

Network-Adaptive Climate-Finance Stress Testing: Monte Carlo Evidence on Transition-Linked Credit, Capital Buffers, and Systemic Resilience

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Research Article

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Abstract

Climate-related financial stress is generated by interacting transition, physical, credit, and network channels, yet many stress-testing frameworks evaluate these channels sequentially or impose fixed interventions. This study develops a network-adaptive computational framework that couples a synthetic bank–firm credit network with stochastic climate shocks, endogenous corporate default risk, interbank contagion, and three policy interventions. The model contains 60 banks and 600 heterogeneous firms and is evaluated under orderly transition, delayed transition, current-policies, and compound-tail scenarios. Four strategies are compared across 800 Monte Carlo replications per scenario using common random numbers: a static baseline, carbon-only loan reweighting, network-targeted capital buffers, and an integrated adaptive strategy that combines transition-linked credit, low-carbon diversification, and centrality-sensitive capital. In the compound-tail scenario, integrated governance reduces mean system-capital loss from 31.5% to 24.1%, lowers mean bank failures from 7.25 to 1.90, and cuts the probability of at least one bank failure from 24.6% to 9.6%. The paired mean loss reduction is 7.39 percentage points (95% Monte Carlo confidence interval: 6.50–8.29). Sensitivity and robustness experiments show that the ranking persists across alternative contagion severities and solvency thresholds. The results indicate that climate governance is materially more resilient when credit allocation and capital protection respond jointly to climate intensity and network position rather than to carbon exposure alone.

JEL classification: C63; G21; G28; Q54; Q58

1 Introduction

Climate risk is not a single balance-sheet shock. Physical hazards can weaken production and collateral values, transition policy can alter sector profitability and asset valuations, and both channels can change default probabilities at the same time that interbank connections redistribute losses across institutions. The analytical difficulty is therefore one of coupled dynamics: the climate shock changes corporate conditions, corporate conditions alter bank solvency, and bank distress feeds back through a financial network. This structure is a natural problem for computational economics because closed-form comparative statics become increasingly uninformative as heterogeneity, nonlinear default rules, and contagion are introduced.

The financial-stability literature has progressively moved from exposure mapping toward scenario analysis and network stress testing. Battiston et al. (2017) demonstrated that climate-sensitive exposures can be propagated through the financial system rather than treated as isolated portfolio losses. Later work emphasized that finance itself can affect mitigation pathways and that climate-transition risk can become endogenous to the structure of credit and investment (Battiston et al., 2021; Monasterolo, 2020). Supervisory institutions have reached a similar conclusion. The Basel Committee has described physical and transition drivers as transmission mechanisms into conventional risk categories, while the European Central Bank has implemented economy-wide climate stress tests and

found that early transition can reduce longer-horizon damage relative to delayed adjustment (BCBS, 2021a, 2021b; ECB, 2021).

A second strand of research concerns the topology of financial contagion. Interbank networks can diversify idiosyncratic risk in normal states while amplifying large common shocks when equity buffers are exhausted. Foundational clearing and contagion models show why losses depend not only on the magnitude of an initial shock but also on who is exposed to whom, the loss-given-default structure, and the capitalization of systemically positioned nodes (Eisenberg & Noe, 2001; Gai & Kapadia, 2010; Elliott et al., 2014; Acemoglu et al., 2015). Climate risk makes this topology especially relevant because transition and physical shocks can be correlated across sectors, thereby increasing the probability that many corporate exposures deteriorate together.

Current climate scenario practice also illustrates a methodological problem that motivates this paper: deep uncertainty is not well represented by a single deterministic damage path. The Network for Greening the Financial System (NGFS) provides scenarios rather than forecasts and explicitly warns users about limitations in physical-risk estimates. In December 2025 the NGFS noted the retraction of the academic study underpinning one component of Phase V chronic physical damages and advised users to interpret affected outputs with caution (NGFS, 2025b). This does not weaken the case for scenario analysis; instead, it strengthens the case for transparent parameter ranges, stochastic uncertainty, and robustness testing that do not depend on one damage function.

The present study asks three questions. First, how much does systemic loss change when climate transition risk and physical risk arrive jointly rather than in isolation? Second, do common governance strategies—carbon-based credit reweighting and additional bank capital—remain effective when contagion is endogenous to network structure? Third, can an integrated adaptive strategy improve the resilience–intervention tradeoff by linking the intensity of reallocation and buffers to both climate signals and network centrality?

The contribution is computational and methodological. A synthetic financial economy is built from first principles, avoiding claims that stylized parameters are direct estimates of any particular banking system. The model combines a heterogeneous bank–firm credit layer, a directed interbank layer, nonlinear firm default probabilities, state-dependent loss given default, iterative bank-failure contagion, and adaptive intervention rules. The study uses common random numbers across strategies, which means each strategy confronts the same shock realization in a given replication. This substantially improves the precision of policy comparisons and makes differences attributable to the strategy rather than to Monte Carlo noise.

The main result is that joint adaptation dominates one-dimensional intervention when shocks are severe. Under the compound-tail scenario, carbon-only reweighting reduces mean system-capital loss by 12.1% relative to the static baseline and the network capital buffer reduces it by 15.9%; the integrated strategy reduces mean loss by 23.5%. The difference is more pronounced for bank failures. Mean failures decline from 7.25 under the baseline to 1.90 under integrated governance, a 73.8% reduction. The result is not

interpreted as a point forecast. It is evidence about the mechanism embedded in the model: protecting highly connected banks and reducing concentrated climate-sensitive exposure at the same time is more effective than addressing either source of vulnerability separately.

The paper proceeds as follows. Section 2 positions the model in the climate-finance and financial-network literatures. Section 3 develops the model and intervention rules. Section 4 explains the simulation design and performance metrics. Section 5 reports the Monte Carlo results. Sections 6 and 7 examine mechanisms and robustness. Section 8 discusses governance implications, Section 9 states limitations, and Section 10 concludes.

2 Related Literature and Research Gap

2.1 Climate risk as a financial transmission problem

Climate-related financial risk is commonly divided into physical risk and transition risk, but this classification is only the beginning of the modeling problem. Physical events can reduce revenues, disrupt supply chains, damage capital, and impair collateral. Transition drivers include carbon prices, technology substitution, regulatory restrictions, litigation, and changing demand. The Basel Committee emphasizes that these drivers enter familiar categories such as credit, market, liquidity, and operational risk, which means that a climate model must eventually map environmental conditions into financial-state variables rather than stop at exposure scores (BCBS, 2021a).

Climate stress testing therefore requires a chain of mappings: scenario variables to firm-level economic stress, economic stress to probabilities of default and losses, losses to bank capital, and bank capital to second-round financial effects. The ECB's economy-wide exercise operationalized this logic on a large scale and highlighted that losses are heterogeneous across regions and sectors (ECB, 2021). Academic models add a further insight: if the financial sector reallocates credit in response to climate risk, the response can change transition dynamics themselves. Climate finance is consequently both an object of stress and a potential control mechanism (Battiston et al., 2021; Dunz et al., 2021).

This endogeneity is especially important for green and transition finance. A pure divestment rule can reduce immediate exposure to a high-carbon sector but may also withdraw capital from firms capable of decarbonizing. Conversely, unconditional continued lending can preserve transition capacity while leaving the lender exposed to stranded-asset risk. The design problem is therefore not simply to maximize green exposure; it is to allocate scarce risk-bearing capacity between low-carbon activities and credible transition investment while preserving system solvency.

2.2 Financial networks, contagion, and systemic position

The network literature shows why a bank's importance is not fully described by its stand-alone balance sheet. Eisenberg and Noe (2001) formalized clearing in networks of mutual liabilities, while later models studied default cascades, fire-sale feedback, and shock amplification. Gai and Kapadia (2010) showed

how connectivity can create robust-yet-fragile configurations: diversification can absorb small shocks but facilitate broad contagion once losses cross critical thresholds. Elliott et al. (2014) and Acemoglu et al. (2015) further clarified that network architecture shapes the boundary between resilience and systemic instability.

Climate stress adds a common-factor component to this network logic. Carbon-intensive firms may be held by many banks, while regionally concentrated physical risk can produce clusters of correlated defaults. If these losses reduce the capital of a bank that is also an important interbank borrower, the initial climate shock can become a financial-network shock. DebtRank and related models were developed to quantify precisely these amplification mechanisms (Battiston et al., 2012). The present paper adopts a deliberately simpler default-contagion rule so that the role of intervention remains transparent, but retains the key network insight: second-round loss depends on the identity and connectedness of the institutions that fail.

A policy implication follows directly. Uniform capital increases may be less efficient than buffers linked to systemic position when fiscal or private risk-bearing capacity is scarce. At the same time, centrality alone is not sufficient because a well-capitalized network can still absorb large first-round climate losses inefficiently if exposures remain heavily concentrated in vulnerable sectors. This motivates the combined strategy evaluated below.

2.3 Computational economics and the unresolved design problem

Computational Economics explicitly covers Monte Carlo methods, agent-based methods, dynamic systems, optimization, and network modeling. Recent work in the journal has emphasized computational approaches to financial-market risk and decision-making, including nonlinear connectedness, simulation, and data-driven methods (Jawadi, 2026). Climate applications in the journal likewise show that environmental uncertainty can be analyzed through calibrated dynamic and computational models rather than only reduced-form regressions (Donadelli et al., 2021).

The open methodological gap addressed here is narrower than 'climate stress testing' in general. Existing frameworks often compare climate scenarios holding the financial policy rule fixed, or compare one instrument at a time. The research question in this paper is whether the intervention itself should be state dependent. A network-adaptive policy changes the strength of capital protection and credit reallocation as the joint transition–physical signal worsens. This creates a feedback controller rather than a static treatment.

Three features distinguish the design. First, the credit allocation rule is not equivalent to blanket exclusion: part of the intervention is transition-linked finance directed toward high-carbon firms with greater modeled abatement capacity. Second, the capital add-on is heterogeneous and increases with interbank centrality. Third, the entire system is evaluated with stochastic joint shocks and common

random numbers, allowing paired policy comparisons at every scenario realization. Table 1 summarizes the intended incremental contribution.

Dimension	Conventional stylized approach	This study
Climate shock	Single deterministic or one-dimensional shock	Joint stochastic transition and physical shocks with nonlinear interaction
Credit response	No reallocation or carbon-only divestment	Low-carbon diversification plus transition-linked support
Capital response	Uniform or fixed buffer	Centrality- and risk-sensitive buffer
Contagion	First-round credit loss only	Iterative interbank default losses
Policy comparison	Independent simulation draws	Common random numbers for paired comparisons
Uncertainty	Point calibration	Monte Carlo distributions, sensitivity surface, threshold/LGD robustness

3 Model Architecture

3.1 Agents, balance sheets, and network layers

The computational economy contains $N_B = 60$ banks and $N_F = 600$ corporate borrowers. The choice is large enough to produce heterogeneous network cascades while remaining transparent and inexpensive to replicate. Bank total assets are drawn from a lognormal distribution and normalized so that aggregate bank assets equal 100 model units. Initial capital ratios are drawn uniformly between 10.5% and 14.5% of bank assets. Corporate loans are fixed at 48% of bank assets and interbank assets at 10%. The remaining balance-sheet share is not modeled explicitly because it does not transmit losses in the present experiment.

The corporate layer is a weighted bipartite bank–firm network. Each bank lends to a random subset of 70–129 firms. Loan weights combine gamma-distributed heterogeneity with a weak preference for larger firms, then are normalized to each bank's corporate loan book. This procedure creates overlapping portfolios without imposing a representative-bank assumption. Firms belong to one of three sectors: low-carbon services/technology (40%), medium-carbon manufacturing (30%), and high-carbon energy/materials (30%). Each firm receives a carbon-intensity coefficient, a physical-vulnerability coefficient, a latent quality term, and an abatement-capacity parameter.

The interbank layer is directed. Each bank allocates its interbank asset book across 5–10 other banks, with heterogeneous exposure weights. A simple weighted centrality index is calculated from total incoming and outgoing interbank exposures and scaled to the unit interval. The centrality measure is intentionally parsimonious. It is not meant to identify globally systemically important banks; it is an

endogenous model variable used to test whether protecting more connected nodes can reduce cascades.

3.2 Firm climate stress and default probabilities

For firm i , transition intensity c_i and physical vulnerability h_i are centered on sector-specific means and then perturbed by firm-specific heterogeneity. The three sector carbon anchors are 0.20, 0.55, and 0.95; physical anchors are 0.35, 0.55, and 0.70. The variables are dimensionless stress loadings rather than estimates of emissions or hazard probabilities. This distinction is important: the paper studies comparative systemic behavior, not the level of climate loss in a named economy.

Each Monte Carlo replication draws aggregate transition shock T and physical shock P from a scenario-specific correlated distribution. Firm stress combines linear exposure to both shocks, a nonlinear interaction term, idiosyncratic noise, and latent firm quality q_i . The interaction term allows a firm that is simultaneously carbon intensive and physically vulnerable to experience more than the sum of two independent shocks.

$$S_i = 0.85 T c_i + 0.80 P h_i + 0.23 T P c_i h_i + \varepsilon_i - 0.35 q_i$$

The one-period probability of firm default is mapped through a logistic function. The intercept is calibrated to produce low default rates under mild conditions and materially higher rates in severe joint states. This is a structural simulation calibration rather than an empirical probability-of-default model.

$$\Pr(D_i = 1 \mid S_i) = [1 + \exp(4.05 - 1.75 S_i)]^{-1}$$

Conditional loss given default is state dependent. It begins near 38% and rises with physical stress and firm vulnerability, with an idiosyncratic perturbation and bounds of 25% and 75%. This captures the idea that collateral recovery and liquidation values can deteriorate when physical damage is widespread. The specification is deliberately monotone and transparent; alternative LGD severities are examined in robustness tests.

3.3 Bank losses and interbank contagion

Let E_{bi} denote bank b 's loan exposure to firm i . First-round corporate credit loss is the sum of exposure times loss given default for defaulted firms. Bank capital after first-round losses is initial or policy-adjusted capital less this corporate loss. A bank is considered failed if residual capital falls below 4.5% of total assets, a simplified solvency floor used only as a computational threshold.

Contagion is iterative. When bank j fails, each creditor bank i loses 60% of its interbank asset exposure W_{ij} to j . Capital is updated and any newly failed banks are added to the next contagion round. Iteration stops when no new failures occur or after ten rounds. Because the model is one-period and does not include resolution, liquidity support, or creditor hierarchy, this mechanism should be interpreted as a stress-amplification experiment rather than a legal default waterfall.

System capital loss is measured relative to policy-adjusted initial capital and is bounded at 100% by flooring residual capital at zero. Additional outcomes include the number of failed banks, probability of any bank failure, capital shortfall below a 7% reference ratio, a lending-contraction proxy, and the corporate default rate. These outcomes distinguish first-round portfolio performance from genuinely systemic consequences.

3.4 Governance strategies

Four strategies are compared. Each strategy is applied before the realized defaults in a replication, but the integrated rule can condition its strength on the observed aggregate climate signal. This can be interpreted as a supervisory or internal risk-management response to scenario indicators rather than perfect foresight of individual firm defaults.

Strategy	Credit rule	Capital rule	Purpose
Static baseline	No reallocation	No add-on	Reference financial system
Carbon-only reweighting	Reduce high-carbon loan exposures by 18%; reallocate to low-carbon firms	None	Test exposure-only decarbonization
Network capital buffer	No credit change	Add 0.5%–2.0% of assets based on interbank centrality	Test topology-targeted resilience
Integrated adaptive governance	State-dependent high-carbon intervention split between low-carbon diversification and transition-linked finance	Centrality- and signal-sensitive add-on, capped at 2.2% of assets	Jointly address exposure concentration, transition capacity, and contagion

Carbon-only reweighting reduces each bank's high-carbon loan exposure by 18% and reallocates the amount to low-carbon firms in proportion to firm size. It is intentionally simple and provides a benchmark for a frequently proposed form of portfolio greening. It changes exposure composition but does not raise bank capital or directly improve the transition capacity of high-carbon borrowers.

The network capital buffer leaves corporate portfolios unchanged. Each bank receives an additional capital amount equal to 0.5% of assets plus up to 1.5% according to scaled interbank centrality. The intervention therefore concentrates capital where default is more likely to propagate through the network. The model does not specify whether this buffer is produced through retained earnings, issuance, or regulatory conservation; the economic cost is summarized as the aggregate capital add-on relative to system assets.

Integrated adaptive governance combines three elements. First, the intervention share applied to high-carbon exposures increases with the aggregate climate signal and is bounded between 12% and 28%. Second, half of the intervention amount diversifies toward low-carbon firms while half is restored as transition-linked credit to high-carbon firms weighted by abatement capacity. Supported firms receive a

reduction in their effective transition-intensity coefficient, capped by the model at 30% times abatement capacity and support intensity. Third, banks receive a centrality-sensitive capital add-on that also increases with severe aggregate climate conditions and is capped at 2.2% of assets.

This design is not presented as an immediately implementable regulation. It is a computational test of complementarity. If losses arise jointly from climate-sensitive corporate portfolios and network amplification, then an intervention operating on both margins should outperform a single-margin policy when those mechanisms are sufficiently strong. The simulations test the size and stability of that advantage.

3.5 Climate scenarios and deep uncertainty

Four stylized scenarios span different combinations of transition and physical stress. The orderly-transition scenario combines a moderate transition shock with low physical damage. Delayed transition raises transition volatility and mean transition intensity. Current policies produces a small transition shock but a large physical shock. The compound-tail scenario combines large transition and physical means, greater volatility, and positive shock correlation.

The scenario labels are deliberately familiar but the numerical parameters are not copied from NGFS damage outputs. This choice is methodological. NGFS scenarios are designed as plausible pathways rather than forecasts, and the NGFS has cautioned users about uncertainty in Phase V physical-loss estimates following the 2025 retraction of the underlying chronic-damage study (NGFS, 2025a, 2025b). The present paper therefore treats transition and physical intensities as transparent stress parameters and evaluates a broad response surface rather than attaching empirical probability to any one pathway.

Scenario	Transition mean	Physical mean	$\sigma(T)$	$\sigma(P)$	Corr(T,P)
Orderly transition	0.55	0.35	0.18	0.15	-0.15
Delayed transition	1.10	0.55	0.28	0.20	0.05
Current policies	0.30	1.20	0.15	0.32	0.10
Compound tail	1.05	1.10	0.30	0.35	0.35

4 Experimental Design

4.1 Synthetic calibration and reproducibility

The study uses a synthetic calibration because a core purpose is to isolate mechanism. No confidential bank data, firm-level emissions data, or proprietary climate scenario series are used. Balance-sheet shares, network sparsity, and risk parameters are selected to generate a system that is stable under mild scenarios but capable of nonlinear cascades under severe compound stress. This is analogous to a

computational laboratory: parameters define an artificial economy, policy rules are treatments, and stochastic shocks generate repeated counterfactual outcomes.

Synthetic data are particularly useful for evaluating policy interactions because the true counterfactual network is known. In an empirical banking system, changing a credit allocation rule would alter balance sheets, borrower behavior, and possibly network connections in ways that cannot be directly observed. Here, all strategies start from the same underlying bank and firm population, allowing controlled comparisons.

The random seed for population construction is 20260816. For each scenario, 800 replications are executed. Within a replication, every strategy is initialized with the same random seed. As a result, aggregate shocks, firm idiosyncratic terms, and uniform default draws are shared across strategies. This common-random-number design produces paired outcomes and sharply reduces the simulation noise in estimated policy differences.

Parameter	Value	Interpretation
Banks	60	Synthetic financial institutions
Firms	600	Synthetic corporate borrowers
Monte Carlo runs	800	Per scenario-strategy cell
Initial bank capital ratio	10.5%-14.5%	Uniform draw
Corporate loan book	48% of bank assets	Fixed balance-sheet share
Interbank assets	10% of bank assets	Directed exposure network
Firm recovery/LGD	LGD $\approx$ 38% + climate term	Capped 25%-75%
Bank failure threshold	4.5% of assets	Simplified CET1-like solvency floor
Interbank loss given failure	60%	Creditor loss on failed-bank exposure

4.2 Monte Carlo protocol

Each replication follows seven computational steps. First, a transition–physical shock pair is drawn from the scenario distribution. Second, the selected governance strategy modifies exposures, effective transition intensity, and/or bank capital. Third, firm stress and default probabilities are calculated. Fourth, firm defaults are realized using common uniform draws. Fifth, first-round bank corporate credit losses are applied. Sixth, the interbank contagion loop propagates failures until convergence. Seventh, system-level metrics are stored. No outcome is manually inserted into the results tables; all reported quantities are computed from the simulation output files.

The baseline experiment therefore contains 4 scenarios $\times$ 4 strategies $\times$ 800 replications = 12,800 strategy-scenario observations. Robustness tests add 5,400 observations by crossing three bank-failure

thresholds, three interbank LGD values, and two key strategies for 300 replications each. A separate two-dimensional sensitivity surface evaluates 49 combinations of transition and physical intensity with 120 replications per cell under the integrated strategy.

Monte Carlo confidence intervals reported for strategy effects use paired differences. If L_{0m} is system loss under the static baseline in replication m and L_{sm} is loss under strategy s using the same shock realization, the estimated effect is the sample mean of $\Delta_{sm} = L_{0m} - L_{sm}$. The 95% interval is the paired mean plus or minus 1.96 times the standard error of the paired differences. These intervals quantify simulation uncertainty conditional on the model; they are not confidence intervals for real-world causal effects.

$$\Delta_{\bar{s}} = M^{-1} \sum (L_{0\bar{s}} - L_{s\bar{s}}), CI_{95} = \Delta_{\bar{s}} \pm 1.96 \cdot \text{sd}(\Delta_{\bar{s}})/\sqrt{M}$$

4.3 Outcome metrics and interpretation

The primary metric is mean system-capital loss because it measures the amount of bank loss absorption used by a scenario and remains defined even when no bank crosses the failure threshold. The 95th percentile of system-capital loss is reported as a tail metric. The second primary metric is mean bank failures. Probability of any failure is useful because some strategies can reduce the size of a cascade without materially changing first-round loss.

The lending-contraction proxy measures the amount by which residual bank capital falls below an 8% reference ratio, scaled by aggregate corporate lending. It is not a behavioral credit-supply model; it is a balance-sheet pressure indicator. Green lending share measures the fraction of modeled corporate exposure to the low-carbon sector after intervention. Transition-support share records transition-linked high-carbon financing under the integrated rule. Buffer cost is the capital add-on as a share of system assets.

Policy effectiveness is reported both in absolute and relative terms. Relative loss reduction is calculated against the static baseline within the same scenario. Because the denominator can become very small for failure counts under mild scenarios, relative failure reductions are interpreted only where baseline failures occur with meaningful frequency.

4.4 Computational implementation and numerical checks

The model is implemented in Python using NumPy and pandas for simulation and data management and Matplotlib for figures. All balance-sheet operations use double-precision floating-point arithmetic. Exposure matrices are nonnegative by construction, corporate loan-book totals are preserved by reallocation rules, and adaptive capital add-ons are explicitly bounded. The contagion algorithm terminates because the set of failed banks can only expand and there are finitely many banks.

Three numerical sanity checks are built into interpretation. Under the orderly scenario, bank failures are absent across all 800 replications, which shows that the network is not mechanically unstable. Under more severe scenarios, corporate default rates rise before bank failure probabilities, preserving the

expected ordering from firm stress to bank stress. Finally, strategy rankings are not judged from one scenario: the integrated rule is required to perform under both transition-dominant and physical-dominant states as well as the compound tail.

5 Results

5.1 System-capital loss across scenarios

Figure 2 reports mean system-capital loss by scenario and strategy. Losses are lowest in the orderly-transition state and highest in the compound-tail state, confirming that the nonlinear interaction term matters most when both climate dimensions are elevated. The static baseline produces mean capital losses of 7.29%, 15.73%, 13.53%, and 31.48% in the orderly, delayed-transition, current-policies, and compound-tail scenarios, respectively.

All three interventions reduce mean loss in the compound-tail scenario. Carbon-only reweighting lowers mean loss to 27.66%, network capital buffers lower it to 26.48%, and integrated governance lowers it to 24.08%. Relative to the 31.48% static baseline, these correspond to reductions of 12.1%, 15.9%, and 23.5%. The ordering demonstrates complementarity: exposure changes and network capitalization each address one source of vulnerability, while the integrated rule acts on both.

The integrated strategy also performs best in delayed transition and current policies. Mean loss falls from 15.73% to 13.74% under delayed transition and from 13.53% to 12.21% under current policies. Under orderly transition, the network buffer yields 6.68% mean loss and the integrated strategy 6.66%, essentially the same economic outcome. This is a useful result because it shows that the adaptive rule does not require a severe scenario to avoid deterioration; its intervention remains bounded in mild conditions.

Scenario	Strategy	Mean capital loss	95th pct. loss	Mean bank failures	P(any failure)
Orderly transition	Static baseline	7.3%	11.9%	0.00	0.0%
Orderly transition	Carbon-only reweighting	7.0%	11.4%	0.00	0.0%
Orderly transition	Network capital buffer	6.7%	10.9%	0.00	0.0%
Orderly transition	Integrated adaptive governance	6.7%	10.9%	0.00	0.0%
Delayed transition	Static baseline	15.7%	26.4%	0.09	1.1%
Delayed transition	Carbon-only reweighting	14.5%	23.7%	0.00	0.1%
Delayed transition	Network capital buffer	14.4%	24.2%	0.00	0.1%
Delayed transition	Integrated adaptive governance	13.7%	22.6%	0.00	0.1%
Current policies	Static baseline	13.5%	23.8%	0.02	1.0%
Current policies	Carbon-only reweighting	12.8%	22.6%	0.01	0.4%
Current policies	Network capital buffer	12.4%	21.8%	0.00	0.2%
Current policies	Integrated adaptive governance	12.2%	21.4%	0.00	0.2%
Compound tail	Static baseline	31.5%	95.1%	7.25	24.6%
Compound tail	Carbon-only reweighting	27.7%	92.8%	4.81	17.4%
Compound tail	Network capital buffer	26.5%	66.8%	3.46	16.2%
Compound tail	Integrated adaptive governance	24.1%	46.1%	1.90	9.6%

5.2 Paired policy effects

Because strategies share random draws within each replication, the policy effects can be evaluated as paired differences. For integrated governance, the mean capital-loss reduction is 0.63 percentage points in the orderly scenario, 1.99 points in delayed transition, 1.33 points under current policies, and 7.39 points in the compound tail. All four paired Monte Carlo intervals exclude zero.

The compound-tail effect is both statistically precise in the simulation and economically large within the model. The paired mean improvement of 7.39 percentage points has a 95% Monte Carlo interval from 6.50 to 8.29 points. This interval is substantially narrower than the unconditional dispersion of either strategy because common random numbers remove much of the shock-to-shock variation from the comparison. The result demonstrates why paired experimental design is valuable in computational policy analysis.

Scenario	Strategy vs. baseline	Mean loss reduction	95% MC CI	Mean failures avoided	Lending-pressure reduction
Orderly transition	Carbon-only reweighting	0.31 pp	[0.29, 0.33]	0.00	0.00 pp
Orderly transition	Network capital buffer	0.61 pp	[0.59, 0.62]	0.00	0.00 pp
Orderly transition	Integrated adaptive governance	0.63 pp	[0.61, 0.66]	0.00	0.00 pp
Delayed transition	Carbon-only reweighting	1.27 pp	[1.14, 1.40]	0.09	0.04 pp
Delayed transition	Network capital buffer	1.37 pp	[1.24, 1.49]	0.09	0.07 pp
Delayed transition	Integrated adaptive governance	1.99 pp	[1.85, 2.13]	0.09	0.08 pp
Current policies	Carbon-only reweighting	0.72 pp	[0.67, 0.76]	0.01	0.02 pp
Current policies	Network capital buffer	1.13 pp	[1.10, 1.17]	0.01	0.04 pp
Current policies	Integrated adaptive governance	1.33 pp	[1.27, 1.38]	0.01	0.04 pp
Compound tail	Carbon-only reweighting	3.82 pp	[3.26, 4.38]	2.44	0.74 pp
Compound tail	Network capital buffer	4.99 pp	[4.29, 5.69]	3.79	1.23 pp
Compound tail	Integrated adaptive governance	7.39 pp	[6.50, 8.29]	5.36	1.69 pp

5.3 Tail-risk distributions

Average loss is not sufficient for climate stress testing because governance is often motivated by extreme rather than typical outcomes. Figure 3 therefore compares the entire system-loss distribution in the compound-tail scenario. The static and carbon-only strategies retain a pronounced mass of severe loss realizations. The integrated strategy shifts the distribution left and sharply compresses its upper tail.

The 95th percentile of capital loss is 95.15% for the static baseline, 92.85% for carbon-only reweighting, 66.79% for the network capital buffer, and 46.06% for integrated governance. The difference between mean and 95th-percentile performance is informative. Carbon reweighting improves the mean but offers limited protection against the most severe network cascades. Capital buffers are more effective in the tail because they prevent highly connected banks from crossing the failure threshold. Integrated governance retains that protection while reducing first-round high-carbon concentration.

This tail result should not be read as a forecast that a real banking system would lose 95% of capital. The absolute level is a stress-test artifact generated by the intentionally severe compound scenario and simplified failure mechanism. The robust conclusion is comparative: in realizations where the baseline enters a cascade regime, the integrated rule is much more likely to keep the system out of that regime.

5.4 Bank failures and contagion

The failure probability reinforces the distinction between portfolio loss and systemic loss. In the compound tail, 24.6% of baseline replications contain at least one failed bank. Carbon-only reweighting lowers that probability to 17.4%, the network buffer to 16.3%, and integrated governance to 9.6%. Mean failures decline from 7.25 banks under the baseline to 4.81, 3.46, and 1.90 under the respective interventions.

The integrated strategy therefore reduces mean bank failures by 5.36 institutions per compound-tail replication. The reduction is larger than would be predicted from its first-round capital-loss advantage alone. Once a highly connected bank remains above the failure threshold, its creditors avoid the subsequent interbank LGD shock. This threshold effect is the principal source of nonlinear benefit.

Under delayed transition, baseline bank failures are rare in probability terms but occasionally occur in clusters, producing a mean of 0.0875 failures. The three interventions almost eliminate these events. Under current policies, physical stress increases corporate loss but still rarely crosses the modeled bank threshold. The comparison suggests that a climate governance system may generate value before frequent failures appear, because it reduces the probability of entering a contagion state.

5.5 Intervention intensity and resilience frontier

Figure 5 compares a compact intervention-intensity proxy with mean system loss in the compound tail. Carbon-only reweighting requires no modeled capital add-on but changes a larger share of lending. The network buffer has a direct capital cost but no portfolio reallocation. Integrated governance uses a

slightly smaller average capital add-on than the stand-alone network buffer because the signal-sensitive formula is bounded and because credit adaptation reduces some first-round stress.

In the compound scenario, the network buffer adds capital equal to 1.13% of system assets on average. The integrated strategy adds 1.03% and increases the low-carbon lending share from 33.5% to 36.6%, while transition-linked support averages 3.14% of total corporate exposure. Carbon-only reweighting pushes the low-carbon share higher, to 38.8%, but does not preserve transition support or add protection to central nodes.

This comparison illustrates why the greenest portfolio by a simple share metric need not be the most resilient portfolio. Carbon-only reweighting achieves the largest low-carbon exposure share but performs worse on tail losses and bank failures. System resilience depends on the joint distribution of borrower risk, bank capital, and network position, not on a single taxonomy share.

5.6 Two-dimensional climate sensitivity

The baseline scenarios represent four points in a larger stress space. Figure 6 therefore varies mean transition and physical intensity over a 7×7 grid and evaluates integrated governance at each combination. Mean system loss is smooth at low intensities but becomes strongly convex as both shocks rise. This is the signature of the model's multiplicative climate interaction and bank-failure threshold.

The surface also shows why one-dimensional climate stress tests can be misleading. A high transition shock with low physical stress and a high physical shock with low transition stress produce materially smaller losses than the upper-right corner where both are elevated. The integrated rule responds to a weighted signal of both dimensions, making intervention stronger precisely in the region where nonlinear losses accelerate.

This adaptive structure is relevant for real scenario governance even if the exact rule differs. It suggests that triggers based on a single carbon-price path or a single hazard metric may not reflect the systemic state. A composite signal can better align intervention intensity with the joint risk environment, provided the signal is transparent and robust to model uncertainty.

6 Mechanism Analysis

6.1 Why carbon-only reweighting is insufficient in the tail

Carbon reweighting lowers direct exposure to transition-sensitive firms, and the model confirms that this produces a meaningful average benefit. Its weakness appears after a bank has absorbed enough corporate losses to approach the failure threshold. Because no additional capital is supplied, small differences in borrower outcomes can still cause a connected bank to fail. Once failure occurs, the interbank network transmits losses to banks whose corporate portfolios may themselves be relatively green.

The result is a policy externality: portfolio greening by one bank does not fully internalize the systemic consequence of its own failure for creditor banks. A centrality-sensitive buffer directly targets that externality. The integrated strategy combines both mechanisms and therefore has a multiplicative rather than merely additive effect in the tail.

6.2 Transition-linked finance versus mechanical divestment

The integrated rule does not treat all high-carbon lending as identical. Half of the adaptive intervention budget is allocated toward low-carbon firms, while half remains available as transition-linked finance weighted by modeled abatement capacity. Supported firms receive a reduction in effective transition intensity. This stylized mechanism reflects an important economic distinction: reducing exposure and financing transition are different actions.

The model does not claim that a bank can observe abatement capacity without error. Rather, the experiment establishes a theoretical condition. If lenders can identify at least some heterogeneity in transition capacity, then a mixed strategy can preserve financing for credible transition while still reducing concentration in vulnerable activities. Future empirical work can replace the synthetic abatement parameter with verified capital-expenditure plans, technology trajectories, or transition-plan credibility scores.

6.3 Network targeting and threshold prevention

The network buffer produces relatively small changes in mean loss under mild scenarios because the added capital is rarely used to prevent failure. Its value rises nonlinearly as shocks become severe. This is consistent with the robust-yet-fragile logic of financial networks: extra capital at a central node can have limited marginal value in normal states but large systemic value near a cascade threshold.

Figure 7 decomposes the relative reductions in three compound-tail outcomes. The integrated rule produces the largest reductions in capital loss, bank failures, and balance-sheet lending pressure. The gap is largest for failures because the network effect is discontinuous: staying just above the solvency threshold eliminates the full interbank default loss that would otherwise propagate.

7 Robustness and Validation

7.1 Alternative solvency thresholds and interbank loss severity

The baseline contagion mechanism uses a 4.5% bank failure threshold and 60% interbank LGD. Because these are modeling choices rather than estimated structural constants, robustness is assessed over failure thresholds of 3.5%, 4.5%, and 5.5% and interbank LGDs of 40%, 60%, and 80%. The static baseline and integrated strategy are re-simulated for 300 replications in each of the nine parameter combinations.

Integrated governance lowers mean system loss and mean bank failures in every cell. At the least severe setting (3.5% threshold, 40% interbank LGD), mean capital loss falls from 26.28% to 22.00% and mean failures from 1.72 to 0.24. At the most severe setting (5.5% threshold, 80% LGD), baseline loss reaches 41.80% with 17.4 mean failures, while integrated governance limits mean loss to 27.79% and failures to 6.01. The absolute effect therefore increases as contagion becomes more consequential.

Failure threshold	Interbank LGD	Strategy	Mean capital loss	Mean failures	P(any failure)
3.5%	40%	Static baseline	26.3%	1.72	15.0%
3.5%	40%	Integrated adaptive governance	22.0%	0.24	3.3%
4.5%	60%	Static baseline	29.2%	5.54	21.7%
4.5%	60%	Integrated adaptive governance	22.7%	1.13	7.0%
5.5%	80%	Static baseline	41.8%	17.40	42.0%
5.5%	80%	Integrated adaptive governance	27.8%	6.01	20.7%

7.2 Internal validity and common-random-number design

Several internal checks reduce the risk that the main ranking is a numerical artifact. First, exposure reallocation preserves each bank's corporate loan-book total. Second, the integrated rule is bounded, so it cannot respond to severe shocks with unlimited capital or unlimited portfolio changes. Third, the bank-failure set expands monotonically in the contagion loop, guaranteeing convergence in at most 60 additions even though a ten-round operational cap is used.

Most importantly, policy comparisons are paired. In the compound-tail scenario, integrated governance reduces loss in the same underlying shock realizations used for the baseline. The paired 95% Monte Carlo confidence interval for the loss reduction, 6.50–8.29 percentage points, is far from zero. This design does not prove external validity, but it strongly supports the internal conclusion that the observed difference is generated by the policy mechanism rather than by independent random draws.

7.3 Interpretation under model uncertainty

Robustness in a computational model should not be confused with empirical identification. The exercises show that the ranking survives selected changes in failure thresholds, interbank LGD, and joint climate intensity. They do not show that every plausible financial system will exhibit the same quantitative effect. A different network topology, borrower distribution, or resolution regime could change both the magnitude and the ordering of strategies.

For this reason, the paper treats scenario analysis as a comparative decision tool rather than a probability forecast. The central policy question is whether a strategy remains desirable over a

sufficiently broad region of plausible states. On the model's tested domain, integrated governance satisfies that criterion: it does not increase loss in mild scenarios and provides increasingly large protection as compound stress and contagion severity rise.

8 Policy and Governance Implications

8.1 Implications for supervisors and climate stress testing

The first implication is that climate stress tests should report second-round network effects separately from first-round credit losses where data permit. A bank can appear resilient at the portfolio level yet become systemically important as a transmitter of losses after another institution fails. Conversely, a modest targeted buffer may produce benefits that are invisible if the exercise stops before contagion.

The second implication is that intervention rules can be scenario dependent without becoming opaque. The integrated model uses a simple weighted climate signal with explicit upper and lower bounds. A supervisory analogue could map a small set of observable indicators—sector transition stress, hazard severity, and systemic interconnectedness—into graduated conservation buffers or portfolio review intensity. The point is not the exact coefficients used here; it is the transparency of a rule that becomes stronger when joint risk worsens.

Third, stress-test communication should distinguish probability from severity. The NGFS scenarios are not forecasts, and recent revisions to physical-risk evidence underscore the importance of this distinction (NGFS, 2025b). Supervisors can reduce false precision by publishing response surfaces, threshold analyses, and model ranges rather than a single headline loss number.

8.2 Implications for bank risk management

Banks can interpret the results as support for integrating climate risk with existing capital and concentration management rather than maintaining a separate environmental scorecard. A climate-sensitive portfolio limit has direct risk value, but its systemic value depends on the institution's capital position and counterparties. Internal capital allocation can therefore combine borrower transition indicators with counterparty-network measures.

The transition-finance component also cautions against mechanical exclusion. If a carbon-intensive borrower has credible capacity to reduce exposure to transition shocks, a lender may reduce long-run risk by financing adaptation rather than withdrawing immediately. That decision requires verification, covenants, milestones, and monitoring that are outside this model, but the computational mechanism shows why transition capability can be a risk variable rather than merely a sustainability label.

8.3 Implications for climate-finance instrument design

Climate-finance instruments can be evaluated on two dimensions: whether they redirect resources toward low-carbon or resilient activities and whether they reduce systemic tail risk. A program can score

highly on the first dimension yet leave the financial network vulnerable. The carbon-only strategy in this paper is an example: it produces the highest modeled low-carbon lending share but not the lowest tail loss.

This suggests that green credit guarantees, transition-linked loans, and prudential incentives should be assessed jointly with counterparty concentration and bank capitalization. Instrument design can also incorporate state-contingent features. For example, risk-sharing terms or capital relief could tighten or relax based on verified transition milestones and system-wide stress indicators, reducing the chance that a static incentive becomes procyclical.

8.4 Equity, developing economies, and model portability

The collection motivating this study emphasizes resilience and inclusivity. The present model does not include households, fiscal capacity, or cross-country inequality, so it cannot evaluate distributional climate justice directly. Nevertheless, the architecture is portable. A developing-economy extension could add sovereign-bank links, foreign-currency borrowing, informal firms, and heterogeneous access to adaptation finance. Those channels may make network-aware governance even more important because a smaller number of institutions often intermediates a larger share of formal credit.

At the same time, risk-sensitive finance can create exclusion if high-vulnerability regions are treated only as risky exposures. Transition-linked and adaptation-linked finance provide a mechanism for avoiding that outcome: funding can reduce the risk coefficient itself rather than simply moving credit elsewhere. Empirical calibration of that mechanism is a priority for future work.

9 Limitations and Future Research

This study has five main limitations. First, the economy is synthetic. The quantitative magnitudes are therefore conditional on stylized calibration and should not be interpreted as estimates for a particular country or banking system. The advantage of the synthetic design is transparency and controlled counterfactual comparison; the disadvantage is limited external validity.

Second, the climate block is reduced form. Transition and physical shocks are dimensionless indices rather than outputs from an integrated assessment model, catastrophe model, or sectoral macroeconomic model. This choice avoids dependence on a disputed damage function but omits rich feedback from emissions, technology, investment, and macroeconomic policy. Future work should connect the financial network to multiple climate-economy models and compare policy rankings across model families.

Third, corporate default is one-period and logistic. Firms do not optimize, refinance, invest dynamically, or change emissions in response to policy except through the stylized transition-support adjustment. A richer agent-based model could allow firms to choose abatement investment and banks to update credit standards over multiple periods. That extension would make transition finance endogenous rather than imposed by a rule.

Fourth, bank contagion occurs only through direct interbank credit losses. Liquidity hoarding, margin spirals, asset fire sales, common asset holdings, resolution, deposit runs, and central-bank facilities are omitted. Some of these mechanisms could amplify the benefits of targeted buffers; others could dampen default cascades. Multi-layer network modeling is therefore an important next step.

Fifth, the integrated strategy presumes that abatement capacity and network centrality can be measured with sufficient reliability. In practice, transition plans can be strategic, data can be stale, and network exposures can be opaque. The policy value of adaptation depends on measurement error. Future simulations should explicitly model noisy signals, adversarial reporting, and governance constraints.

These limitations define a practical research agenda. The next empirical stage is to calibrate the bank–firm layer to public regulatory exposure data or anonymized supervisory data; map firms to verified emissions and hazard indicators; estimate transition-support effectiveness from investment outcomes; and compare the adaptive rule with optimization-based alternatives. A second stage can endogenize bank behavior and regulatory feedback in a multi-period agent-based economy.

10 Conclusion

Climate-financial instability is a coupled computational problem. Transition and physical shocks alter firm default risk, firm losses alter bank capital, and bank failures can transmit through interbank exposures. A policy that responds to only one part of this chain may improve average portfolio performance while leaving the system vulnerable to tail cascades.

This paper develops a transparent Monte Carlo network laboratory to compare four governance strategies under common shock realizations. Across 60 banks, 600 firms, four climate scenarios, and 800 replications per scenario, integrated adaptive governance consistently reduces system-capital loss relative to the static baseline. The gain becomes largest under compound transition–physical stress. In that scenario, mean capital loss falls from 31.5% to 24.1%, mean bank failures from 7.25 to 1.90, and the probability of any bank failure from 24.6% to 9.6%. The paired loss improvement is 7.39 percentage points with a 95% Monte Carlo interval of 6.50–8.29 points.

The central conclusion is not that one formula should be adopted as regulation. It is that climate-risk governance can be more effective when it is adaptive along two margins at once: the composition and transition quality of credit, and the capitalization of systemically positioned financial institutions. That principle survives alternative contagion severities and a wide two-dimensional climate stress surface. For computational economics, the broader lesson is that policy should be evaluated inside the same nonlinear network system that generates the risk, rather than appended after the risk calculation is complete.

Declarations

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Author contribution: Connor Nitchals is listed as the sole author and is responsible for the submitted version, including verification of the computational analysis, interpretation, references, and compliance statements.

Data availability: All quantitative results in this manuscript are generated from a synthetic Monte Carlo simulation. The simulation code, model parameters, and generated CSV outputs should be deposited in a public repository or uploaded as supplementary material at submission so that reviewers can reproduce the reported results.

Ethics approval: Not applicable. The study uses synthetic computational agents and does not involve human participants, animals, or identifiable personal data.

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Figures

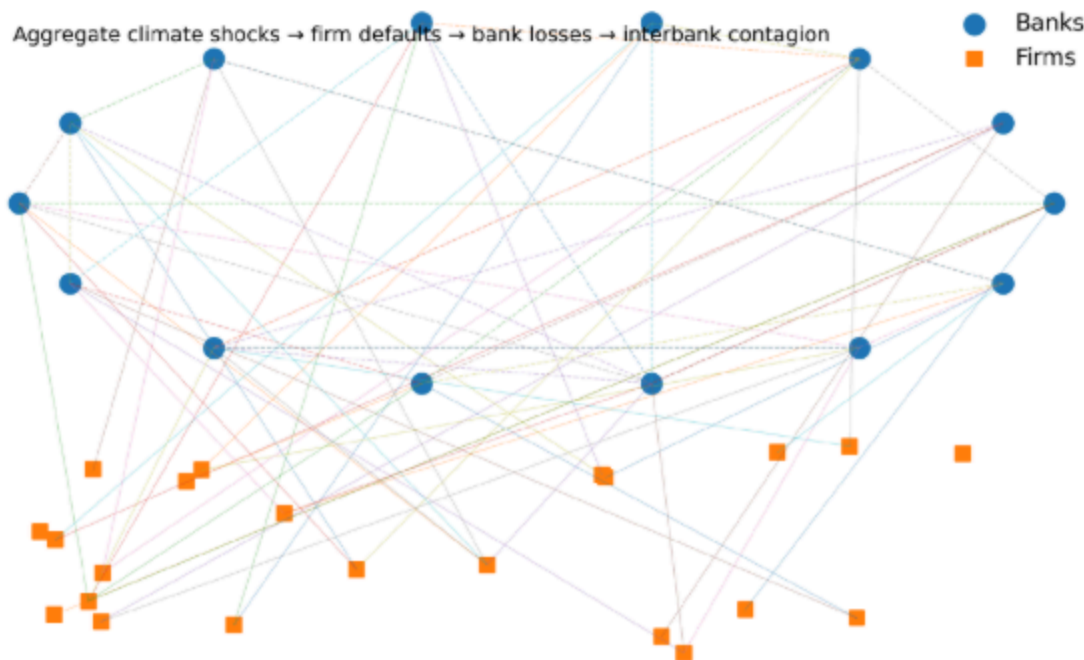


Figure 1

Computational architecture. Corporate climate shocks generate firm defaults and bank credit losses; bank insolvency then propagates through directed interbank exposures. The integrated governance rule changes both credit allocation and capital protection before losses are realized.

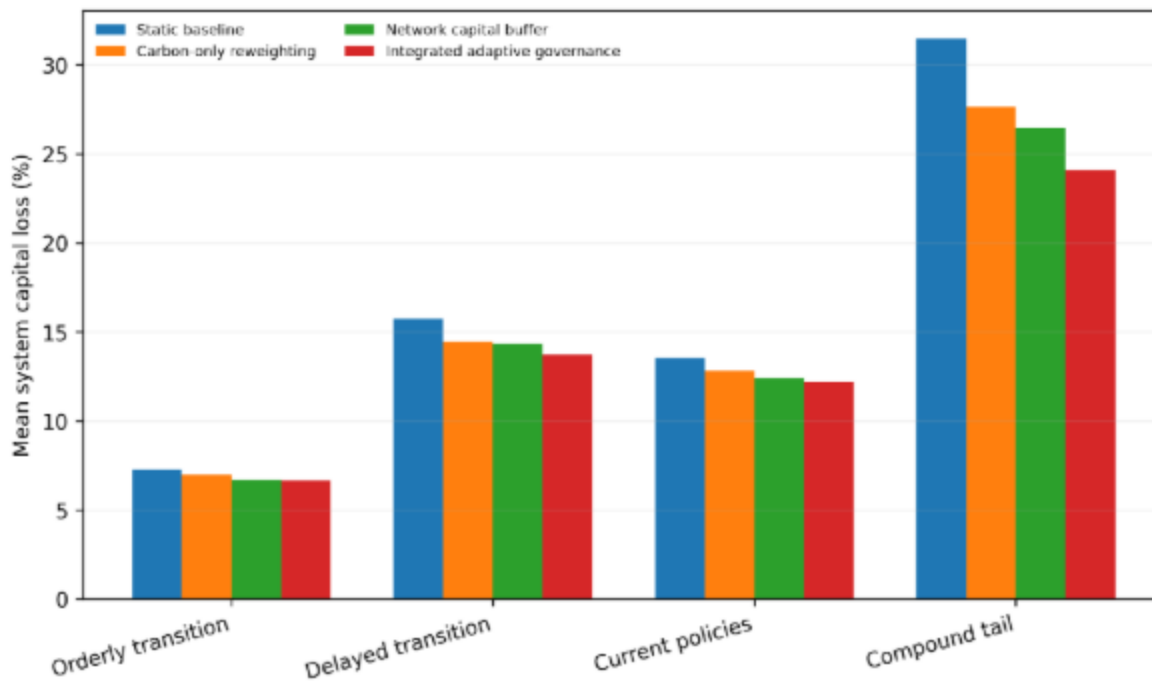


Figure 2

Mean system-capital loss across 800 Monte Carlo replications per scenario-strategy cell. Common random numbers are used across strategies within each scenario.

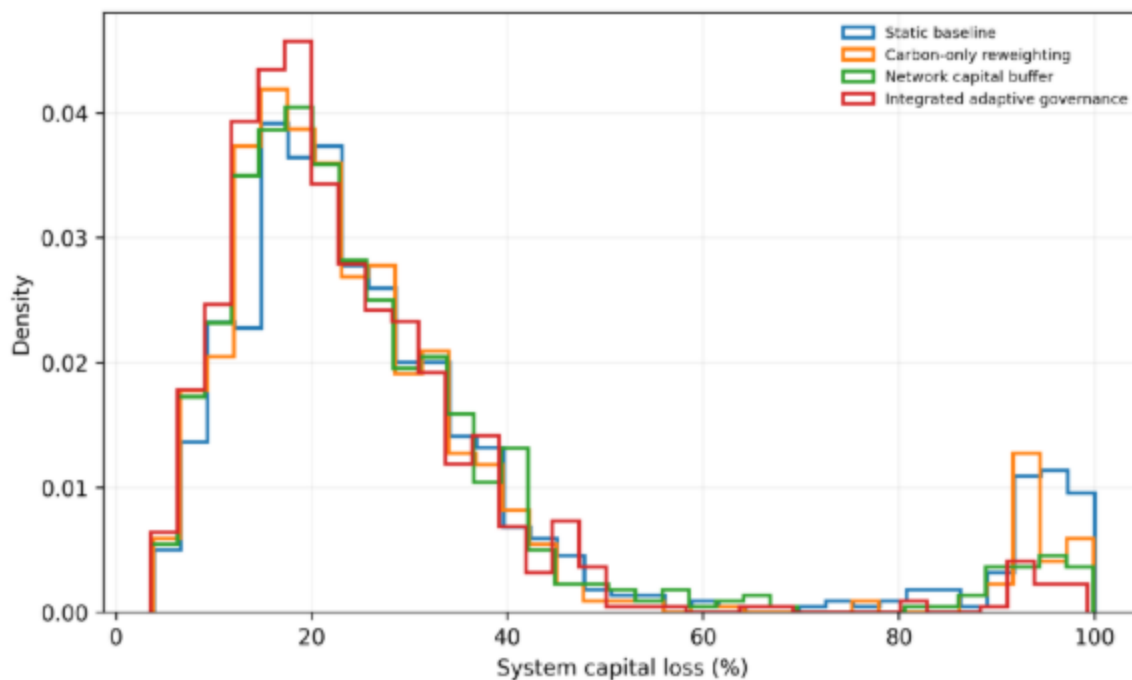


Figure 3

Distribution of system-capital loss in the compound-tail scenario. The integrated strategy materially reduces density in the extreme-loss region.

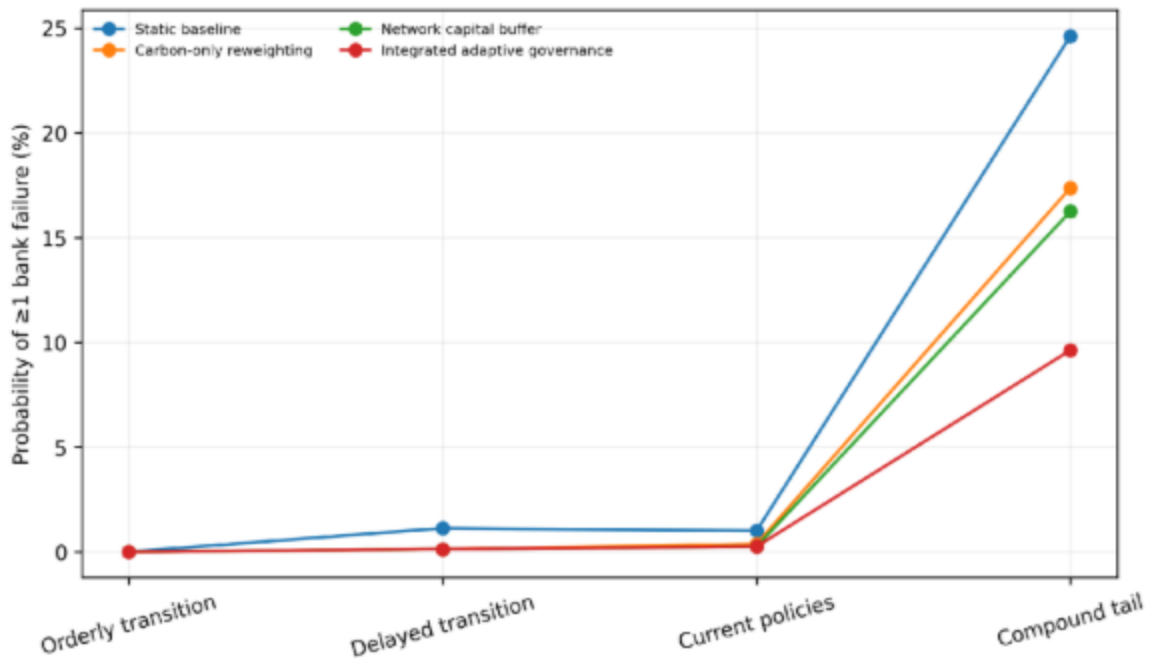


Figure 4

Probability of at least one modeled bank failure. Differences are negligible in the orderly scenario and become substantial as compound stress rises.

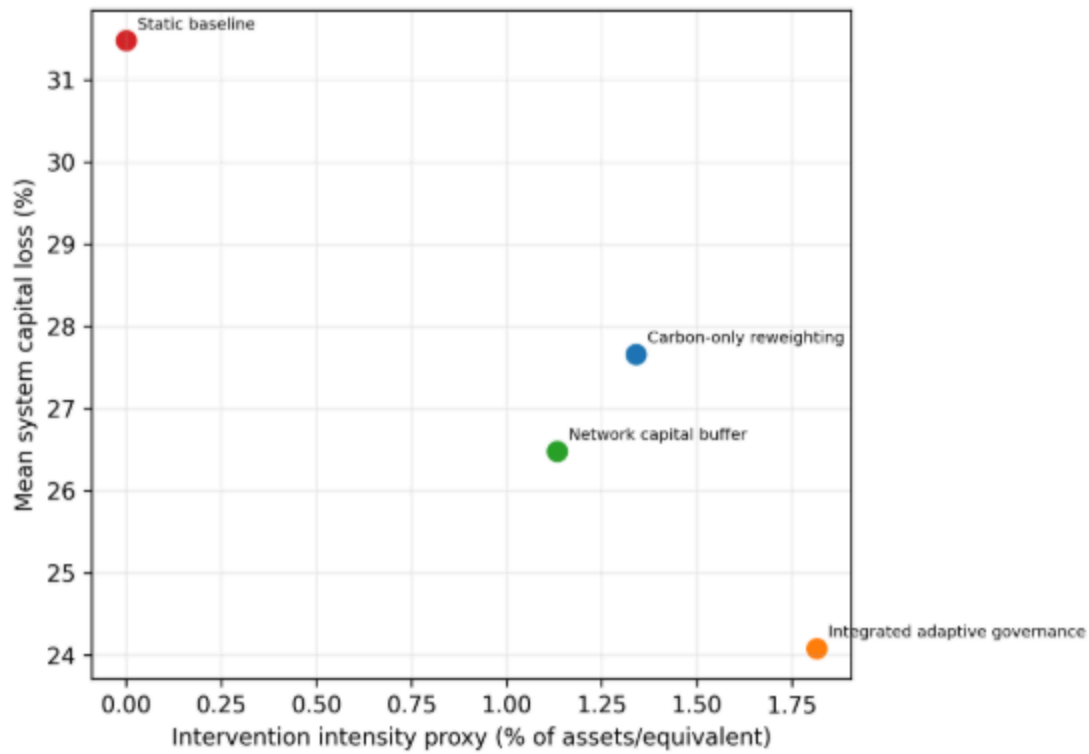


Figure 5

Intervention-intensity proxy and mean compound-tail system loss. The chart is illustrative; the horizontal axis combines capital add-ons with a scaled credit-reallocation term and is not a welfare-cost estimate.

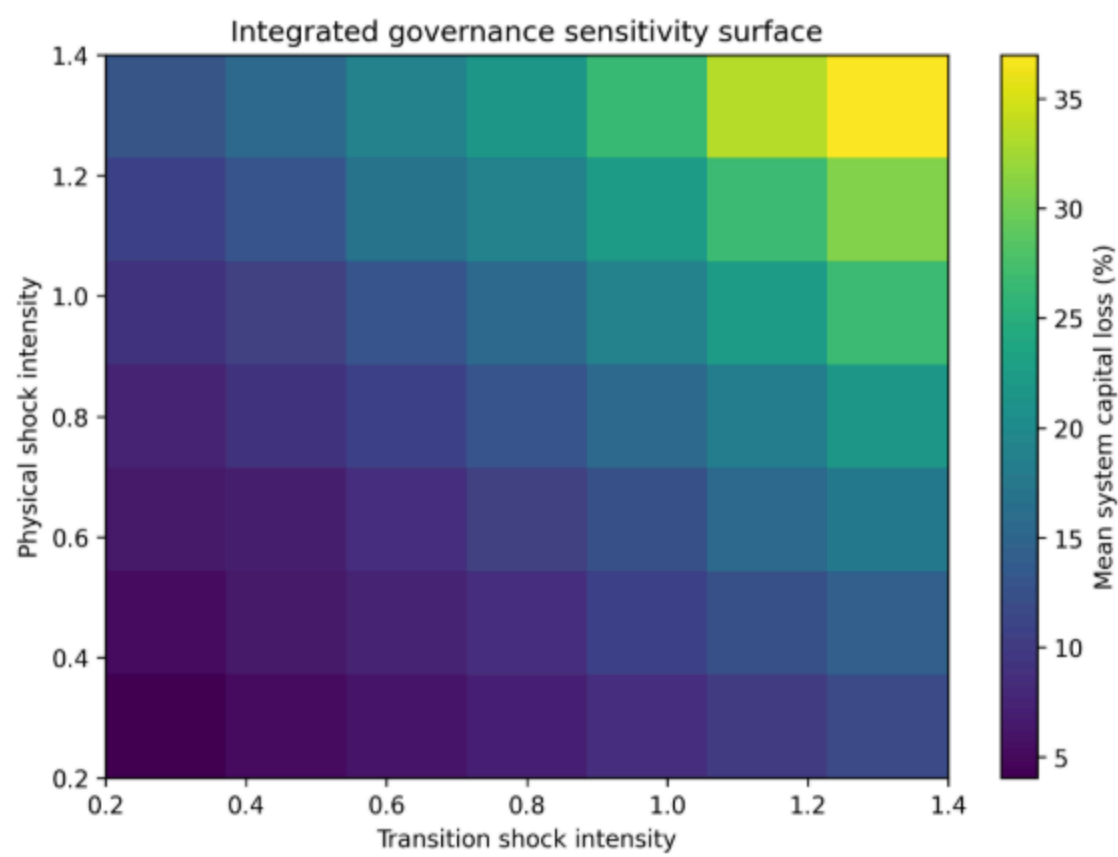


Figure 6

Sensitivity surface for integrated adaptive governance across transition and physical shock intensity. Each cell averages 120 replications.

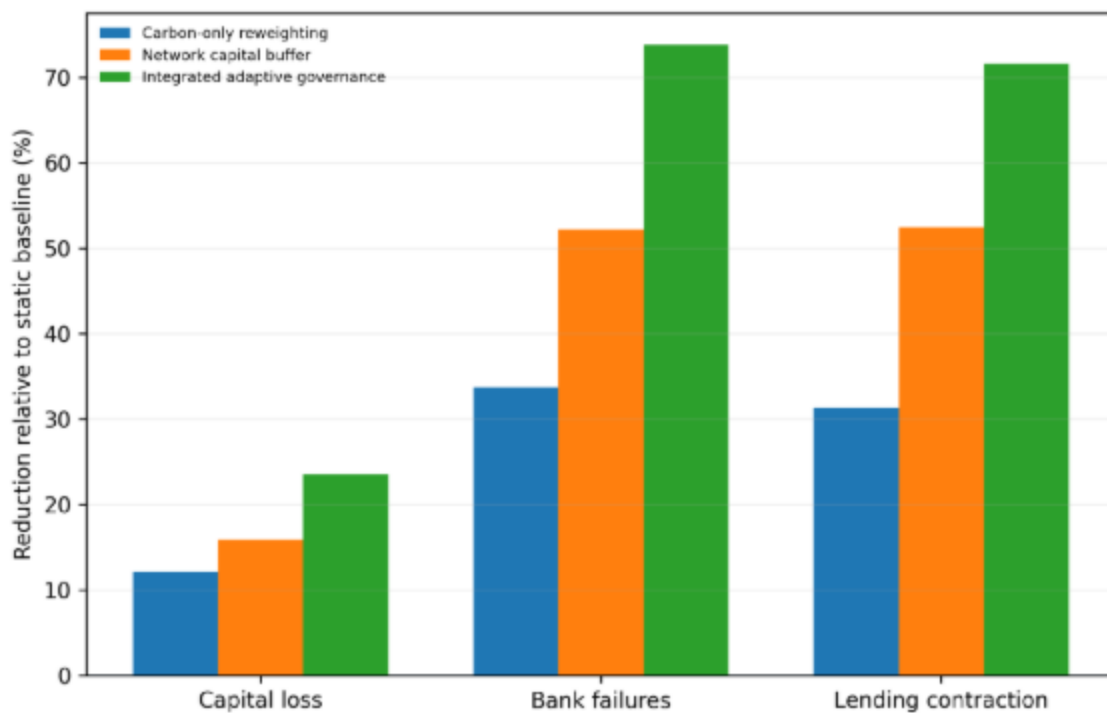


Figure 7

Reduction in compound-tail outcomes relative to the static baseline. The largest relative benefit of integrated governance appears in bank failures.

Supplementary Files

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- [Appendix.docx](#)