  |
|                    | Ali et al. (2021)            | ●                                    | ○                                | ○                      |                    |                                 |                  |
|                    | Chowdhury and Quaddus (2015) | ○                                    | ○                                | ○                      |                    | ●                               |                  |

● = Addresses this theme      ○ = Mentions (limited focus)      | = Focus on small firms

Figure 13. Findings reported in selected pre 2025 studies, by level of analysis. Circles mark the reported finding types and squares mark a small firm focus. Blank cells mean the finding is not reported. The classification is by the authors and is not a pooled effect estimate.

60.7% of buyers for buyer tolerances of 15, 30, and 60 days (Figure 9b), which shows why concentrated buyers with short tolerance make SME exporters fragile.

**Losses and adaptation.** With a 20 day buffer, expected annual loss at the baseline is 147.2 against 400 without a buffer, and at triple the hazard frequency it is 441.6 against 1200 (Figure 10a). An adaptation investment with  $k = 150$  and  $L_e = 2000$  breaks even at  $h^* = 0.25, 0.15$ , and  $0.107$  for risk reductions of  $0.3, 0.5$ , and  $0.7$  (Figure 10b), so at the baseline frequency of  $0.2$  only investments that cut risk by at least half pay for themselves.

### 5.3 SCRI Illustration

For the hypothetical SMEs in Figure 11, the equal weighted SCRI is 25.0 for the single-source exporter, 46.7 for the buffer-heavy SME, and 60.0 for the diversified and digital SME. Under stock-and-cash weights,

the scores are 26.3, 56.5, and 51.8, so that the buffer-heavy SME overtakes the diversified SME. Which weights are appropriate depends on the hazard: a flood prone firm may rightly value stocks and cash over visibility, whereas a firm facing correlated regional hazards may value diversification more.

### 5.4 Cross Country and Bangladesh Context

The climate-trade relationship depends on income and institutions. Jones and Olken (2010) find effects in poor but not rich countries, and Osberghaus (2019) concludes that small, poor, and hot countries with weak institutional quality are most affected. Findings from Japan and the United States (??) concern economies with strong infrastructure and insurance, while the SME recovery evidence is from Pakistan (?). In Bangladesh the top disruption drivers identified for the garment industry are cyclones, flooding, and heavy rain (?). These hazards affect suppliers, road and port links, and workers at the same time, so the

correlated hazard case of Equation (3) is a realistic starting point, and SMEs in export supply chains should be studied together with their buyers and logistics providers.

### 5.5 Research Propositions

The synthesis and models support five propositions. Table 10 states each with its empirical test.

## 6. Discussion

The evidence and models support three broad messages. First, climate disruptions matter to SMEs less through average warming than through the timing and location of discrete events at suppliers and along trade routes, and the network evidence shows that a shock somewhere else in the chain can be as damaging as a direct hit (Pankratz and Schiller, 2024). Second, resilience is a cost decision as well as a technical one. The buffer model shows that a higher cost of capital, which is typical for SMEs, lowers the optimal buffer, and the survival model shows that thin cover leaves SMEs exposed as hazards intensify. Third, diversification is valuable only when it spreads across hazard regions, so counting suppliers is not enough.

The trade results add that SMEs' exposure to delay depends on the product and the buyer. Time sensitive products and short buyer tolerance make delays costly, in line with the larger effects of delay on time sensitive goods found by ? and ?. The finding by Pankratz and Schiller (2024) that customers terminate relationships and switch to less exposed suppliers implies that repeated climate disruptions can lead to permanent loss of business, not only temporary losses.

### 6.1 Managerial Implications

SME owners can screen suppliers and routes for shared hazards and map at least tier-2 suppliers; hold buffers for inputs that are specific and hard to substitute rather than for all inputs; keep cash cover matched to plausible disruption durations; and negotiate delivery terms and contingency arrangements with buyers. Lead firms can support supplier resilience through shared inventory, supplier development, and contingent payment terms, since supplier disruptions transmit to customers (?). Banks and insurers can offer contingent credit and parametric or index insurance that pays out quickly after a defined hazard, thereby lowering the SME holding cost  $c$  and raising cash cover  $K$ .

### 6.2 Policy Implications

Public policy can reduce the hazard exposure of shared infrastructure, such as roads and ports, and improve early warning and information on flood and heat risk. Trade facilitation that shortens clearance and dwell times reduces the tariff equivalent of delay, and resilience of customs and port systems during hazards protects all exporters. Targeting adaptation support at high exposure SMEs raises benefit-cost ratios, as Equation (12) implies. Public data on flood extents, port disruptions, and firm outcomes, made available for research under privacy safeguards, would allow SME specific evidence to be built. Table 11 links actions to the mechanisms they target.

### 6.3 Implications for Bangladesh and Emerging Economies

In Bangladesh, cyclones, flooding, and heavy rain are leading disruption drivers for the garment industry (?), and export activity depends on a small number of transport corridors and a principal seaport. If suppliers and routes share the same hazard exposure, then diversification across suppliers alone will not reduce joint risk, as Equation (3) shows. SME exporters that supply larger exporters can be affected by delays and stoppages they do not control. A research and policy priority is therefore evidence on SME exporters and on the links between SME suppliers and larger exporters, using the designs in Section 4. Because holding costs are high for small firms, finance and insurance instruments that lower  $c$  and raise  $K$  may be as important as physical adaptation.

## 7. Limitations and Future Research

The study has several limitations. First, it is a structured evidence synthesis and does not estimate new causal effects. Second, the strongest

network evidence comes from Japan and the United States and from large or listed firms, and the SME evidence is mostly from case and survey studies, which limits generalization to Bangladesh. Third, the closed form models rest on simplifying assumptions: exponential disruption durations, independence across events, linear holding costs, no re-optimization of other inputs, and independent hazard regions. Fourth, the numerical illustrations use assumed parameters and are not estimates; they show mechanisms and orderings, not magnitudes. Fifth, the evidence map classifies reported findings and does not weight studies by quality or size. Table 12 pairs each limitation with a response.

Future research should estimate loss elasticities and recovery paths for SMEs; test whether SME holding costs explain lower buffers and cover; measure hazard correlation across supplier locations; link SME suppliers to the exports of larger firms; study how contingent finance and insurance change resilience choices; and evaluate the benefit-cost ratios of adaptation programs against the thresholds derived here.

## 8. Conclusion

This study examined how climate and other environmental disruptions affect the performance and international trade of SMEs. The evidence available before 2025 shows that hazards at suppliers and along routes reduce firm performance, that shocks propagate through supply links and are amplified when inputs are specific, that delays act as trade barriers, and that higher temperatures harm exports, particularly for poor countries. Evidence specific to SMEs is much thinner and largely descriptive.

The analytic models translate these findings into testable mechanisms. SMEs, with higher costs of capital, optimally hold smaller inventory buffers and face lower survival odds as hazards intensify. Supplier diversification lowers joint disruption risk only when it spans hazard regions. Input specificity determines how far a shock travels. Delays and short buyer tolerance make trade fragile, and adaptation pays only above a break even hazard frequency. These results are illustrative and rest on assumed parameters.

The main conclusion is that SME trade resilience depends on cover, diversification across hazard regions, and access to finance, rather than on avoiding hazards. Future empirical work should test the framework with firm level panels, customs and shipment data, hazard data at firm, supplier, and port locations, and the SCRI, so that policy and business decisions can rest on SME specific evidence.

The findings also suggest that resilience policies should account for the structural differences between SMEs and larger firms. Financial support, affordable working capital, trade credit, insurance access, supplier development, and reliable logistics can increase the capacity of SMEs to maintain operations during environmental disruptions. However, resilience investments should not be treated as universally effective. The value of additional inventory, alternative suppliers, or adaptation technologies depends on the frequency, location, and severity of hazards, as well as on the firm's production structure and customer requirements. Policies that improve access to finance and information may therefore be particularly important where SMEs lack the internal resources required to build adequate buffers. A further implication is that resilience should be evaluated not only by whether an SME survives an individual shock, but also by how quickly it recovers and whether repeated disruptions gradually weaken its financial and competitive position. Frequent climate-related disruptions can reduce working capital, delay deliveries, damage buyer relationships, and discourage investment, creating cumulative effects that are not captured by single-event measures. Future research should therefore examine dynamic resilience over multiple shocks and distinguish between temporary disruption, delayed recovery, and persistent loss of market access. This would provide a more complete basis for understanding how environmental risk affects SME participation in international trade over time.

**Table 10. Research Propositions and Their Empirical Tests**

| No. | Proposition                                                                                                                       | Test                                                      | Expected sign          | Key data                        |
|-----|-----------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|------------------------|---------------------------------|
| P1  | Hazards at supplier locations reduce SME performance, more so when inputs are specific or single sourced                          | Eq. (15): $\beta_3$ and its interaction with specificity  | —                      | Firm panel; supplier locations  |
| P2  | Port and road delays reduce SME exports and buyer retention, more for time sensitive products                                     | Eq. (16): $\delta_2, \delta_3$                            | —                      | Customs and shipment data       |
| P3  | Because SMEs face higher holding costs, they hold smaller buffers and less cash cover and suffer larger losses and lower survival | Eqs. (15),(17): size interactions                         | — (SME)                | Enterprise survey; exit records |
| P4  | Supplier diversification lowers losses only when it spans hazard regions                                                          | Eq. (15): $Haz \times$ suppliers vs. $Haz \times$ regions | — for regions          | Supplier locations              |
| P5  | Adaptation investments pay only above a break even hazard frequency $h^*$                                                         | Eq. (12); difference in differences                       | $BCR > 1$ if $h > h^*$ | Investment and loss records     |

**Table 11. Implications for Actors: Actions, Targeted Mechanisms, and Monitoring Indicators**

| Actor                        | Recommended action                                                                                                  | Mechanism targeted                   | Indicator to monitor                  |
|------------------------------|---------------------------------------------------------------------------------------------------------------------|--------------------------------------|---------------------------------------|
| SME owners                   | Map tier-2 suppliers and hazard regions; hold buffers for specific inputs; match cash cover to disruption durations | Diversification; buffers; liquidity  | SCRI; days of cover; supplier regions |
| Lead firms and buyers        | Shared inventory, supplier development, contingent payment terms                                                    | Absorptive capacity; buyer tolerance | Supplier stoppage days; retention     |
| Banks and insurers           | Contingent credit; parametric insurance for defined hazards                                                         | Holding cost $c$ ; cash cover $K$    | Share of SMEs with cover; payout time |
| Port and customs authorities | Resilient operations and faster clearance during hazards                                                            | Delay; trade cost                    | Dwell time; clearance time            |
| Governments                  | Protect shared infrastructure; target adaptation at high exposure SMEs; open hazard and firm data                   | Exposure; $h^*$ threshold            | BCR of programs; data availability    |
| Researchers                  | Report SME outcomes with trade outcomes; calibrate parameters; report SCRI weight sensitivity                       | Measurement                          | Loss elasticities; $B^*$ ; survival   |

**Table 12. Limitations and Proposed Responses**

| Limitation                                    | Proposed response                                              |
|-----------------------------------------------|----------------------------------------------------------------|
| No new causal estimate                        | Test P1–P5 with firm panels, event studies, and PPML models    |
| Evidence from large firms and other countries | Collect SME and Bangladesh data; replicate across regions      |
| Stylized models                               | Calibrate $h, \mu, m, c$ from data; use heavy tailed durations |
| Assumed parameters                            | Replace with estimated values and report sensitivity           |
| Independent hazard regions                    | Model spatial correlation of hazards                           |
| Static resilience choices                     | Add dynamic investment and learning                            |

## Data Availability

No new primary dataset was collected for this evidence synthesis. The paper is designed to support future testing with enterprise surveys, customs and shipment records, and hazard data. The code used to produce the illustrative figures and numerical results is available from the authors on request.

## Conflict of Interest

The authors declare no conflict of interest.

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