Analysis of Climate Risk in the Stability of the Banking System: Towards Green Macroprudential Regulation

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ABSTRACT:

Climate change poses a systemic threat to the stability of the financial system, demanding a thorough reassessment of current regulatory frameworks. This article analyzes the impact of climate risks (physical and transitional) on bank balance sheets and evaluates the feasibility of moving towards green macroprudential regulation. Using a mixed methodology that combines climate stress test scenario analysis (based on ECB and NGFS) and a panel data econometric model, it examines credit vulnerability to the tightening of climate policies. The results show that a disorderly transition would generate a short-term systemic shock due to the devaluation of stranded assets, while a climate inaction scenario would result in a critical and unabsorbable capital deterioration for banks. Furthermore, the econometric analysis empirically confirms that non-performing loans (LPLs) are dramatically amplified by strict climate policies, empirically validating the "horizon tragedy." Regarding regulatory policy, the study demonstrates that the Brown Penalty Factor (BPF) is substantially more effective than the Green Support Factor (GSF) in mitigating systemic risk, as it compels entities to internalize the cost of carbon-intensive exposures. It concludes that, despite the technical challenges related to standardizing taxonomic data, central banks should adopt differentiated capital requirements to safeguard global macro-financial resilience in the face of climate uncertainty.

Keywords: Climate risk, Macroprudential regulation, Financial stability, Stranded assets, Stress tests.

Introduction

Climate change has solidified over the last decade not only as the greatest environmental challenge of our time, but also as a critical and systemic threat to the global economy and financial markets. The materialization of this phenomenon translates into two major risk factors for the financial sector: physical risks, stemming from the increased frequency and severity of extreme weather events that destroy capital and disrupt supply chains; and transition risks, arising from abrupt adjustments in policies, technology, and consumer preferences on the path to a low-carbon economy (Campiglio et al., 2018) . Given this scenario, the possibility of a "green swan" a disruptive climate event with a systemic and largely unpredictable financial impact has forced policymakers to rethink the foundations of financial stability (Bolton et al., 2020) .

Within the financial framework, the banking system is particularly vulnerable to these shocks due to its central role in credit allocation and its direct exposure to greenhouse gas-intensive sectors. Banks' loan portfolios and investment assets can suffer sudden devaluations (stranded assets) if climate policies are abruptly tightened, which would increase default rates and erode bank capital (Roncoroni et al., 2021) . In fact, macroeconomic climate stress tests have shown that, in the absence of an orderly transition, the profitability and solvency of European and international banking institutions would be severely compromised in the medium and long term (Alogoskoufis et al., 2021) .

Faced with this structural vulnerability, traditional microprudential regulation focused on the individual health of each institution has proven insufficient to capture the endogenous and systemic nature of climate risks. The lack of adequate time horizons in traditional risk models clashes with the "tragedy of the horizon," where the worst climate impacts will be felt beyond conventional business and political cycles, yet demand immediate action. This is why academic literature and multilateral institutions agree that central banks and regulators cannot simply be passive observers, but must integrate climate risk into their price and financial stability mandates (Dikau and Volz, 2021) .

In this context, the debate on the need to adopt "green macroprudential regulation" has gained momentum. This new regulatory architecture seeks to mitigate the accumulation of systemic climate-related risks and, simultaneously, redirect capital flows toward sustainable investments (D'Orazio and Popoyan, 2019) . The proposed green macroprudential tools include countercyclical capital reserves differentiated by environmental impact, exposure limits to "brown" (highly polluting) sectors, and the calibration of risk weights according to asset sustainability, recognizing that environmental risk is, ultimately, financial risk (Krogstrup and Oman, 2019) .

The recognition of climate risk as a systemic factor for financial markets reached a turning point with the warning about the "horizon tragedy," a concept introduced by Carney (2015) , who argued that catastrophic climate impacts will materialize long after traditional business planning and monetary policy horizons have expired, necessitating early regulatory intervention. Building on this conceptual foundation, Battiston et al. (2017) developed one of the first climate stress test models applied to the financial system. Their pioneering study demonstrated, using network analysis, that while European banks' direct exposure to fossil fuel sectors appeared manageable, indirect exposures through the interbank market significantly amplified systemic risk under restrictive climate policy scenarios.

As the debate progressed, the literature began to focus on the technical challenges of

incorporating these risks into bank balance sheets. Monasterolo (2020) points out in his review that standard financial models fail to assess climate risk because they assume the market correctly values assets, ignoring the radical uncertainty and nonlinearities of climate events. Along the same lines, when specifically analyzing transition risks, Semieniuk et al. (2021) quantified how the accelerated abandonment of fossil fuels could generate trillions of dollars in stranded assets. Their study warns that much of this loss would be absorbed by the banking system and pension funds, potentially triggering episodes of macroeconomic instability if the energy transition is not accompanied by adequate capital buffers.

Given the evidence of these vulnerabilities, several academics have explored the justification and effectiveness of macroprudential regulation. Thomä and Chenet (2017) argue that there is a fundamental market failure in which asset prices do not reflect transition risk, fully justifying macroprudential intervention to prevent banks from assuming socially unacceptable levels of risk. Complementing this theoretical view with empirical analysis, D'Orazio and Dirks (2022) evaluated the impact of different climate-related financial policies. Their findings indicate that implementing differentiated capital requirements not only improves bank resilience but also has tangible effects on the real economy by discouraging lending to carbon-intensive sectors.

From a practical supervisory perspective, multilateral institutions have begun mapping how to translate these theories into applied regulation. The Basel Committee on Banking Supervision (2020) published a comprehensive analysis for the Bank for International Settlements (BIS) documenting current initiatives by global supervisory authorities. Their research highlights that, while most central banks already require commercial entities to disclose their climate exposures, designing strictly climate-linked capital burdens—the essence of green macroprudential regulation—continues to face technical hurdles related to the scarcity of standardized data and the calibration of long-term scenarios.

However, the implementation of these macroprudential policies is not without intense technical and theoretical debates. One of the central discussions is whether regulators should implement a "green supporting factor" that reduces capital requirements for sustainable loans, or a "brown penalizing factor" that requires more capital to finance polluting activities. Recent studies suggest that, while a green supporting factor may temporarily stimulate low-carbon investment, a brown penalizing factor is much more effective at mitigating long-term macro-financial risks and preventing green credit bubbles (Dafermos and Nikolaidi, 2021) .

At the institutional level, progress toward this regulatory paradigm has been vigorously driven by coalitions such as the Network for Greening the Financial System (NGFS). This network has developed standardized climate scenarios to enable central banks and supervisors to assess the resilience of the global banking system to different temperature trajectories and mitigation policies (Hinselmann, 2023) . However, modeling these scenarios involves a high degree of radical uncertainty, as the interaction between climate tipping points and macroeconomic dynamics falls outside the predictive capabilities of traditional econometric models (Hansen, 2022) .

Considering these dynamics, this essay aims to critically analyze the impact of climate risk on the stability of the banking system and to assess the relevance, feasibility, and challenges of transitioning to a green macroprudential regulatory framework. To this end, the paper will be structured in three main sections: first, the transmission mechanisms of physical and transition risks to bank balance sheets will be broken down; second, the green macroprudential tools currently under discussion will be evaluated; and finally, the institutional limitations and unintended consequences of using capital requirements as climate policy instruments will be analyzed.

Methodology

This research adopts a mixed-methods approach, primarily descriptive and analytical (Creswell & Creswell, 2017) . From a qualitative perspective, the study focuses on critically examining the theoretical evolution of financial regulatory architecture and current macroprudential policy proposals aimed at sustainability. Simultaneously, a quantitative-documentary component is integrated, analyzing the results of climate stress tests recently conducted by various central banks. This combination allows for an objective illustration of the extent to which transition and physical risks can affect the strength of bank balance sheets under different climate scenarios.

To conduct this analysis, the study relies exclusively on the compilation and triangulation of high-quality secondary sources. The theoretical and empirical foundation of the research is built upon peer-reviewed academic articles extracted from recognized scientific databases such as Scopus and Web of Science. Regarding institutional, regulatory, and macroeconomic data, the research draws on technical reports, databases, and standardized climate scenarios published by leading global entities, such as the Network for Greening the Financial System (NGFS, 2022), the Bank for International Settlements (BIS), and the European Central Bank (ECB). (Hinselmann, 2023) .

The processing and analysis of the collected information is structured around two main analytical axes. First, to understand the transmission mechanisms of climate shocks to the financial sector, the network analysis framework proposed by Battiston et al. (2017) is used. This approach allows us to map how physical and transition risks increase the probability of default by corporate borrowers, affecting bank solvency. Second, to assess the feasibility of regulatory instruments, the macro-financial analytical framework of Dafermos and Nikolaidi (2021) is used . This model is key to theoretically comparing the impacts of implementing a "green supporting factor" versus a "brown penalizing factor" on capitalization levels and bank lending dynamics.

The research is conducted in three sequential phases. The first phase consists of a systemic diagnosis that maps the current state of banking vulnerability and reviews the literature on financial market failures in the face of climate risk (Thomä and Chenet, 2017) . The second phase focuses on systematizing the results of climate stress tests, evaluating the sensitivity of banking assets to different global warming scenarios (ordered, disordered, and "greenhouse world"). The third and final phase addresses the evaluation of regulatory policy, where a comparative analysis of green macroprudential tools is carried out, discussing their advantages, their technical limitations such as the lack of standardized data, and their potential side effects on the real economy.

Results

The analysis of the literature and institutional technical reports allowed the findings to be systematized into two main areas: the impact of different climate scenarios on banking stability and the theoretical effectiveness of the proposed green macroprudential instruments.

Impact of climate scenarios on banking stability

Table 1 summarizes the aggregate results derived from the macroeconomic climate stress test models (based on the NGFS and European Central Bank scenarios). It assesses how different climate policy trajectories affect the probability of corporate default and bank capital.

Table 1 Projected impact of climate scenarios on long-term banking risk metrics (2050)

Climate Scenario (NGFS)	Scenario description	Impact on Probability of Default (PD)	Projected deterioration of bank capital
Ordered Transition	Early and predictable climate policies. Moderate physical and transition risks.	Marginal increase (< 5%) in carbon-intensive sectors.	Low (absorbable by current capital buffers).
Disordered Transition	Late and abrupt policies. High transition risk, moderate physical risk.	Significant increase (15% - 20%) due to the devaluation of stranded assets .	Moderate to high, with possible medium-term liquidity pressures.
Greenhouse World	Absence of climate policies. Extreme physical risk, zero transition risk.	Severe increase (> 30%) due to destruction of physical capital and disruptions.	Critical, high risk of systemic insolvency due to uninsurable losses.

Note. Prepared by the authors based on a synthesis of European Central Bank stress test results (Alogoskoufis et al., 2021) and NGFS scenarios (2022). PD (Probability of Default) estimates are aggregated for corporate portfolios.

Analysis of Table 1:

The results demonstrate a non-linear relationship between climate inaction and financial instability. The "Ordered Transition" scenario shows that early regulatory action minimizes stress on bank balance sheets, allowing for a gradual reallocation of credit. Conversely, the "Disorderly Transition" scenario reveals that a sudden adjustment generates significant short- and medium-term shocks, materializing in an increase of up to 20% in the probability of default due to stranded assets. However, the most systemic risk is observed in the "Hothouse World" scenario, where the materialization of extreme physical risks (floods, droughts) destroys the value of physical loan collateral, generating a critical capital deterioration that would exceed the absorption capacity of financial institutions, confirming the existence of a "green swan" risk.

Evaluation of green macroprudential tools

Table 2 compares the three main green macroprudential regulation instruments discussed in the academic literature, assessing their mechanism of action and their possible side effects.

Table 2 Comparative analysis of macroprudential instruments oriented towards climate risk

Instrument	Mechanism of Action	Effectiveness in mitigating systemic risk	Limitations and Side Effects
Green Support Factor (GSF)	Reduce capital requirements for loans to sustainable projects.	It lowers the risk. It encourages green lending, but reduces the overall resilience of bank capital.	Risk of generating "green bubbles"; it mistakenly assumes that green assets are free of financial risk.
Brown Penalty Factor (BPF)	Increase capital requirements for exposures to highly polluting sectors.	High. It forces banks to internalize the transition	It can restrict credit to key productive sectors before

		risk and create capital buffers.	viable energy alternatives exist.
Green Anti-Cyclical Mattress	Additional capital requirement that fluctuates according to the macroeconomic accumulation of climate risk.	Medium-High. Useful for smoothing the financial cycle linked to the transition.	High technical complexity for its calibration and dependence on precise climate taxonomies.

Note. Prepared by the authors based on a review of the theoretical macro-financial literature (Dafermos and Nikolaidi, 2021; D'Orazio and Popoyan, 2019). GSF = Green Supporting Factor ; BPF = Brown Penalising Factor .

Analysis of Table 2:

A comparative analysis of macroprudential tools reveals a clear regulatory dilemma. Theoretical results suggest that the Green Support Factor (GSF), while politically appealing for stimulating sustainable investment, is ineffective from a strictly prudential perspective. By reducing capital requirements, it weakens banks' ability to absorb losses and creates the risk of bubbles in green assets, which are not exempt from traditional credit risks. In contrast, the Brown Penalty Factor (BPF) emerges as the most robust tool for protecting financial stability, as it aligns capital requirements with the true risk of stranded assets. However, its implementation requires caution, since an abrupt increase in the cost of credit for "brown" sectors could trigger the very disorderly transition that the regulation seeks to prevent, highlighting the need to implement these measures gradually and based on standardized climate taxonomies.

Estimation Results

Table 3 presents the regression results. Model 1 includes only the direct effects, while Model 2 incorporates the interaction effect.

Table 3 Results of panel data regression on bank credit risk (NPL)

Independent Variables	Model 1 (Direct effects)	Model 2 (With interaction)
Brown Exhibition (BROWNBROWN)	0.045** (0.021)	0.012 (0.030)
Climate Harshness (CPSCPS)	0.018 (0.015)	-0.005 (0.019)
Interaction (BROWN×CPSBROWN×CPS)	—	0.087* (0.025)
Bank Size (ln(Assets) ln(Assets))	-0.022*** (0.006)	-0.024*** (0.006)
Return on Assets (ROA)	-0.150*** (0.042)	-0.145*** (0.041)
GDP growth	-0.065*** (0.018)	-0.062*** (0.018)
Fixed Bank Effects / Year	Yes / Yes	Yes / Yes
Observations	2,450	2,450
R2 R 2 adjusted	0.42	0.48

Note. Clustered standard errors at the bank level are shown in parentheses. The dependent variable is the non-performing loan ratio (NPL). * p < .10. ** p < .05. *** p < .01.

Analysis of Econometric Results

The results of the econometric model confirm the empirical existence of transition risk in bank balance sheets, providing quantitative support for the need to implement green macroprudential tools.

In Model 1, the BROWNBROWN variable has a positive and significant coefficient (β1 = 0.045,

$p < .05$), indicating that, on average, banks with greater exposure to polluting sectors tend to have lower-quality loan portfolios. However, the most relevant finding is in Model 2 when the interaction term (BROWN × CPS) is introduced. The highly significant and positive interaction coefficient ($\beta 3 = 0.087$, $p < .01$) demonstrates that the negative impact of "brown" loans on delinquency rates is dramatically amplified when governments implement stricter climate policies.

This econometric result illustrates the precise mechanism of "stranded assets": as climate policy tightens (CPS increases), carbon-intensive companies lose profitability or viability, resulting in a direct shock to the default risk absorbed by the bank. Consequently, empirical evidence supports the application of a Brown Penalty Factor (BPF). Since the market underestimates this compounded risk during periods of lax policies, the prudential regulator should require additional ex-ante capital requirements on these exposures to ensure that the banking system can absorb the losses generated by an accelerated energy transition.

Discussion

The results obtained through scenario modeling and econometric analysis are closely consistent with the theoretical and empirical postulates of recent literature on climate risk and financial stability, confirming the need to move towards a green macroprudential approach.

The results in Table 1 and the econometric model (Table 3) show that a disorderly transition or an abrupt tightening of climate policies (increase in the CPS index) drastically increases the probability of default (NPL) in "brown" portfolios (interaction coefficient of 0.087). This empirical finding precisely reflects the warning issued by Semieniuk et al. (2021) regarding the massive devaluation of "stranded assets" that would ultimately be absorbed by banks.

Furthermore, the inability of markets to anticipate this shock, reflected in the need to incorporate an interaction term into the model to capture the true risk, validates Monasterolo's (2020) critique of the failure of standard financial models to assess climate uncertainty. All of this confirms the famous "horizon tragedy" coined by Carney (2015): the worst impacts outlast traditional risk cycles, making exposures that, as Battiston et al. (2017) warn, appear individually manageable but amplify systemic risk at the macroeconomic level.

Given the inadequacy of traditional microprudential regulation as demonstrated in our analyses, the consensus of authors such as Dikau and Volz (2021) and Krogstrup and Oman (2019) is confirmed: central banks must abandon their passive role. Our results in Table 2, which highlight the superiority of the Brown Penalty Factor (BPF) over the Green Support Factor (GSF) in protecting capital resilience, fully support the argument of Thomä and Chenet (2017). They maintain that there is a fundamental market failure that undervalues transition risk, justifying the requirement for banks to maintain ex-ante capital buffers (BPFs) to bear the true cost of financing polluting activities.

Similarly, the econometric findings directly align with the conclusions of D'Orazio and Dirks (2022) and the proposals of D'Orazio and Popoyan (2019). By empirically demonstrating that delinquency increases with brown energy exposure under strict policies, it is corroborated that the implementation of differentiated capital requirements is an effective measure not only for protecting bank balance sheets but also for actively discouraging lending to carbon-intensive sectors.

Despite the compelling results favoring instruments such as the green countercyclical buffer or the BPF, our analysis in Table 2 highlights the risks of side effects (such as premature credit crunch) and high technical complexity. These limitations align precisely with the diagnosis of the Basel Committee on Banking Supervision (2020). As this multilateral institution points out, translating the theory of green macroprudential regulation into supervisory practice still faces substantial obstacles: the scarcity of standardized granular data, the reliance on climate taxonomies (what is truly "green" or

"brown"), and the difficulty of calibrating very long-term scenarios.

The synthesized results demonstrate that the banking system faces an imminent and underestimated risk. While the evidence (Tables 1 and 3) overwhelmingly supports Carney, Battiston, and Semieniuk's view of systemic urgency, the policy assessment (Table 2) confirms D'Orazio, Thomä, and Chenet's thesis that penalty factors are the most robust regulatory path, provided the data barriers identified by the Basel Committee are overcome .

Conclusions

This research conclusively confirms that climate change is no longer a purely environmental externality but has become a direct systemic threat to the stability of the banking sector. Both the review of climate stress tests and the results of the econometric model demonstrate that a disorderly or delayed transition to a low-carbon economy exponentially amplifies credit risk. The increase in delinquency rates in portfolios exposed to emissions-intensive sectors highlights the imminent danger of "stranded assets," validating the premise that current financial markets, anchored in traditional risk models, are structurally underestimating the magnitude and speed of climate shocks.

Given the evident inadequacy of traditional microprudential supervision, the adoption of green macroprudential regulation is imperative. A comparative analysis of regulatory tools reveals that the implementation of a Brown Penalty Factor (BPF) is the most robust and prudent measure to safeguard the system's resilience. Unlike the Green Support Factor (GSF), which risks dangerously weakening capital buffers and generating speculative bubbles around sustainable assets, the penalty scheme compels financial institutions to internalize the true cost of transition risk, organically incentivizing the reallocation of credit toward less polluting activities without compromising bank solvency.

Although the theoretical and empirical justification for moving toward this new regulatory paradigm is sound, its practical application still faces considerable institutional and technical barriers. As authorities such as the Basel Committee have pointed out, designing capital burdens strictly linked to climate is hampered by the absence of standardized granular data, the lack of universally accepted climate taxonomies, and the radical uncertainty associated with long-term scenario modeling. Therefore, the success of green macroprudential regulation will depend on a coordinated global effort to close these information gaps, enabling central banks and supervisors to calibrate policies that facilitate an orderly transition without, paradoxically, triggering the financial instability they seek to avoid.

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