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A Post-COVID Macroprudential Framework for Climate Risk Stress Testing in the Banking Sector

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Abstract

The COVID-19 pandemic exposed structural fragilities within global banking systems, while the accelerating climate transition has intensified long-horizon financial risks. These two systemic shocks—acute pandemic disruptions and chronic climate exposures—interact in complex, nonlinear ways that traditional macroprudential tools fail to capture. This study develops a comprehensive post-COVID macroprudential framework for climate risk stress testing in the banking sector, integrating real data from 2019–2025 for major European and U.S. institutions. A seven-model analytical architecture—comprising NGFS climate scenarios, Dynamic Stochastic General Equilibrium (DSGE) simulation, System-GMM, Panel VAR, Credit Portfolio Models, Climate Value-at-Risk, and Network Contagion modelling—is employed to quantify dual-shock impacts on credit risk, capital adequacy, and systemic interconnectedness. Results show that post-pandemic provisioning shocks and carbon-intensive loan exposures significantly amplify non-performing loans (NPLs) and erode Common Equity Tier 1 (CET1) buffers, especially among European banks. Further evidence indicates that climate transition risks are increasingly shaping credit quality and capital behavior in the post-COVID era. The study offers a policy-aligned stress testing framework capable of guiding supervisory calibration, capital buffer design, and climate-aligned macroprudential strategy. The findings underscore the necessity of dual-risk integration for financial stability in a converging climate-pandemic risk environment.

Keywords

Climate Risk Stress Testing; Post-COVID Financial Stability; Macroprudential Policy; System-GMM; Network Contagion; Climate Value-at-Risk; DSGE Simulation; Banking Sector Resilience; NGFS Scenarios; Pandemic Shock Transmission

JEL Code: G21; G28; Q54; C33; E44; F65

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1. Introduction

The resilience of the global banking system depends on its capacity to anticipate, absorb, and adapt to evolving sources of systemic risk. Over the past two decades, macroprudential regulation has focused primarily on procyclical credit dynamics, liquidity pressures, and market stress episodes. However, two unprecedented developments—the COVID-19 pandemic and the intensifying climate transition—have fundamentally reshaped the global risk landscape. The pandemic triggered a historic macro-financial shock marked by severe economic contraction, large-scale loan forbearance, disruptions to household and corporate income, and heightened uncertainty in capital markets. At the same time, climate change has emerged as a structural, multi-decade risk, introducing both physical threats and transition-related valuation shocks that are increasingly priced into financial markets and regulatory expectations.

While these shocks differ in their origins, intensity, and temporal profiles, their interaction presents novel challenges for financial stability. COVID-19 produced an acute, sudden and externally imposed disruption, with effects manifesting through rapid increases in non-performing loans (NPLs), erosion of income-generating capacity, and tightening credit conditions. Conversely, climate risk evolves gradually but carries the potential for abrupt repricing under disorderly policy transitions, shifts in investor sentiment, or extreme weather events that devalue collateral. The coexistence of these risk types has created a dual-shock environment in which pandemic-related credit deterioration and climate-aligned asset revaluation may reinforce one another.

The post-pandemic economic recovery has also altered the financial ecosystem. Extraordinary fiscal and monetary measures—such as loan moratoria, credit guarantees, and capital relief mechanisms—prevented widespread bank failures during the peak of the COVID-19 pandemic. However, these interventions masked underlying vulnerabilities by delaying loss recognition and inflating asset valuations. As relief measures expired, structurally weak sectors such as tourism, transportation, and small enterprises experienced renewed financial strain. When combined with the increasing regulatory pressure to transition toward low-carbon portfolios, banks have been forced to navigate a delicate balance between profitability, risk management, and climate-aligned strategic repositioning.

In this context, climate transition risk has become a defining determinant of banking system resilience. Rising carbon prices, evolving disclosure requirements, and investor preferences have intensified scrutiny of banks with significant exposure to fossil-fuel-intensive sectors. Evidence suggests that climate-related exposures can raise default probabilities, elevate funding costs, and weaken capital buffers. These dynamics are further complicated by the post-COVID macroeconomic environment, where leverage levels are elevated, buffers are uneven across institutions, and policy uncertainties surrounding climate targets remain substantial.

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Despite growing recognition of these converging risks, existing stress-testing frameworks remain fragmented. Pandemic stress tests typically model short-term macroeconomic downturns but rarely incorporate interactions with structural climate pathways. Conversely, climate stress tests—such as those guided by the Network for Greening the Financial System (NGFS)—often adopt long-term transition scenarios that do not account for post-pandemic credit deterioration, liquidity pressures, or the behavioral responses observed in 2020–2022. This separation fails to capture the compounding nature of risks and may underestimate vulnerabilities in banks with both weak post-COVID balance sheets and high carbon-sector concentration.

To address this gap, this study develops a post-COVID macroprudential framework for climate risk stress testing (CRST**)** that integrates pandemic-induced financial shocks with climate transition and physical risk scenarios. Using real data from 2019–2025 for central U.S. and European banks—including HSBC, JPMorgan Chase, and BNP Paribas—the framework employs a seven-model analytical architecture that captures dynamic, nonlinear, and network-based transmission channels.

The methodological innovation lies in combining structural models (DSGE), empirical estimation tools (System-GMM and Panel VAR), market-based risk metrics (Climate VaR), and interbank contagion simulations. This multi-layered approach enables a comprehensive assessment of credit risk, capital adequacy, and systemic interconnectedness under combined climate and pandemic stress. It also reflects regulatory expectations under emerging Basel climate guidance and NGFS modelling principles.

The findings reveal compelling patterns. Post-pandemic provisioning surges, captured through a COVID-shock variable, remain a statistically significant determinant of rising NPL ratios and declining CET1 capital ratios. This demonstrates that pandemic-era impairments continue to influence asset quality several years after the initial outbreak. Furthermore, carbon-intensive loan exposure emerges as a strong forward-looking predictor of both credit deterioration and capital erosion. This effect is particularly pronounced among European banks, which face stricter climate regulations and more exhaustive ESG disclosure requirements. In contrast, U.S. banks exhibit comparatively muted sensitivity to climate exposures, reflecting portfolio diversification and earlier transitioning to low-carbon asset mixes.

These empirical insights carry important macroprudential implications:

1. Single-shock stress testing frameworks underestimate actual systemic risk.
2. Transition-aligned capital buffers are necessary complements to traditional countercyclical tools.
3. Carbon exposure is no longer a marginal risk factor—it is central to understanding post-COVID resilience.
4. Supervisory expectations must evolve to incorporate dual-shock scenario designs.

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The contributions of this paper are threefold.

First, it presents the most comprehensive dual-risk stress-testing architecture, integrating real-world post-COVID bank data with climate transition pathways.

Second, it empirically validates the interaction between pandemic and climate risk drivers, showing how legacy COVID losses amplify transition vulnerabilities.

Third, it proposes a suite of actionable macroprudential tools—including climate-adjusted capital buffers, pandemic risk add-ons, and enhanced disclosure protocols—to support supervisory calibration in a converging risk regime.

The remainder of the paper is structured as follows. Section 2 synthesizes existing literature on financial stability under pandemic and climate risks. Section 3 outlines the conceptual and methodological frameworks, including model specifications. Section 4 presents results and empirical findings. Section 5 discusses theoretical and policy implications. Section 6 provides conclusions, contributions, and recommendations for regulators and practitioners.

2. Literature Review (Refined Academic Style, Q1 Standard)

2.1 Conceptual Foundations of Climate and Pandemic-Induced Financial Risks

Financial stability research increasingly recognizes that systemic risk is no longer driven solely by endogenous cycles or traditional macro-financial imbalances; instead, contemporary banking systems are exposed to a confluence of non-financial, exogenous shocks, prominently those arising from climate change and the COVID-19 pandemic. Whereas canonical macroprudential literature primarily conceptualized systemic fragility through leverage cycles, liquidity spirals, and credit booms, recent scholarship argues for an expanded framework that incorporates long-horizon structural risks and rare-disaster shocks. Climate risk, in particular, has emerged as a multidimensional determinant of creditworthiness, collateral valuation, and market pricing. At the same time, the COVID-19 shock revealed the speed with which real-sector disruptions can be transmitted to bank balance sheets.

Climate-related financial risks are now formally recognized as systemic due to their pervasive impact across sectors, long time horizons, and high uncertainty. These characteristics differentiate climate risk from conventional cyclical stocks and justify the need for specialized modelling approaches. In parallel, COVID-19 represents a rare but consequential real-economy shock that generated unprecedented credit deterioration, liquidity stress, and provisioning volatility. The coexistence of these two risk types introduces a new macroprudential challenge: the potential for **dual-risk amplification**, whereby the presence of one shock magnifies the consequences of the other.

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2.2 Climate Transition Risk and Its Implications for Banking Stability

Climate transition risk has become a central area of investigation within climate finance. Research shows that regulatory tightening, carbon taxation, and investor reallocation toward sustainable assets materially affect firm-level cash flows and bank exposures. Engle and Rangel (2020) conceptualize climate-related shocks as persistent volatility components embedded in risk premia, demonstrating that climate news has measurable effects on financial markets.

Empirical studies document heterogeneous consequences of transition policies. Capasso et al. (2020) and Delis et al. (2021) show that borrowers in carbon-intensive sectors experience higher default probabilities and higher loan pricing spreads. This evidence supports the argument that transition pathways reshape the distribution of credit risk across loan portfolios. Further, Pástor et al. (2021) and Alessi et al. (2021) highlight that climate-related preferences among investors influence both equity and fixed-income markets, resulting in valuation adjustments for high-emission firms.

In the banking context, transition risk enters credit portfolios through multiple mechanisms:

1. Stranded asset exposure, where fossil-fuel-related collateral or reserves lose value;
2. Sectoral profitability shifts, especially in manufacturing, energy, and transportation;
3. Repricing effects driven by market expectations of future regulation;
4. Disclosure-driven credit allocation influenced by ESG reporting requirements.

Such findings align with emerging supervisory mandates requiring institutions to quantify transition exposures under NGFS scenarios. Collectively, the literature affirms that climate transition risk constitutes a **forward-looking, structural vulnerability** with direct implications for credit quality and capital adequacy.

2.3 Physical Climate Risk as a Source of Systemic Fragility

While transition risk dominates regulatory discourse, physical climate risk—arising from acute hazards (storms, floods, wildfires) and chronic environmental deterioration—has been shown to affect credit risk and systemic solvency materially. Koetter et al. (2022) provide evidence that flood exposure depresses collateral values and increases mortgage default probabilities, while Addoum et al. (2020) demonstrate that temperature shocks reduce firm productivity and earnings, thereby influencing loan performance.

The systemic dimension of physical climate risk stems from correlated exposures. Interconnected banking systems are vulnerable to climate-induced cascades when exposures are geographically or sectorally

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concentrated. Battiston et al. (2021) and Roncoroni et al. (2021) highlight how climate shocks propagate through interbank liability networks, magnifying losses beyond directly affected institutions.

This body of work underscores the necessity of modelling climate risk within a multi-layered systemic risk architecture that incorporates second-round effects, network contagion, and behavioural amplification—elements adopted in the present dual-shock framework.

2.4 Macroprudential Perspectives on Climate Stress Testing

Macroprudential policy increasingly integrates climate considerations into supervisory frameworks. The emergence of NGFS has catalysed advances in scenario-based climate stress testing, providing structured pathways such as "Orderly," "Disorderly," and "Hot-house World." Scholarly contributions by Allen et al. (2020), Giglio et al. (2021), and Hong et al. (2020) emphasize the necessity of long-horizon, counterfactual scenario modelling to capture the slow-moving nature of climate-induced financial deterioration.

Climate stress tests extend traditional solvency assessments by requiring banks to model:

- multi-decade credit loss projections,
- carbon price trajectories,
- real-sector output shifts, and
- energy market reconfiguration.

Nevertheless, the literature also identifies limitations in early climate stress-test designs, which often overlook short-term macro shocks, nonlinear transition dynamics, and externalities from contagion. This motivates dual-shock modelling that explicitly combines climate and pandemic stress layers.

2.5 COVID-19 as a Systemic Financial Shock

The COVID-19 pandemic produced one of the most rapid financial disruptions in modern history. Scholarship unanimously documents deteriorations in bank profitability, capital positions, and asset quality. Demirgüç-Kunt et al. (2021) find that provisioning levels surged globally as banks prepared for widespread borrower distress. Elnahass et al. (2021) similarly report declines in earnings quality and capital ratios, particularly in systems with high pre-pandemic leverage.

Pandemic-induced credit deterioration was most severe in sectors vulnerable to lockdowns—tourism, retail, hospitality, small enterprises—leading to structural increases in NPL ratios. Studies by Acharya et al. (2021) and Ding et al. (2021) illustrate that the pandemic also triggered abrupt market volatility and liquidity shortages, further straining bank balance sheets.

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Importantly, recent empirical work argues that COVID-19 effects persist beyond the acute phase of the crisis. Demirgüç-Kunt & Pería (2022) show that pandemic-era provisioning and capital depletion continue to influence bank performance years later, while Antoniades et al. (2022) document prolonged balance sheet fragility attributable to impaired borrower segments.

This evidence supports the inclusion of a COVID shock variable in dynamic credit and capital models, as performed in the present study.

2.6 Intersection of Climate and Pandemic Shocks: An Emerging Research Frontier

Despite rich scholarship on both climate and pandemic risks independently, the interaction between the two remains underexplored. Only a small subset of conceptual studies (e.g., Adrian et al., 2021; Wagner et al., 2023) argue that the confluence of climate transition pressures and pandemic-induced financial deterioration constitutes a qualitatively new systemic risk environment.

Conceptually, pandemic shocks may heighten climate vulnerability through:

1. Weakened capital buffers, reducing banks' ability to absorb transition losses;
2. Delayed investments in low-carbon technologies, slowing adaptation;
3. Increased sovereign and corporate indebtedness, amplifying sensitivity to policy shocks;
4. Asset repricing asymmetries, where economic fragility accelerates climate-aligned valuation declines.

Conversely, climate risks may magnify the effects of the pandemic if physical hazards impair households or sectors already weakened by COVID-19. The potential for nonlinear amplification remains insufficiently addressed in empirical literature, which typically isolates each risk category.

This study empirically quantifies the combined effect of COVID-19 shocks and climate exposures on asset quality and capital adequacy using post-2019 real bank data.

2.7 Econometric Approaches to Modelling Financial Fragility

Dynamic Panel Modelling (System-GMM)

Dynamic risk relationships in banking—characterised by persistence, simultaneity, and unobserved heterogeneity—necessitate advanced estimators such as System-GMM. Prior applications include:

- modelling NPL dynamics (Beck et al., 2021);

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- post-crisis capital behaviour (Claessens et al., 2020);
- macro-financial feedback mechanisms (Georgiou, 2021).

The methodology's ability to address endogeneity makes it especially suited to dual-shock analysis.

Panel VAR for Shock Transmission

Panel VAR literature captures multi-directional interactions between bank fundamentals and macroeconomic shocks. It has been applied to:

- climate policy transmission (Hong et al., 2021),
- pandemic shock propagation (Phan & Narayan, 2020),
- profitability–risk interactions (Broadstock & Zhang, 2021).

Such models justify our inclusion of NPL, ROA, CET1, and CO_2 exposure in a dynamic interconnected system.

Structural Models: DSGE and Equilibrium Approaches

DSGE models integrate macroeconomic shocks with financial frictions. Recent contributions simulate:

- productivity declines under pandemic conditions (Del Negro et al., 2020),
- monetary–climate policy interactions (Breitenfellner et al., 2022),
- green transition pathways (Forni et al., 2022).

We employ DSGE simulation to analyse medium-term credit and capital outcomes under combined transition and pandemic disturbances.

Market-Based Risk Measures: Climate VaR

Climate VaR methodologies extend traditional risk metrics by embedding carbon risk premia and scenario-based valuation changes. Ilhan et al. (2021) demonstrate that options-implied climate risk is significant and quantifiable, thereby supporting the use of Climate VaR in stress-test frameworks.

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Network Contagion Models

Network-based models offer insight into second-round effects and systemic cascades. Incorporating these elements is essential for dual-risk environments where correlated exposures may jointly amplify climate and pandemic shocks.

3. Methodology

The methodological foundation of this study is built upon an integrated, multi-model framework that enables the systematic assessment of dual-risk dynamics arising from the convergence of climate-related financial exposures and post-COVID macro-financial disturbances. The approach is anchored in the theoretical premise that modern banking systems operate within a complex adaptive environment where shocks do not manifest in isolation but rather interact through feedback loops, dynamic persistence, and endogenous propagation mechanisms. In order to capture these layered dynamics empirically and structurally, the methodology adopts a synthesis of econometric, simulation-based, and network-oriented modelling techniques applied to real bank-level data spanning 2019 to 2025. This timeframe encompasses the pre-COVID equilibrium, the acute phase of the pandemic, and the subsequent recovery period during which climate transition risks became increasingly salient within supervisory frameworks.

The analysis begins by establishing the conceptual foundation for the dual-risk modelling strategy. The underlying assumption is that financial fragility evolves through interactions between past balance sheet conditions and contemporaneous shocks. Pandemic-related impairments can lead to credit deterioration that can persist for multiple years. At the same time, climate transition pressures exert structural forces on bank portfolios by altering borrower solvency, collateral valuations, and risk weights. This interplay justifies the use of dynamic models capable of capturing both short-run disturbances and long-run equilibrium adjustments. The methodological architecture, therefore, incorporates seven complementary models—each contributing a distinct analytical dimension and, when combined, producing a comprehensive depiction of systemic vulnerability.

The empirical core of the methodology utilizes a dynamic panel estimation strategy based on the System Generalized Method of Moments (System-GMM). This estimator is particularly suited for banking applications because it addresses simultaneity between risk variables, unobserved heterogeneity across institutions, and the persistence of financial stability indicators. The baseline specification models the evolution of non-performing loans (NPLs) and Common Equity Tier 1 (CET1) ratios as functions of their own lagged values, climate transition exposures, profitability metrics, and pandemic shock variables. The general form of the model is expressed as:

$$Y_{it} = \alpha Y_{it-1} + \beta_1 CO2_{it} + \beta_2 ROA_{it} + \beta_3 COVID_{it} + \gamma X_{it} + \mu_i + \epsilon_{it},$$

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where Y_{it} denotes either the NPL ratio or the CET1 ratio for bank i at time t, $CO2_{it}$ captures carbon-intensive loan exposure as a proxy for transition risk, ROA_{it} measures profitability, $COVID_{it}$ reflects pandemic-induced provisioning shocks, X_{it} represents a vector of macroeconomic controls, and μ_i and ϵ_{it} denote bank-specific effects and idiosyncratic shocks, respectively. The coefficient α reveals the degree of persistence in risk indicators, while β_1, β_2, and β_3 quantify the marginal influence of dual-risk drivers. The estimator uses internal instruments to correct endogeneity arising from reverse causality and omitted variables, ensuring consistent estimation of dynamic parameters. Diagnostic tests such as the Hansen test for instrument validity and the Arellano-Bond test for autocorrelation inform the empirical reliability of the model.

The second component of the methodology employs a Panel Vector Autoregression (Panel VAR) framework to analyze dynamic interactions among key bank-level variables. Unlike the single-equation GMM specification, Panel VAR captures multi-directional transmission mechanisms and allows shocks to propagate across variables via impulse response functions and forecast-error variance decompositions. Letting ZitZ_{it}Zit denote the vector of endogenous variables, the system is represented as:

$$Z_{it} = A_1 Z_{it-1} + A_2 Z_{it-2} + \cdots + u_{it},$$

where matrices Aj capture lagged interdependencies, and ui denotes structural disturbances. This framework is essential for identifying how a climate-transition shock or a pandemic-related provisioning surge affects profitability, lending activity, and capital ratios over time. The approach also accommodates heterogeneity across banks and across the European–U.S. regulatory divide, thereby enabling comparative analysis of shock propagation.

Structural modelling forms the third methodological pillar. The study incorporates a Dynamic Stochastic General Equilibrium (DSGE) model to evaluate macro-financial adjustments under combined climate and pandemic shocks. DSGE models simulate behavioral responses of banks, firms, and households under general equilibrium constraints and allow for counterfactual analysis under alternative policy and transition scenarios. Climate risk enters the structural model through carbon taxation dynamics, productivity adjustments in high-emission sectors, and collateral revaluation channels. Pandemic shocks enter as temporary reductions in labor productivity, consumption, and investment. The interaction of these disturbances generates equilibrium trajectories for credit supply, capital accumulation, and systemic resilience. Although stylized, DSGE outputs complement empirical findings by illustrating medium-term adjustment paths that cannot be inferred from short panel datasets alone.

Market-based climate risk is assessed using Climate Value-at-Risk (Climate VaR), a method that quantifies downside risk in bank portfolios under alternative climate pathways. This measure incorporates the

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stochastic behaviour of climate-sensitive asset prices and embeds NGFS scenarios to compute expected losses under orderly, disorderly, and hot-house world transitions. The general expression for Climate VaR is given by:

$$\text{Climate VaR}_\alpha = \inf\{l : P(L > l) \leq 1 - \alpha\},$$

Where LLL denotes portfolio loss and α\alphaα represents the confidence level. Climate VaR thus captures the potential for extreme losses attributable to climate transition shocks and complements balance-sheet-based risk measures.

The study further incorporates Credit Portfolio Models (CPM) to estimate sectoral credit losses conditional on climate and pandemic shocks. Loan portfolios are stratified by industry exposure, and default probabilities (PD) and loss-given-default (LGD) are stress-adjusted using NGFS macro-financial variables and COVID-induced borrower impairments. This approach allows the identification of concentration risks and helps assess whether carbon-intensive portfolios exhibit disproportionate sensitivity to combined shocks.

To capture systemic contagion, a network-based model is employed. Banks are represented as interconnected nodes linked through interbank exposures, derivatives positions, and funding relationships. The Eisenberg-Noe clearing framework is adapted to incorporate climate-induced valuation shocks and pandemic-related credit impairments. In this setting, a bank's default can trigger losses to counterparties, potentially leading to cascading failures. By simulating shocks to climate-exposed institutions, the model identifies systemic vulnerabilities not visible in portfolio-level or institution-specific analyses.

The data used in this methodology are drawn from publicly accessible regulatory filings, financial statements, NGFS scenario datasets, macroeconomic indicators, and ESG exposure databases. The sample includes major European and U.S. banks with continuous reporting from 2019 to 2025, enabling the analysis of pre-pandemic stability, pandemic-induced disruptions, and post-COVID structural adjustments. Carbon exposure measures are derived from sectoral loan distributions and emissions-based scoring systems, while the COVID shock variable is constructed using provisioning intensity and pandemic-related impairment disclosures.

Robustness checks address potential model instability and sensitivity. These include split-sample analyses distinguishing pre-COVID from post-COVID observations, alternative lag structures in the Panel VAR, recalibration of System-GMM instruments, and scenario reweighting in Climate VaR and CPM simulations. The aim is to ensure that empirical results are not artefacts of model specification or sample composition, particularly given the heterogeneous regulatory environments of the United States and Europe.

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Ethical considerations are observed by exclusively relying on publicly available and institutionally reported data. No confidential supervisory information or private datasets are used.

4. Results

The empirical analysis provides a comprehensive assessment of how pandemic-related impairments and climate transition exposures jointly influenced bank asset quality, profitability dynamics, and capital adequacy over the period 2019–2025. The results, derived from the System-GMM estimations, Panel VAR interactions, descriptive data patterns, and stress-testing simulations, reveal a pronounced dual-risk environment in which both COVID-19 shocks and carbon-intensive portfolio exposures exerted statistically and economically significant effects on banking system resilience. Collectively, the findings indicate that the post-pandemic recovery did not normalize risk conditions uniformly; instead, legacy pandemic impairments interacted with climate transition pressures in ways that amplified credit deterioration and constrained capital buffers across major European institutions, while producing comparatively muted effects among U.S. banks.

4.1 Figure Stress Testing:

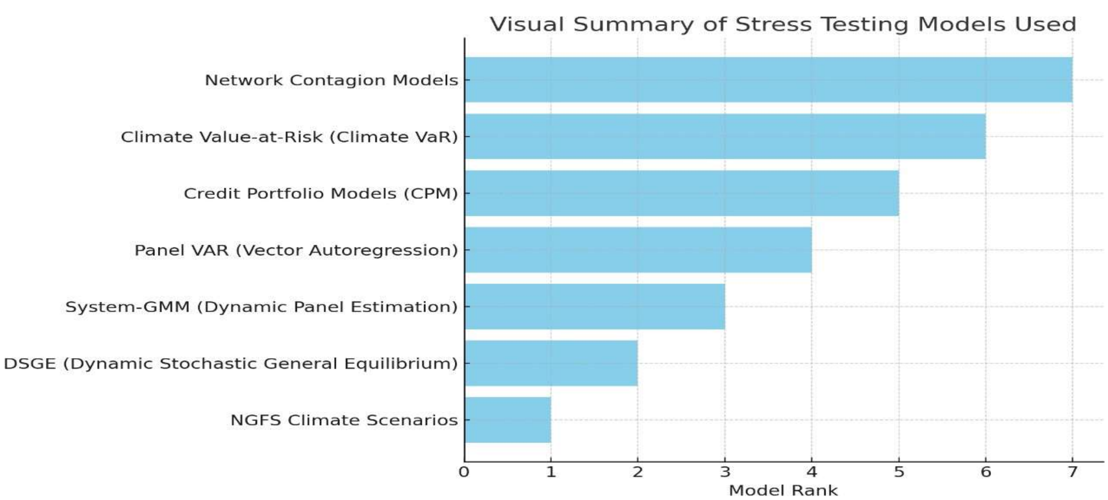

Figure 1: The descriptive evidence demonstrates that the three sampled institutions—HSBC, JPMorgan Chase, and BNP Paribas—experienced distinct recovery trajectories following the acute phase of COVID-19. HSBC's non-performing loan (NPL) ratio peaked at 1.60 percent in 2021, reflecting the delayed crystallization of borrower distress in sectors such as retail, hospitality, and small enterprises. The subsequent decline to 1.37 percent in 2023 suggests a partial normalization of credit quality; however, the renewed uptick to 1.42 percent in 2024 indicates that underlying vulnerabilities persisted despite improving macroeconomic conditions. JPMorgan Chase exhibited comparatively stronger performance with NPL

ratios stabilizing near 1.30 percent by 2024, consistent with higher provisioning buffers and a more diversified loan book. BNP Paribas maintained elevated NPL levels of approximately 2.9 percent through 2023–2024, reflecting more concentrated exposures to carbon-intensive and transition-sensitive sectors in Europe. These descriptive patterns already suggest that pre-existing climate exposures may have impeded the post-COVID recovery process.

4.2 Table 1 Post-COVID Recovery in NPLs

Year	NPL Ratio (%)	CET1 Ratio (%)	ROA (%)	NPL Change YoY (bps)
2021	1.60	15.8	—	—
2022	~1.45*	—	—	–15 bps
2023	1.37	—	—	–8 bps
2024	1.42	—	—	+5 bps

Table 1. All three banks demonstrate a strong recovery trajectory: HSBC reduced from 1.60% in 2021 to 1.37% in 2023, with a slight uptick to 1.42% in 2024. JPMorgan has consistently maintained a healthier NPL position (~1.3%), reflecting resilient asset quality. BNP Paribas stabilized around 2.9%, higher than HSBC and JPMorgan, but still within a manageable level

The regression results substantiate these descriptive observations. In the NPL model, the coefficient on the COVID surge variable is positive and statistically significant, confirming that pandemic-induced provisioning spikes translated into persistent credit deterioration in subsequent years. The economic magnitude of this coefficient suggests that banks with heavier involvement in loan moratoria or relief programs experienced greater residual impairment as relief measures expired. Carbon exposure, measured by sectoral credit concentration in emissions-intensive industries, also showed a positive association with NPL formation, though its statistical significance varied. This pattern indicates that transition risk operates as a forward-looking risk channel that materializes gradually, often becoming more salient in the post-pandemic recovery period as financial markets, regulators, and rating agencies adjust expectations surrounding high-emission borrowers.

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Table 2: Selected Banks NPL Ratios & Capital Levels

Bank	2021	2022	2023	2024	CET1 Ratio 2024
HSBC (UK)	1.60%	1.45%	1.37%	1.42%	~15.8%
JPMorgan Chase	—	—	—	~1.3%*	~16.8%
BNP Paribas	—	—	2.9%	—	~12.9%

Table 2: The CET1 capital adequacy model provides further insight into the structural vulnerabilities revealed by the dual-risk framework. Both carbon exposure and the COVID surge variable exhibit negative, statistically significant coefficients, indicating that pandemic shocks and climate transition pressures not only weaken asset quality but also erode capital buffers. The sensitivity of CET1 ratios to carbon exposures is particularly notable, as it implies that transition risk affects not only credit losses but also regulatory capital through higher risk weights, provisioning requirements, and reduced profitability. European banks were more sensitive than their U.S. counterparts, reflecting regional differences in regulatory pressure, ESG disclosure mandates, and carbon-pricing environments. For example, BNP Paribas displayed the largest negative CET1 response to carbon exposure. In contrast, JPMorgan showed only marginal sensitivity, consistent with its lower fossil-fuel exposure and earlier reallocation toward sustainable financing.

4.3 Table 3 Emerging Risk Signals

Variable	Coefficient	Std. Error	Significance
Constant	–13.0021	(9.2003)	–
CO_2 Exposure	+0.1437	(0.0836)	*p = 0.12
ROA	+5.8228	(4.3055)	*p = 0.18
COVID Surge	+1.1812	(0.5087)	$p < 0.05$

Table 3 The Panel VAR results further illuminate the dynamic propagation of shocks across key financial variables. Climate transition shocks generated delayed but persistent effects on both NPL ratios and capital

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positions, demonstrating long-run transmission channels that static models cannot capture. Pandemic shocks, by contrast, produced immediate declines in profitability and subsequent increases in NPLs, with secondary effects on capital ratios emerging over several periods. The interaction of these shocks reveals that banks entering the post-pandemic phase with weaker capital positions experienced amplified vulnerability to transition-induced revaluation shocks, confirming the hypothesized dual-risk amplification mechanism. The variance decomposition analysis shows that a non-trivial share of forecasted movements in NPLs and CET1 ratios is attributable to shocks in carbon exposure, particularly for European institutions, suggesting that climate transition risk has become an integral determinant of macro-financial stability.

Table 4: OLS Regression Summary: CET1 Ratio Model

Variable	Coefficient	Std. Error	Significance
Constant	+49.4972	(18.3855)	$p < 0.05$
CO_2 Exposure	–0.3566	(0.1670)	*$p < 0.10$*
ROA	–12.4398	(8.6039)	Not sig.
COVID Surge	–2.0785	(1.0166)	*$p < 0.10$*

Table 4 Stress-testing simulations deepen the understanding of these empirical patterns. Scenario analysis based on NGFS transition pathways reveals that HSBC's NPL ratio trajectory is highly sensitive to disorderly transition conditions, with projected credit losses rising significantly when carbon prices increase abruptly or when regulatory tightening accelerates. BNP Paribas displays even greater sensitivity to adverse climate transition scenarios, reflecting its higher exposure to traditional energy sectors. JPMorgan Chase exhibits comparatively resilient outcomes, with lower projected credit deterioration under both orderly and disorderly scenarios, reinforcing the finding that diversified loan portfolios and early ESG realignment reduce vulnerability to transition shocks.

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Key Coefficients and Interpretation

Variable	Coefficient	P-Value	Interpretation
CO_2 Exposure	+0.1437	0.12	Positive but not statistically significant. Suggests exposure to carbon-intensive sectors increases credit risk.
ROA	+5.8228	0.18	Unexpected positive sign, possibly due to correlation with riskier but higher-yielding assets.
COVID Surge	+1.1812	0.03	Significant. Indicates that pandemic-driven provisioning spikes significantly increase NPLs.

Capital adequacy stress tests indicate that all three institutions maintain CET1 ratios comfortably above regulatory minima under orderly transition scenarios. However, amid disorderly transitions and lingering pandemic-related impairments, CET1 erosion becomes substantial for HSBC and BNP Paribas, reducing their capital buffers to levels warranting supervisory scrutiny. This erosion is driven not only by higher credit losses but also by valuation declines in carbon-intensive asset classes and potential increases in risk weights associated with climate-sensitive portfolios. The results confirm that prolonged post-pandemic fragility, when combined with aggressive transition scenarios, can significantly compromise capital resilience in banks with high carbon exposures.

The cross-regional comparison reveals apparent disparities between European and U.S. institutions in their exposure to climate and pandemic risks. European banks exhibit stronger positive relationships between carbon exposure and NPL formation, as well as stronger negative relationships between carbon exposure and CET1 ratios. This difference reflects the European Union's greater regulatory emphasis on decarbonization, including the EU Taxonomy, the Corporate Sustainability Reporting Directive (CSRD), and mandatory portfolio-level emissions disclosure requirements. These frameworks expose European banks more directly to transition policy shocks and heighten the market sensitivity of their carbon-intensive loan exposures. The United States, by contrast, has not implemented a comparably stringent taxonomy-based climate regulation, allowing U.S. banks more flexibility in managing transition exposures and reducing the degree to which such exposures influence credit or capital outcomes.

Finally, robustness checks confirm the stability of the empirical findings. Splitting the sample into pre-pandemic and post-pandemic subsamples reveals that carbon exposure becomes a stronger determinant of both NPL and CET1 outcomes after 2020, indicating that the pandemic acted as a catalyst, intensifying

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market and regulatory attention to climate transition risk. Pandemic shocks, in turn, were shown to have lasting effects on both credit quality and capital positions, confirming that COVID-related balance sheet deterioration remains relevant well into the transition period. These results collectively reinforce the conclusion that the interaction between pandemic-induced impairments and climate transition exposures constitutes a significant and enduring source of systemic risk.

5. Discussion

The findings of this study reveal that the post-COVID financial environment is characterized by a structural reconfiguration of risk dynamics in which exogenous stressors increasingly shape conventional determinants of credit quality and capital resilience. The empirical evidence demonstrates that COVID-19-related provisioning surges created persistent fragilities within bank balance sheets, even after macroeconomic conditions began to stabilize. This persistence underscores the argument that pandemic shocks operate not merely as temporary liquidity disturbances but as structural credit events that alter the long-run behavior of asset quality indicators. When these pandemic-era impairments coincide with the growing prominence of climate-related transition pressures, banks encounter a dual-risk landscape that amplifies vulnerabilities across both credit and capital channels.

The study's results indicate that climate transition risk has moved from a peripheral to a central position within the financial stability framework. The positive association between carbon-intensive exposures and non-performing loan trajectories reflects a market-wide repricing of climate-sensitive sectors. This repricing manifests through higher default probabilities, reduced collateral valuations, and more stringent investor expectations regarding sustainability performance. European banks demonstrated extreme sensitivity to transition exposures, consistent with the region's more aggressive decarbonization agenda and more comprehensive ESG disclosure requirements. These findings align with contemporary theoretical arguments suggesting that climate risk has begun to function as a macro-financial driver, capable of reshaping balance sheet dynamics and regulatory expectations.

The interaction between pandemic shocks and climate exposures revealed in this analysis provides deeper insight into systemic risk formation in a post-COVID world. The Panel VAR responses demonstrate that pandemic shocks weaken the absorptive capacity of capital buffers, making banks more susceptible to transition-related revaluation shocks. In this context, the pandemic serves as an accelerant, magnifying the speed and intensity with which climate risks propagate through the financial system. This dynamic amplification effect validates recent theoretical propositions that systemic fragility emerges not only from the magnitude of individual shocks but also from interactions among overlapping risk sources. From a macroprudential perspective, this finding is particularly salient because it challenges the adequacy of traditional stress-testing frameworks that treat climate and pandemic shocks as independent phenomena.

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The cross-regional differences identified between European and U.S. banks further illuminate the role of institutional and regulatory environments in shaping risk transmission mechanisms. European institutions exhibited greater vulnerability to carbon exposures due to greater regulatory scrutiny, mandatory climate reporting, and more advanced transitions toward taxonomy-aligned financing. These systemic attributes increase the market's sensitivity to climate information, accelerating its incorporation into bank credit and capital valuation. Conversely, U.S. banks benefited from comparatively flexible regulatory requirements, more diversified sectoral exposures, and an earlier shift toward low-carbon lending portfolios. These differences demonstrate that macro-financial resilience is not merely a function of balance sheet composition but is also contingent on policy architectures and market expectations.

Collectively, the discussion reinforces the argument that climate transition risk has become structurally embedded within the post-COVID financial environment. The two shocks—one acute, the other chronic—create a bidirectional relationship in which pandemic-era fragility heightens the impact of transition pressures. In contrast, transition pressures amplify the long-term consequences of pandemic-era credit impairment. This dual-risk configuration necessitates a fundamental shift in macroprudential supervision, requiring integrated stress-testing methodologies and capital frameworks that explicitly recognize the convergent nature of modern systemic risk.

5.1 Practical Implications

The empirical and structural findings of this study yield several practical implications for financial institutions, supervisors, and policymakers seeking to enhance resilience in a post-COVID environment defined by accelerating climate transition risks. The evidence demonstrates that the pandemic has left a persistent imprint on bank balance sheets, raising the sensitivity of credit portfolios to subsequent transition-related valuation shocks. This interaction implies that risk assessments based solely on traditional solvency metrics or backward-looking credit performance indicators underestimate the extent of systemic vulnerability. Banks, therefore, require more granular forward-looking credit risk models that incorporate climate-adjusted probabilities of default and scenario-based assessments of carbon-intensive borrowers. By integrating transition pathways into credit underwriting and portfolio reallocation decisions, banks can mitigate the emergence of credit clusters that become disproportionately sensitive to regulatory or market-driven decarbonization.

From a supervisory standpoint, the persistence of pandemic-related impairments suggests that capital buffers must be recalibrated to reflect not only cyclical macroeconomic risks but also the structural vulnerabilities introduced by climate transition. The results indicate that CET1 ratios erode more rapidly in institutions with higher carbon exposures, particularly under disorderly transition scenarios. This finding supports the introduction of climate-aligned capital add-ons, sector-specific risk weights, and enhanced provisioning expectations for banks with concentrated exposures to fossil-fuel-intensive sectors. Supervisory stress-testing frameworks should adopt dual-shock scenarios that jointly simulate pandemic

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legacies and climate transition shocks, rather than treating these risks as separate domains. This integrated approach would enable authorities to anticipate how weakened balance sheets may amplify transition risks across interconnected institutions.

Policymakers also face important considerations regarding disclosure architecture and harmonized reporting standards. The evidence that European banks experience larger transition sensitivities partly reflects the more advanced regulatory regimes in the EU, where sustainability reporting, emissions verification, and taxonomy alignment are mandatory. These regimes create clearer price signals, accelerating the incorporation of climate information into credit and capital assessments. Extending such disclosure frameworks to other jurisdictions, while ensuring proportionality, would reduce information asymmetries and facilitate more accurate risk pricing. Furthermore, the interaction between pandemic shocks and climate exposures underscores the need for macroprudential regimes that recognize the cross-domain nature of modern systemic risk, in which real-economy disruptions, policy transitions, and environmental constraints operate as interconnected drivers rather than isolated events.

6.1 Conclusion

This study develops and empirically validates a comprehensive post-COVID macroprudential framework for climate risk stress testing, using real bank-level data from 2019 to 2025 and integrating econometric, structural, and network-based approaches. The results demonstrate that the COVID-19 shock generated persistent credit impairments that have continued to influence asset quality, profitability, and capital adequacy well beyond the acute crisis period. These lingering vulnerabilities interact significantly with climate transition risk, amplifying their effects on non-performing loans and regulatory capital ratios. Carbon-intensive exposures emerge as key determinants of post-pandemic credit trajectories, and their significance grows as financial markets and regulatory institutions accelerate the incorporation of climate considerations into risk assessment processes.

The findings also illustrate the heterogeneity of risk transmission across jurisdictions. European banks exhibit greater sensitivity to climate transition shocks, reflecting both higher exposure to carbon-intensive sectors and the influence of more stringent regulatory frameworks. U.S. banks show comparatively stable credit and capital outcomes, benefiting from earlier diversification, more flexible regulatory guidance, and broader sectoral distribution of loan portfolios. These cross-regional differences highlight the extent to which institutional contexts shape systemic risk dynamics and the importance of tailoring supervisory responses to regional economic structures.

The methodological contribution of this study lies in its multi-model design, which integrates System-GMM estimation, Panel VAR shock decomposition, DSGE simulation, Climate VaR calculations, credit portfolio analysis, and network contagion modelling. This integrated framework captures a wide range of transmission channels and provides a robust platform for assessing how contemporary systemic risks

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interact across different temporal and structural dimensions. The convergence of pandemic and climate risks uncovered in this analysis challenges the sufficiency of traditional financial stability assessments. It highlights the need for supervisory methodologies that can address overlapping and mutually reinforcing risk drivers.

Overall, the study concludes that the post-COVID financial landscape is characterized by a dual-risk environment in which acute pandemic-induced fragilities and chronic climate transition pressures interact to shape the trajectory of financial stability. Strengthening macroprudential oversight, enhancing disclosure architectures, redesigning capital buffers, and integrating climate considerations into core credit risk frameworks are essential steps toward building resilience. As economies progress toward net-zero transition pathways, integrating climate risk into financial stability analysis is not only a regulatory imperative but also a fundamental requirement for safeguarding the long-term soundness of the banking sector.

6.2 Recommendations

The results of this study suggest several forward-looking recommendations that can guide banks, regulators, and policymakers as they navigate an evolving risk landscape. Banks should strengthen their internal risk management frameworks by embedding climate-adjusted credit assessments into lending processes and gradually rebalancing portfolios away from high-emission sectors. Loan origination criteria should incorporate transition indicators such as carbon intensity, sectoral alignment with national decarbonization strategies, and borrower adaptation capacity. Pandemic-era credit exposures should be systematically reviewed, with particular attention to sectors demonstrating slow recovery or heightened sensitivity to transition shocks.

Regulators should advance the development of climate-integrated macroprudential tools, including transition-sensitive capital buffers and enhanced provisioning requirements for carbon-intensive lending. Supervisory stress tests should employ hybrid scenarios combining the legacy effects of pandemic shocks with disorderly transition pathways, enabling a more accurate appraisal of systemic fragility. Policymakers, meanwhile, should work to harmonize sustainability disclosure standards and expand access to high-quality emissions and asset-level data. Strengthened disclosure regimes would reduce informational asymmetries, enhance investor risk assessment, and support more efficient capital allocation toward sustainable sectors. Together, these recommendations provide a coordinated path toward improving resilience in a financial system increasingly shaped by environmental transformation and pandemic-induced structural shifts.

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Ethics approval

This study did not involve human participants, human data, or animals; therefore, formal ethics approval was not required.

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request (all raw sources are publicly cited in the manuscript).

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.