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Climate Change As A Trade Shock: Firm Resilience, Global Value Chains, And Competitive Advantage

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Abstract

Climate change is usually analysed as a slow-moving environmental or macroeconomic problem. This paper argues that, for internationally engaged firms, it is better understood as a trade shock: a recurring disturbance that raises trade costs, interrupts input supply, shifts comparative advantage and, through carbon-border measures, changes the price of market access. We develop a conceptual framework linking three groups of climate shocks (acute physical, chronic physical and transition) to three transmission channels (trade-cost, supply and comparative-advantage), and show how firm-levxel mediators such as sourcing structure, inventory buffers and adaptation investment determine who absorbs the loss and who gains share. We then evaluate the framework in two ways. First, we review six recent climate-related disruptions to trade and production, from the 2011 Thai floods to the 2023–24 Panama Canal drought. Second, we build a stylised Monte Carlo model of 500 firms sourcing from 80 suppliers in eight regions with spatially correlated hazards. The simulation shows that diversification across regions matters more than the mere number of suppliers; that single-sourced firms face tail losses of roughly 70 per cent of output at baseline hazard; and that the competitive payoff to resilience is regime-dependent, with lean diversified firms leading at moderate hazard and buffered firms overtaking them once hazard intensity roughly doubles. We derive six testable propositions and outline implications for managers, trade policymakers and developing-country exporters.

Keywords: climate change; trade shocks; global value chains; supply-chain resilience; competitive advantage; carbon border adjustment; adaptation

1. INTRODUCTION

In the final quarter of 2011, floodwaters inundated industrial estates north of Bangkok and, within weeks, manufacturers of hard disk drives and automotive electronics on other continents were rationing output. In 2018, record low water on the Rhine forced barge operators to carry partial loads, constraining chemical and steel supply chains deep in Europe. In 2023 and 2024, drought-induced restrictions at the Panama Canal pushed shippers to queue, reroute or pay premiums for scarce transit slots. None of these episodes was a failure of demand or of domestic policy. Each was a climatic disturbance that travelled through trade and production networks and landed, often far from its origin, on firms that had no direct exposure to the hazard itself.

These episodes motivate the central claim of this paper: climate change should be analysed as a **trade shock**. A trade shock is a change in the conditions under which goods, services and inputs cross borders, whether through costs, availability, relative prices or rules. Climate change fits that definition on every margin. Physical hazards damage ports, rivers and canals and thereby raise the cost and variance of transport. They destroy or idle productive capacity in specific places, which matters disproportionately when those places are nodes in a concentrated global value chain (GVC). Chronic warming and water stress alter the productivity of agriculture and energy-intensive activities, and with it the pattern of comparative advantage. Finally, transition policy, most visibly the European Union's Carbon Border Adjustment Mechanism (CBAM), makes the carbon content of a product a determinant of its price at the border.

Treating climate change as a trade shock has two analytical advantages. First, it moves attention from average damages to the distribution and transmission of damages. A firm's exposure depends less on the climate of its own location than on the structure of its network: where its suppliers are, how correlated their hazards are, how much slack exists in logistics, and how quickly it can switch. Second, it makes competitive consequences central. Shocks

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that cause identical physical damage can produce very different winners and losers, because market share is reallocated in the aftermath toward firms that kept delivering.

The paper addresses three research questions. **RQ1:** Through which channels do climate hazards and climate policy operate as trade shocks for firms? **RQ2:** Which firm-level resilience strategies (sourcing diversification, inventory buffering, adaptation investment) most effectively reduce exposure, and how does their effectiveness depend on the spatial correlation of hazards? **RQ3:** Under what conditions does resilience translate into durable competitive advantage rather than a cost penalty?

Our contribution is threefold. We offer an integrated framework that links physical and transition shocks within one trade-theoretic lens. We provide a transparent, reproducible simulation that isolates the role of spatial correlation and strategy complementarity in a GVC setting. And we derive propositions that distinguish regimes in which resilience pays from those in which it does not, a distinction that is often missing in normative calls for 'more resilient supply chains'.

The remainder of the paper is organised as follows. Section 2 reviews the literature. Section 3 presents the framework and propositions. Section 4 describes the research design. Section 5 reviews case evidence and Section 6 reports simulation results. Section 7 discusses competitive advantage, Section 8 draws implications, Section 9 notes limitations, and Section 10 concludes.

2. LITERATURE AND THEORETICAL BACKGROUND

2.1 Climate, productivity and comparative advantage

A first strand establishes that temperature and weather shape economic output and trade. Dell, Jones and Olken (2012) show that higher temperatures reduce growth in poor countries, and Burke, Hsiang and Miguel (2015) document a non-linear relationship between temperature and productivity, with output peaking at moderate temperatures and declining beyond. Hsiang et al. (2017) map heterogeneous damages across US counties, highlighting that losses are unequally distributed in space. For trade, the key implication is that climate acts on relative productivity. In the Ricardian tradition of Eaton and Kortum (2002), shifts in sectoral productivity across countries change specialisation. Costinot, Donaldson and Smith (2016) apply this logic to agriculture and find that climate-driven shifts in crop productivity alter comparative advantage, with trade and land reallocation dampening aggregate losses. Dingel, Meng and Hsiang (2019) further show that the spatial correlation of climate across countries governs the gains from trade: when hazards are positively correlated across trading partners, trade offers less insurance.

2.2 Global value chains and the propagation of shocks

A second strand studies how shocks propagate through production networks. Acemoglu et al. (2012) demonstrate that idiosyncratic shocks to highly connected nodes can generate aggregate fluctuations. Barrot and Sauvagnat (2016) find that firms suffer when their suppliers are hit by natural disasters, and that losses are larger when the supplier provides specific inputs that are hard to replace. Carvalho et al. (2021), using the Great East Japan Earthquake, show that shocks propagate both upstream and downstream, reaching firms with no direct exposure. Inoue and Todo (2019) reach a similar conclusion for firm-level supply networks. In the GVC literature, Gereffi, Humphrey and Sturgeon (2005) emphasise that governance structure, whether market, modular, relational, captive or hierarchical, determines how easily lead firms can re-source, while Baldwin (2016) highlights that the unbundling of production across borders raised efficiency but also multiplied the points of failure. Antràs and Chor (2022) survey the theory of GVC organisation, in which fragmentation increases exposure to the weakest link.

2.3 Climate risk in supply networks

Pankratz and Schiller (2024) provide firm-level evidence that climate-related disruption propagates through global supply chains and that firms respond by adapting supplier relationships and, in some cases, relocating sourcing. The Intergovernmental Panel on Climate Change (IPCC, 2022) stresses that cascading and compound risks, in which a hazard in one place interacts with transport, energy and financial systems elsewhere, are among the most important and least well-measured impacts of climate change. Evidence of this kind supports the view that physical climate risk is a network property.

2.4 Resilience, dynamic capabilities and strategy

The management literature conceptualises resilience as the capacity to anticipate, absorb and recover from disruption. Sheffi and Rice (2005) argue that resilience combines redundancy with flexibility and that the latter is

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typically cheaper. Teece, Pisano and Shuen (1997) frame the underlying organisational ability as a dynamic capability: the capacity to sense threats, seize alternatives and reconfigure resources. Ivanov and Dolgui (2020) introduce the notion of viability for intertwined supply networks, arguing that survival under repeated shocks, rather than optimal performance under a single scenario, should be the design criterion. Hallegatte (2014) separates direct asset losses from the indirect losses that depend on recovery speed, which is the margin on which firm strategy matters most.

2.5 Transition policy and competitiveness

Transition policy adds a second source of trade shock. The pollution-haven literature (Copeland and Taylor, 2004) asks whether stringent regulation relocates dirty production, while the Porter hypothesis (Porter and van der Linde, 1995) argues that well-designed regulation can spur innovation that offsets compliance costs. Border carbon measures reshape this debate: by taxing embedded emissions at the point of import, they erode the cost advantage of carbon-intensive exporters and reward low-carbon producers regardless of where they are located. For firms in developing economies that supply regulated sectors, this is a shock to market access that is independent of physical hazard.

2.6 Research gap

Existing work tends to examine one channel at a time: macro damages, network propagation, or regulatory competitiveness. Few studies place physical and transition shocks within a single trade lens, and fewer still examine how firm-level resilience strategies interact with the spatial correlation of hazards to determine competitive outcomes. This paper addresses that gap.

3. CONCEPTUAL FRAMEWORK AND PROPOSITIONS

3.1 Climate shocks and transmission channels

We distinguish three classes of climate shock. **Acute physical** shocks (floods, storms, heatwaves) are sudden and localised. **Chronic physical** shocks (drought, sea-level rise, persistent heat) are slow but alter the baseline conditions of production and transport. **Transition** shocks arise from policy and market responses to decarbonisation. These shocks reach firms through three channels, summarised in Figure 1 and Table 1. The trade-cost channel raises the cost and variance of moving goods. The supply channel removes or reduces upstream capacity. The comparative-advantage channel changes relative productivity and energy or water costs across locations, altering who is competitive in which product.

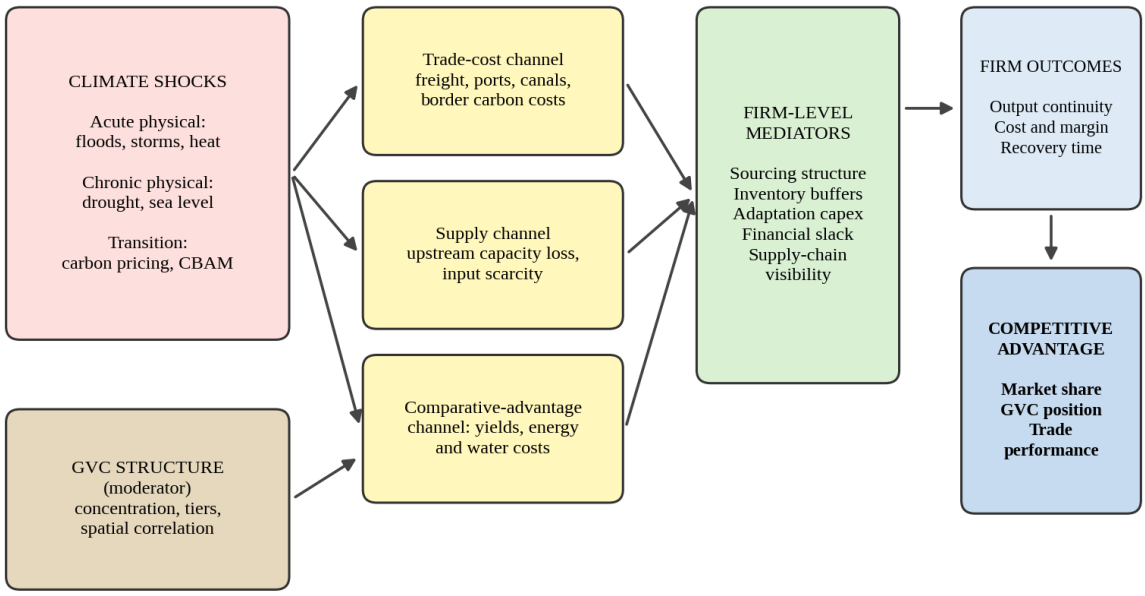


Figure 1. Conceptual framework: climate shocks, transmission channels, firm-level mediators and competitive outcomes

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Table 1. Climate shocks as trade shocks: channels, mechanisms and illustrative exposures

Shock class	Primary channel	Mechanism	Illustrative exposure
Acute physical	Supply; trade cost	Floods, storms and heat damage plants, ports and inland transport; temporary capacity loss	Industrial clusters in flood plains; coastal port complexes
Chronic physical	Trade cost; comparative advantage	Drought lowers river and canal drafts; heat and water stress change agricultural and industrial productivity	Inland waterways; rain-fed crops; water-intensive manufacturing
Transition (policy)	Trade cost; market access	Border carbon charges and reporting rules raise the cost of carbon-intensive exports	Steel, aluminium, cement, fertilisers, electricity exports
Transition (market)	Demand; comparative advantage	Buyer decarbonisation targets reorder supplier lists; energy-price shifts alter cost advantage	Apparel and electronics supplier bases; energy-intensive processing

Source: Researchers' synthesis, drawing on IPCC (2022), Costinot et al. (2016) and Regulation (EU) 2023/956

3.2 Firm-level mediators

Firm outcomes depend on mediators. **Sourcing structure** covers the number of suppliers and, critically, how their locations map onto hazard regions. **Inventory buffers** give time but are costly and only cover short disruptions. **Adaptation investment**, such as flood defences, water recycling and supplier development, lowers the severity of loss when hazards occur. **Financial slack** and **supply-chain visibility** determine how fast a firm can switch and whether it knows which tier-two or tier-three supplier is exposed. The **GVC structure** moderates all of these: when production is concentrated in a few places, as in many electronics and apparel chains, the spatial correlation of hazards across suppliers is high and diversification yields less.

3.3 Propositions

Combining the literature with the framework yields six propositions, summarised in Table 2. They are stated so that they can be tested with firm-level trade and supplier data.

Table 2. Propositions derived from the framework

No.	Proposition	Basis
P1	Holding supplier count constant, the expected loss from climate disruption increases with the geographic concentration of suppliers.	Barrot and Sauvagnat (2016); Dingel et al. (2019)
P2	The risk-reduction benefit of adding suppliers declines as hazards across supplier locations become more positively correlated.	Dingel et al. (2019); IPCC (2022)
P3	Inventory buffers and adaptation investment are complements: buffers cover the short tail of disruption that adaptation does not remove, and vice versa.	Sheffi and Rice (2005); Hallegatte (2014)
P4	The effect of resilience spending on market share is regime-dependent: negative or neutral at low hazard intensity, positive above a threshold intensity.	Ivanov and Dolgui (2020)
P5	Border carbon measures shift competitive advantage toward exporters with lower embedded emissions, independent of physical exposure.	Copeland and Taylor (2004); Porter and van der Linde (1995)
P6	Firms with higher supply-chain visibility and financial slack convert shocks into share gains more often than peers with identical physical exposure.	Teece et al. (1997); Pankratz and Schiller (2024)

Source: Computed from Secondary Data

4. RESEARCH DESIGN

4.1 Approach

The study uses a mixed, theory-building design. A structured review of recent climate-related disruptions illustrates the channels in Section 3 using documented events. A stylised simulation then isolates the mechanisms in P1 to P4 under controlled conditions. The simulation is a thought experiment made explicit: it does not estimate real parameters, but it allows us to examine how strategies perform when spatial correlation, severity and cost are varied. We do not claim that the numerical results predict outcomes in any specific industry. All figures and tables in Sections 6 and 7 are generated by the model described here, with a fixed random seed for reproducibility.

4.2 Simulation model

The model has 500 downstream firms, each procuring a critical input from suppliers drawn from a pool of 80 suppliers distributed across 8 regions. Regions differ in supplier density, reflecting the concentration of real GVCs: the three largest regions host 44 of the 80 suppliers. Each period (interpreted as one year), a climate hazard

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may strike each region with a region-specific baseline probability multiplied by a hazard-intensity factor m. Region-level hazards are linked by a Gaussian copula with correlation ρ = 0.3, which creates the spatial correlation that P2 concerns. A hit supplier loses a fraction of capacity drawn from a Beta(3, 2) distribution (mean 0.6). Severity is drawn once per supplier and is therefore shared by all firms using that supplier, so that firms' outcomes are correlated through common suppliers.

Firms are divided equally into five strategies. **A** single-sources from one supplier. **B** uses three suppliers in the same region. **C** uses three suppliers in three different regions. **D** adopts C plus an inventory buffer that absorbs the first 25 percentage points of any shortfall. **E** adopts D plus adaptation investment that reduces hazard severity by 35 per cent. Multi-sourcing firms can rebalance toward unaffected suppliers, but each supplier can supply at most 125% of its equal share, reflecting limited spare capacity. Output equals the sum of delivered shares, capped at one, less any shortfall not covered by the buffer. Resilience is costly: annual cost is A 0.0%, B 0.4%, C 1.0%, D 2.0%, E 3.0% of revenue.

To study competition, we run 20-year dynamics in which each firm's market share is multiplied each year by its fitness, defined as realised output times one minus the resilience cost, and shares are then renormalised. This reflects customers' reallocation of orders toward reliable suppliers and the price penalty from resilience spending. Operating profit is output times the baseline 10 per cent margin less the resilience cost. We evaluate hazard intensities of 0.5, 1.0, 1.5, 2.0 and 2.5 times baseline. One-period statistics use 3,000 replications; dynamics use 800 replications per intensity.

Table 3. Simulation design and parameters

Element	Specification
Firms / suppliers / regions	500 firms (100 per strategy); 80 suppliers; 8 regions
Supplier density by region	18, 14, 12, 10, 8, 7, 6, 5 suppliers (regions 1 to 8)
Baseline annual hazard probability by region	20%, 15%, 12%, 18%, 10%, 14%, 8%, 12%
Hazard correlation across regions (Gaussian copula)	ρ = 0.3
Capacity loss when hit	Beta(3, 2); mean 60%; shared across firms using the same supplier
Spare supplier capacity (multi-sourcing)	25% above equal share
Inventory buffer (D, E)	Covers first 25 percentage points of shortfall
Adaptation (E)	Reduces severity by 35%
Resilience cost (% of revenue)	A: 0.0; B: 0.4; C: 1.0; D: 2.0; E: 3.0
Baseline operating margin	10% of revenue
Hazard intensity multiplier	0.5, 1.0, 1.5, 2.0, 2.5 x baseline

Note: Parameters are stylised and chosen for transparency, not estimated from data.

4.3 Case selection

For the empirical illustration we select climate-related disruptions that (i) involved a physical hazard rather than a pandemic or conflict, (ii) had documented effects on trade or production beyond the immediate location, and (iii) span different channels and regions. The goal is analytical illustration, not statistical generalisation. Event descriptions below are stated at a level of detail consistent with widely reported public accounts; they are not a substitute for firm-level data.

5. CASE EVIDENCE: CLIMATE HAZARDS THAT BECAME TRADE SHOCKS

Table 4 summarises six events. Three patterns stand out. First, **concentration amplifies**: the Thai floods hit a dense industrial cluster supplying a specialised component, and few downstream producers had qualified alternatives. Second, **chokepoints transmit**: rivers and canals such as the Rhine and Panama Canal are shared infrastructure, so a hydrological hazard raises costs for every user at once. Third, **substitutability determines the loss**: where inputs were standardised, as with many crops, buyers could switch; where they were certified or specific, as with medical products and semiconductors, they could not easily do so.

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Table 4. Selected climate-related disruptions and their trade transmission

Event	Hazard / channel	Transmission to trade and production	Lesson for firms
Thailand floods, 2011	Acute flood; supply channel	Industrial estates in central Thailand inundated; hard disk drive and auto-electronics output disrupted, tightening global supply for several months	Geographic clustering of a specialised component creates correlated exposure
Hurricane Maria, Puerto Rico, 2017	Acute storm; supply channel	Damage to pharmaceutical and medical-device plants contributed to shortages of some hospital supplies in the United States	Single-site production of regulated goods leaves little room for substitution
Rhine low water, 2018	Chronic drought; trade-cost channel	Barges carried reduced loads, raising freight cost per tonne and constraining bulk and chemical supply along the river	Shared infrastructure turns a hydrological shock into an industry-wide cost shock
Taiwan drought, 2021	Chronic drought; supply channel	Severe water shortage prompted water-trucking and rationing for semiconductor fabrication; output was largely protected through emergency measures	Adaptation and public-private coordination can prevent a hazard from becoming a supply shock
Pakistan floods, 2022	Acute flood; supply and comparative advantage	Widespread flooding damaged the cotton crop and rural logistics, affecting textile exporters dependent on domestic fibre	Upstream agricultural exposure feeds directly into export-oriented manufacturing
Panama Canal drought, 2023–24	Chronic drought; trade-cost channel	Water-level restrictions cut daily transits and draft, creating queues, rerouting and premium slot pricing for container, grain and energy cargoes	Chokepoint capacity is a climate-sensitive input; route diversification has a price

Source: Computed from Secondary Data

These cases also show that the same physical event can be a threat to one firm and an opportunity to another. Producers outside the affected cluster that held qualified capacity captured displaced orders, and logistics providers able to offer alternative routings priced the scarcity. Competitive advantage after a shock is therefore partly a function of prior decisions about redundancy, qualification and information.

6. SIMULATION RESULTS

6.1 Output losses by strategy

Table 5 and Figure 2 report one-period output shortfalls. At baseline hazard (1.0x), the single-sourced strategy A loses on average 8.6% of output, and its 95th-percentile loss is 70%. Strategy B, which holds three suppliers in a single region, reduces the mean loss to 1.2% but remains exposed: its tail loss is 7.6% because one regional hazard can disable all three suppliers at once. Geographic diversification (C) cuts the mean to 0.6% and the tail to 2.5%. Buffering (D) and adaptation (E) reduce both to approximately zero at baseline. This is consistent with **P1**: with the same number of suppliers, concentrating them in one region is materially riskier than spreading them out.

Table 5. One-period output shortfall by sourcing strategy (% of output)

Strategy	Mean (1.0x)	P95 (1.0x)	Share of firm-years with loss > 30% (1.0x)	Mean (2.0x)	P95 (2.0x)	Share with loss > 30% (2.0x)
A. Single-sourcing	8.6	69.9	13.2	17.3	80.7	26.4
B. Multi-source, one region	1.2	7.6	1.3	2.8	22.4	2.9
C. Multi-source, diversified	0.6	2.5	0.3	1.6	11.3	1.0
D. Diversified + buffer	0.0	0.0	0.0	0.2	0.0	0.1
E. Diversified + buffer + adaptation	0.0	0.0	0.0	0.0	0.0	0.0

Note: P95 is the 95th percentile of shortfall across firm-years. 1.0x and 2.0x denote the hazard-intensity multiplier. Source: Authors' simulation.

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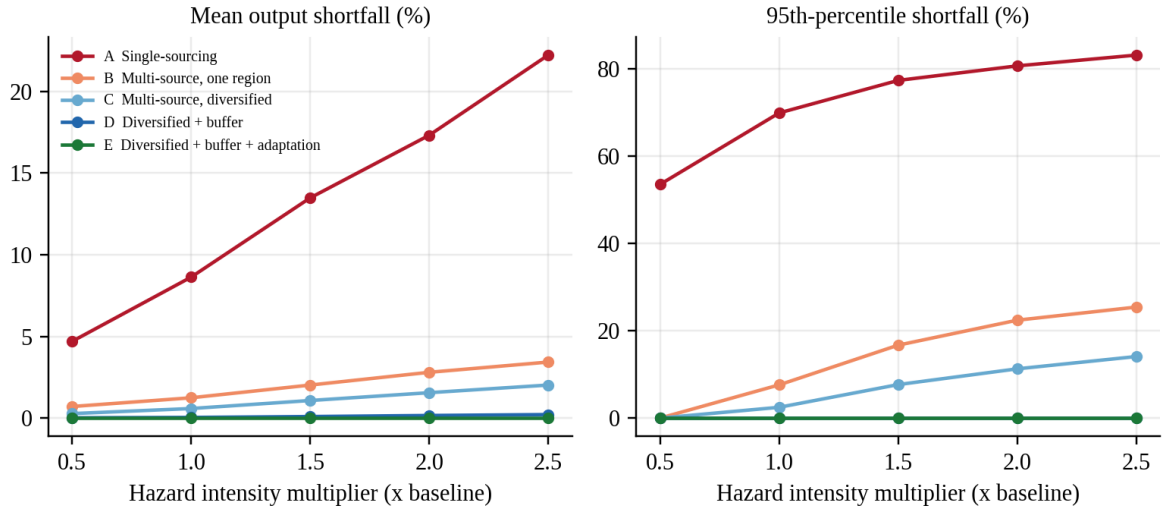


Figure 2. Mean and tail output shortfall by strategy as hazard intensity rises

Figure 2 shows how the gap between strategies widens with hazard intensity. Strategy A's mean shortfall rises from 4.7% at 0.5x to 22.2% at 2.5x. The diversified strategy C rises more gradually, from 0.3% to 2.0%, but its tail loss climbs to 14.1% at 2.5x as simultaneous regional hits become more likely. The model therefore reproduces **P2**: because regional hazards are correlated ($\rho = 0.3$), more intense climates make coincident failures more probable and erode the insurance value of diversification, which is why buffers and adaptation matter at high intensity (**P3**).

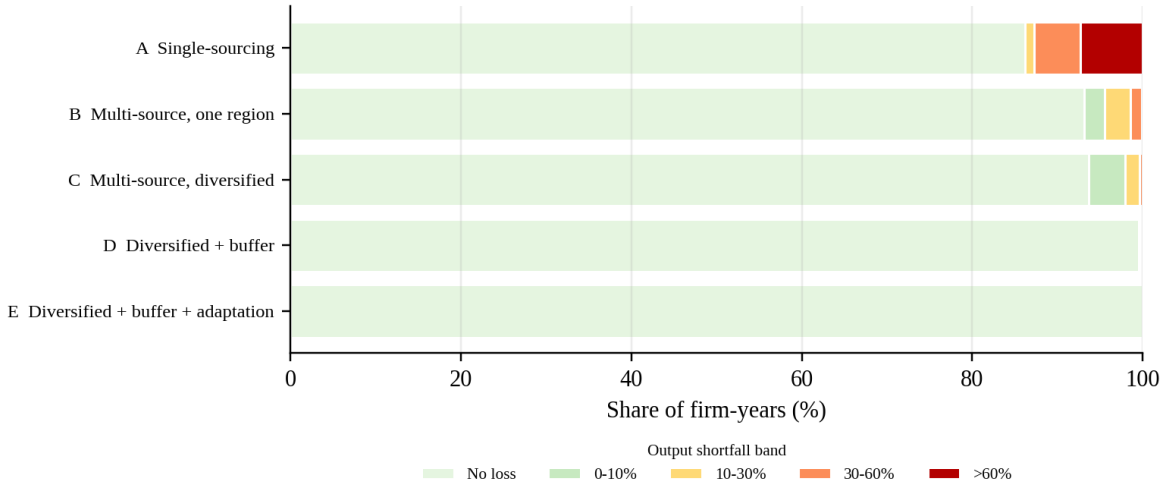


Figure 3. Distribution of annual output shortfall by strategy at baseline hazard intensity

Figure 3 displays the full distribution at baseline. Single-sourced firms are the only group with a visible share of firm-years in the most severe bands. Most multi-sourced firms either experience no loss or a loss below 10 per cent. The distributions illustrate why mean-based evaluation understates the case for resilience: the cost of fragility is concentrated in rare, large events.

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6.2 The resilience–cost frontier

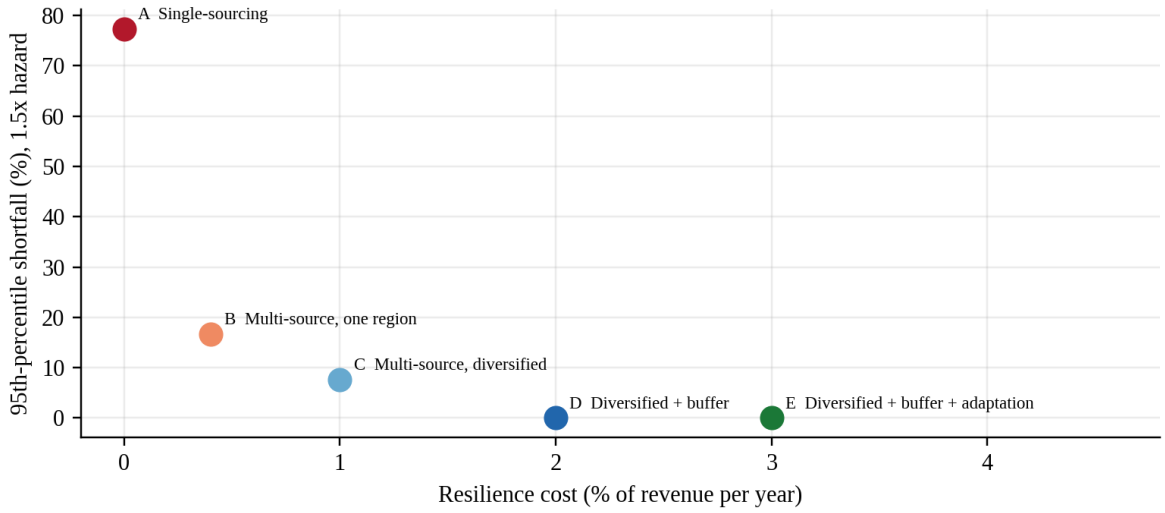


Figure 4. Resilience cost versus tail risk at 1.5x hazard intensity

Figure 4 plots each strategy's annual cost against its 95th-percentile shortfall at 1.5x hazard intensity. The frontier is steeply convex. Moving from single-sourcing (zero cost, 77% tail loss) to regional diversification at 1.0% of revenue removes most of the tail (7.7%). Further spending on buffers and adaptation, at an additional 2.0 percentage points of revenue, removes the remainder. Early dollars buy far more resilience than later ones, which agrees with Sheffi and Rice's (2005) view that flexibility and redundancy have diminishing returns.

6.3 Competition and market share

Does resilience translate into competitive advantage (RQ3)? Figure 5 shows mean market share dynamics at low (0.5x) and high (2.0x) hazard. In the low-hazard regime, lean strategies B and C gain share, reaching 25.1% and 24.2% after 20 years, while the heavily insured strategy E declines to 17.0%: its cost penalty compounds faster than it is repaid. Single-sourcing (A) already loses share, falling to 12.9%, because even moderate disruption leads customers to shift orders. In the high-hazard regime, the ordering changes. Strategy D leads with 27.6%, C reaches 25.4%, E 23.2%, and A is nearly eliminated at 1.4%.

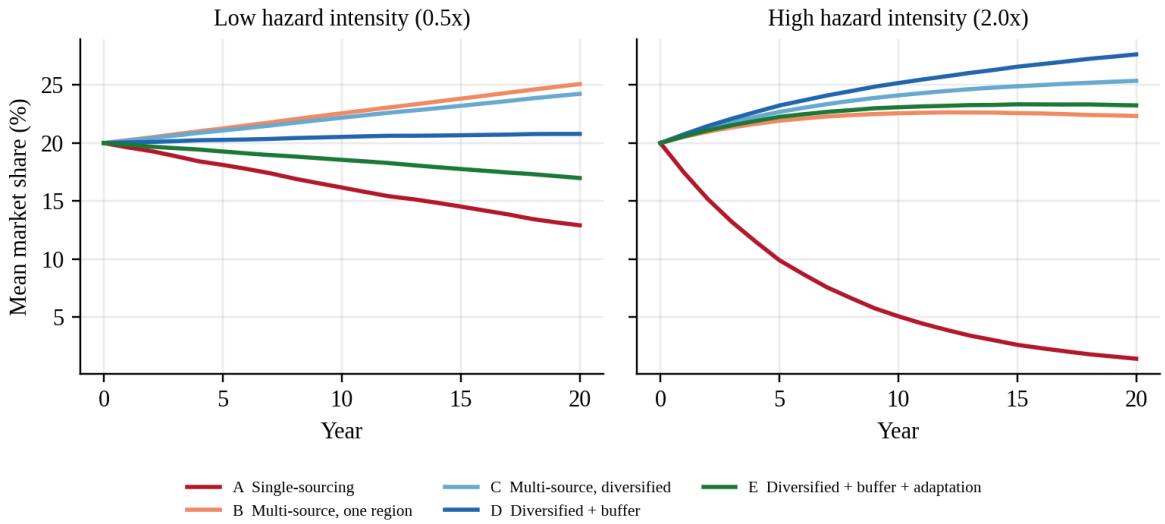


Figure 5. Mean market share dynamics under low and high hazard intensity

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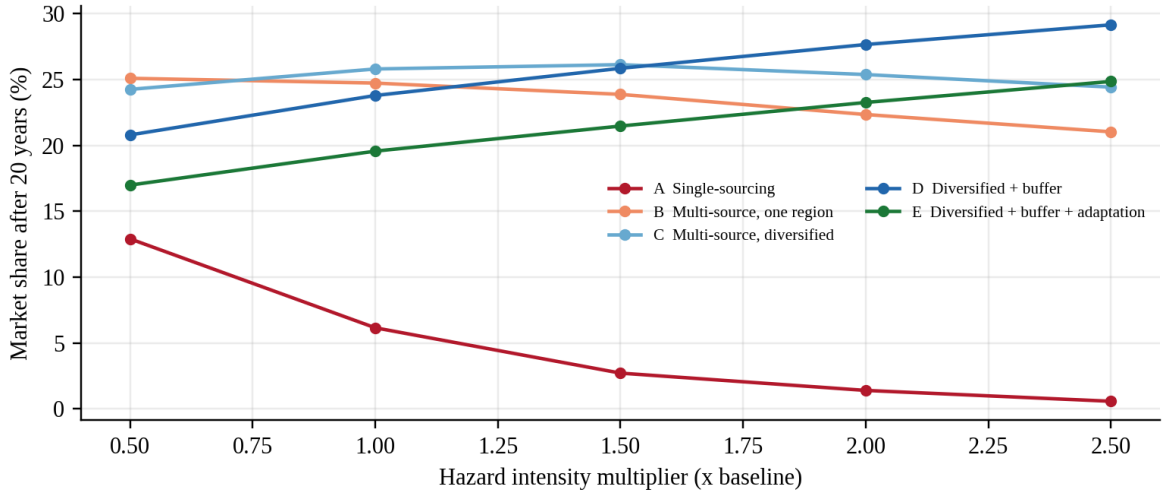


Figure 6. Market share after 20 years as a function of hazard intensity

Figure 6 summarises the regime dependence across the five intensities, and Table 6 reports the underlying numbers alongside cumulative operating profit. At 1.0x and 1.5x, diversified strategy C holds the highest share (25.8% and 26.1%). At 1.5x the buffered strategy D is virtually tied (25.8%), and by 2.0x it has overtaken C (27.6% against 25.4%). By 2.5x the gap is larger (29.1% against 24.4%). The threshold behaviour supports **P4**: the optimal level of resilience investment is not a constant but rises with hazard intensity, and firms that over-insure against a mild climate lose ground to leaner rivals.

Table 6. Market share after 20 years and cumulative operating profit, by hazard intensity

Strategy	Share 0.5x	Share 1.0x	Share 1.5x	Share 2.0x	Share 2.5x	Profit 0.5x	Profit 2.5x
A. Single-sourcing	12.9	6.2	2.7	1.4	0.6	1.91	1.54
B. Multi-source, one region	25.1	24.7	23.9	22.3	21.0	1.91	1.85
C. Multi-source, diversified	24.2	25.8	26.1	25.4	24.4	1.80	1.76
D. Diversified + buffer	20.8	23.8	25.8	27.6	29.1	1.60	1.60
E. Div. + buffer + adaptation	17.0	19.6	21.5	23.2	24.8	1.40	1.40

Note: Share is mean end-of-period market share (%, initial 20% each). Profit is cumulative 20-year operating profit as a multiple of annual revenue. Source: Authors' simulation.

One result deserves emphasis. Cumulative profit and market share do not rank strategies identically. In this calibration, the fully protected strategy E earns the lowest cumulative profit at every intensity (1.40 times annual revenue), because it pays 3.0% of revenue each year and never loses output; the lean strategy B earns the most at moderate hazard. Resilience in the model is therefore valuable for survival and share retention rather than for profit maximisation, and the case for the highest levels of protection rests on benefits that the model omits, such as lower financing costs, insurance premiums, access to premium customers and avoidance of reputational damage. This distinction between the profit and survival criteria echoes Ivanov and Dolgui's (2020) call to design for viability.

7. DISCUSSION: CLIMATE, RESILIENCE AND COMPETITIVE ADVANTAGE

7.1 From resilience to advantage

The results suggest that resilience becomes competitive advantage through three mechanisms. The first is **continuity advantage**: firms that keep shipping during a regional disruption inherit customers displaced from failed rivals, and because relationships are sticky, part of that gain persists. The second is **cost-of-capital advantage**: lenders, insurers and long-term buyers can observe sourcing structure and adaptation, and reward transparency. The third is **option value**: firms that qualify second sources and maintain visibility into lower tiers can exploit relative price shifts after a shock, rather than merely survive it. None of these is automatic. Each requires decisions made before the shock, which is precisely why advantage is hard to imitate quickly afterwards.

7.2 Comparative advantage and GVC position

At the country and industry level, the comparative-advantage channel suggests that climate change will reorder specialisation. Regions where water, heat or flood risk raises production costs will see their relative

competitiveness erode in agriculture and water-intensive manufacturing, while others may gain. Because the effect operates on relative productivity (Costinot et al., 2016), the winners and losers depend on trading partners' climate as well as one's own. For firms in GVCs, position matters: lead firms that coordinate networks can re-source across regions, whereas small suppliers in captive relationships often cannot. Gereffi et al. (2005) predict that captive suppliers bear disproportionate adjustment burdens, and our framework implies that climate risk will intensify that asymmetry unless suppliers upgrade capabilities or diversify their own customer base.

7.3 Strategy trade-offs

Table 7 summarises what each resilience instrument offers and costs. The practical implication is sequencing. Firms should first correct concentration, which is the cheapest source of large risk reduction; then add buffers for the specific, high-criticality inputs whose substitution takes longest; and invest in adaptation where hazards are persistent, where suppliers are hard to replace, or where the firm's own sites are exposed.

Table 7. Resilience instruments: benefits, costs and conditions favouring use

Instrument	Main benefit	Main cost / risk	Most valuable when
Regional diversification of suppliers	Large reduction in tail loss; low incremental cost	Qualification time; loss of scale discounts; hidden common tier-two suppliers	Existing sourcing is concentrated in one hazard region
Inventory buffers	Immediate protection against short disruptions	Carrying cost; obsolescence; no help for long disruptions	Inputs are specific, lead times long, and disruptions brief
Adaptation investment (own sites, supplier development)	Lowers severity at source; benefits all customers of the site	High upfront cost; benefits uncertain; may be captured by others	Hazards are chronic and location cannot easily be changed
Visibility and mapping of lower tiers	Reveals hidden concentration; speeds response	Data and coordination cost; supplier reluctance	Network is deep and multi-tier; critical inputs are shared
Financial slack and insurance	Speeds recovery; supports switching	Opportunity cost; coverage gaps for chronic hazards	Fast re-sourcing requires cash or credit

Source: Computed from Secondary Data by Sheffi and Rice (2005) and Hallegatte (2014).

7.4 Transition shocks and market access

The simulation addresses physical shocks, but P5 concerns transition. Border carbon measures change the trade-cost channel in a way that is deterministic and scheduled, in contrast to the stochastic physical shocks modelled above. The EU's CBAM, established by Regulation (EU) 2023/956, began with a reporting-only transitional period and moves to a financial obligation for importers in covered sectors (such as iron and steel, aluminium, cement, fertilisers, electricity and hydrogen) from 2026. For exporters in these sectors, the carbon intensity of production becomes part of the price of access. In the language of our framework, firms that already measure embedded emissions and invest in lower-carbon processes will experience the policy as a modest cost, while others experience a shock to margin and to buyer relationships. Table 8 lists regimes that matter for internationally engaged firms.

Table 8. Selected policy regimes that transmit climate transition shocks through trade

Regime	What it does	Trade exposure	Firm response
EU CBAM (Reg. 2023/956)	Prices embedded emissions of imports in covered sectors, aligned with EU carbon pricing	Exporters of steel, aluminium, cement, fertilisers, electricity, hydrogen to the EU	Measure product-level emissions; verify data; decarbonise energy and process inputs
EU Emissions Trading System	Caps and prices emissions within the EU	Affects EU competitors' costs and therefore relative export competitiveness	Benchmark against regulated rivals; anticipate price pass-through
Corporate sustainability reporting and due diligence rules	Require disclosure and supply-chain risk management by large firms	Suppliers to covered buyers face data and audit requests	Build emissions and climate-risk reporting capability
Domestic carbon markets (e.g., India's planned carbon credit trading scheme)	Create domestic price signals and offset markets	Shapes exporters' cost structure and readiness for border measures	Align domestic accounting with border-measure requirements

Source: Computed from Secondary Data

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8. IMPLICATIONS FOR MANAGERS, POLICYMAKERS AND DEVELOPING-COUNTRY EXPORTERS

8.1 Managers

- **Map concentration before adding redundancy.** Count suppliers by hazard region, not by contract. Three suppliers in one flood plain are one supplier for risk purposes.
- **Match instruments to the shock profile.** Use buffers for short, sharp disruptions; use adaptation and relocation for chronic hazards.
- **Invest in visibility.** Many failures originate in tier-two and tier-three suppliers that the firm has never audited.
- **Treat carbon intensity as a trade-cost variable.** Embedded emissions affect access to regulated markets and should enter pricing and contract decisions.
- **Scale resilience to the hazard regime.** Over-insurance against mild hazard is a competitive cost, as Section 6.3 shows; under-insurance against intense hazard is an existential one.

8.2 Policymakers

Public policy shapes the hazard side of the equation. Investment in resilient shared infrastructure, such as ports, inland waterways, water supply for industrial clusters and flood defences, benefits all firms using those chokepoints and cannot be provided by any single firm. Disclosure standards that reveal sourcing concentration and climate exposure help markets price risk. Trade policy should also avoid measures that raise the cost of re-sourcing in a crisis, such as export restrictions on key inputs. Finally, designers of border carbon measures should provide clear, early guidance on data requirements and technical assistance to smaller exporters, because compliance cost falls hardest on firms with the least capacity to measure emissions.

8.3 Developing-country exporters

Developing-country exporters face a double exposure: higher physical hazard in many cases and weaker financial and institutional buffers. Small firms in captive GVC relationships have limited ability to diversify customers. Regional cooperation on logistics infrastructure, shared emissions measurement services, access to climate-risk insurance and finance for adaptation, and capacity building for supplier upgrading can reduce the risk that climate change widens existing gaps in GVC participation. For horticulture and agri-food exporters in climate-sensitive regions, where yield variability, cold-chain reliability and market access intersect, such measures are particularly relevant.

9. LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

This paper has several limitations. The simulation is stylised: its parameters are illustrative, there is a single input and a single tier, firms do not re-optimise or learn, and recovery within a year is assumed. Market-share dynamics use a simple multiplicative selection rule that is harsh on weak performers, and a more gradual customer-switching process would soften some results. The case review is qualitative and uses publicly reported accounts rather than firm-level data. The model excludes demand-side effects, price changes, government responses, insurance markets and the possibility that a firm's own plants are hit. The propositions are therefore hypotheses, not findings.

Future research can proceed along four lines. Empirical tests of P1 and P2 are possible with firm-level supplier networks matched to geocoded hazard data, in the spirit of Pankratz and Schiller (2024). Event studies of competitor responses can test P4 and P6. Structural trade models can embed hazard-driven productivity shocks and firm-level resilience choices. And research on border carbon measures can examine P5 using exporter-level emissions data, including for developing-country firms.

10. CONCLUSION

Climate change is already operating as a trade shock. Hazards raise trade costs, interrupt supply and, through policy, change the price of market access. The consequences for firms depend less on whether a hazard occurs in their own location than on how their networks are structured. Our framework and simulation lead to four conclusions. First, regional diversification of suppliers is the highest-return resilience instrument, and counting suppliers without counting regions is misleading. Second, the diversification benefit erodes when hazards are spatially correlated, so buffers and adaptation become more valuable as climate intensifies. Third, the competitive payoff to resilience is regime-dependent: lean diversification wins when hazards are moderate, while buffered strategies overtake it as intensity roughly doubles. Fourth, resilience protects survival and share more reliably than it maximises profit, which

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means that firms and policymakers must justify high levels of protection by reference to tail risk and unmodelled benefits.

For managers, the message is to map hazard exposure across the network, correct concentration first and scale further investment to the hazard regime. For policymakers, it is to provide shared resilient infrastructure and clear transition rules. For researchers, it is to test these propositions with firm-level data. Firms that treat climate as a trade shock, and not as a distant environmental issue, are better positioned to turn disruption into advantage.

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