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Credit Risk Assessment in the Climate Shadow: Evidence From White and Grey Literature

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ABSTRACT

Climate change is reshaping financial stability, making climate risk a critical component of banks' risk management. However, the absence of standardized frameworks validated by central authorities hinders banks' ability to integrate climate risk into existing credit risk models. This study employs a bibliometric and systematic literature review approach to examine the existing white and grey literature regarding the impact of climate change on credit risk components, like probability of default (PD), loss given default (LGD), exposure at default (EAD), and unexpected loss (UL). We highlight that innovations in climate-adjusted credit risk estimation primarily stem from grey literature but lack empirical validation in academic research. This study encourages academics to refine climate-adjusted risk metrics, financial institutions to evaluate their applicability, and policymakers to establish a more coherent regulatory approach. It also offers clarification to bank managers and practitioners on which methodologies are most applicable. Our study explains theoretically how climate risks affect creditworthiness and contributes to the development of standardized methodologies for their consistent integration into risk assessments.

1 | Introduction

The term “climate-related risk” has become commonly used, referring to potential risks arising from climate change or mitigation efforts, including their impacts and economic and financial consequences (BCBS 2021a, 2021b). This includes both physical risks and transition risks (Li et al. 2024; TCFD 2017). Physical risks originate from the direct impacts of climate change on corporate operations, such as workforce, infrastructure, raw materials, markets, and assets. These include acute physical risks and chronic physical risks. Transition risk drivers encompass societal changes, including advancements in technology affordability, shifts in public policy, and changing investor/consumer sentiment towards sustainability, which arise from transitioning to a low-carbon economy (Yang et al. 2024; NGFS 2019).

The financial literature has extensively documented the profound implications of climate change for financial systems and corporate outcomes (Salvi et al. 2025; García-Sánchez et al. 2024). In

particular, the impacts of climate risk drivers on banks' financial risks are multifaceted and interconnected (BCBS 2021a). In the last few years, financial institutions, researchers, regulators, supervisors, and professionals have increasingly focused on understanding how climate risks affect banks (Raimo et al. 2025; Gallego-Álvarez and Pucheta-Martínez 2020). While they manifest distinctive characteristics, there is increasing consensus that the existing Basel risk categories can adequately capture climate-related risks without requiring the creation of additional risk classifications (BCBS 2021b). Indeed, these risks act as drivers for the primary financial risks indicated by the Basel III framework (credit, market, liquidity, and operational risks) and are included in the “E” (Environmental) component of the increasingly important Environmental, Social, and Governance (ESG) criteria for evaluating companies. The magnitude and frequency with which transition and physical risk impact Basel's framework for financial risks depend on the climate scenarios established by the IPCC (TCFD 2017; BCBS 2021a; Alogoskoufis et al. 2021; Allan et al. 2023).

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So, climate-related risks permeate the credit system, significantly impacting banks through different channels (Conlon et al. 2024). The direct impacts of climate change, such as extreme weather events, disrupt business operations by causing production halts, increased repair costs, and asset devaluation, weakening borrowers' repayment capacity and value of collateral and elevating bank credit risk exposure for those borrowers (Klomp 2014; Battiston et al. 2017; Delis et al. 2024). So acute and chronic climate risk components can pressure the banking business, amplifying, for example, liquidity risk in climate-stressed scenarios. Similarly, regulatory changes like carbon taxes increase costs, destabilize customer cash flows, and heighten banks' credit risk exposure. This dynamic reduces the value of assets for banks that are heavily exposed to "brown" sectors, amplifying market risk through increased volatility and potential repricing of assets (Cosma et al. 2024; Adu and Roni 2024). It can simultaneously increase reputational risks associated with large polluters, as stakeholders become increasingly attentive and sensitive to environmental issues. At the same time, transition risk can lead to evolving compliance requirements, such as the expectations outlined by the ECB in November 2020, posing additional challenges to their risk management practices (Brogi et al. 2022; Dietz et al. 2016; Monnin 2018; Colas et al. 2018; Battiston et al. 2021). Moreover, climate-related risks may amplify systemic vulnerabilities, reshaping the foundations of economic stability by disrupting income flows, altering credit dynamics, and affecting sovereign ratings (Klusak et al. 2023) and leading to financial instability or systemic crises (Roncoroni et al. 2021; Battiston et al. 2021; BCBS 2021a; Bolton et al. 2020; ESRB 2021; Sun et al. 2024).

Integrating climate risk into the banking risk management framework is paramount in the present context. In recent years, the scale and scope of climate-related exposures at European financial institutions have expanded significantly. As early as 2016, the European Systemic Risk Board (ESRB) estimated that EU banks, pension funds, and insurance companies had exposures of more than €1 trillion to fossil fuel companies, with potential losses of between €350 billion and €400 billion even assuming an orderly transition. In 2019, the ECB's analysis of a sample of €720 billion of bank exposures indicated that 15% were directed towards the most carbon-intensive companies. More comprehensive assessments conducted at the end of 2020 confirmed that around 14% of euro area banks' balance sheets remain linked to high-emission companies. From a physical perspective, extreme weather events, which have increased in frequency and severity, have already generated more than €453 billion in economic losses across Europe between 1980 and 2017, averaging €7.8 billion per year, of which only 35% was insured. By December 2020, ECB mapping showed that about 30% of euro area banks' corporate exposures, amounting to €4.2 trillion, were to firms located in areas subject to high or increasing physical risks, including floods (10.6%), water stress (12.2%), heat stress (11.2%), and wildfires (4.8%) (ECB 2020, 2021). Also, recent cases like the 2024 floods in Germany and the recurrent wildfires in California have given academics the possibility to show that physical climate events can indirectly hit bank balance sheets and influence default rates. More broadly, in the absence of a timely transition, losses due to physical

risks are expected to prevail within 15 years, with potential global GDP contractions of up to 20% by the end of the century (ECB 2020, 2021).

As credit risk represents the primary source of capital absorption and the most significant driver of financial losses for banks, directly influencing their resilience and sustainability (Alogoskoufis et al. 2021; EBA 2021). Policymakers, financial authorities, and scholars agree that assessing these impacts requires methodologies that differ significantly from those used for conventional credit risk. This challenge arises from the need for more adequate tools and comprehensive data. While it will take time for banks to collect sufficient data, efforts can already begin to improve the frameworks used by academia and financial institutions, which remain underdeveloped as methodologies evolve (BCBS 2021b; EBA 2021; NGFS 2019). So, the limited experience of impacted subjects in quantifying climate-related risks and their effects on credit exposures further underscores the urgent need for substantial refinement of these approaches (Battiston et al. 2017; Bingler and Colesanti Senni 2022; BoE 2022; EBA 2021; ECB 2022a, 2022b; Monasterolo 2020). Climate stress tests conducted by the ECB and other central banks reveal that banks must be prepared to address the credit risk impacts of climate change. Approximately 60% of institutions need more robust methodologies for incorporating climate risks into stress testing, and many struggle to translate stress test results into actionable strategies, leaving credit risk frameworks incomplete and misaligned with supervisory expectations (BoE 2022; ECB 2022a, 2022b). While pressing financial institutions to integrate climate risks into their frameworks, regulators are still navigating this largely uncharted territory. Reflecting this priority, the ECB announced in January 2024 an expansion of its climate initiatives for 2025–2027, focusing on nature-related risks, greener monetary policy, and the financial implications of transitioning to a sustainable economy (Alogoskoufis et al. 2021; ECB 2024a, 2024b).

Among the proposed frameworks persists an absence of unique and centrally approved approaches, which emphasizes the need for refined and standardized methodologies to effectively address the challenges posed by climate change. This highlights the urgency of critically evaluating the fragmented and evolving set of available approaches, in order to identify methodological gaps and support the development of robust, standardized metrics for assessing the impact of climate change on credit risk. This study seeks to bridge this gap by conducting a systematic and bibliometric review of the existing literature about the analyses and computational techniques that describe the impact of climate change risk on credit risk, considering both its expected component (EL) and unexpected component (UL). In particular, it examines how the main components of credit risk, namely, probability of default (PD), loss given default (LGD), and exposure at default (EAD), adapt to the impacts of climate risk drivers.

We add to previous reviews by analyzing *white* and *grey* literature, including non-peer-reviewed knowledge artefacts (Auger 2017). This mixture helps to mitigate publication biases, including studies with negative or neutral results and outputs by policy and regulatory researchers, which may not appear in academic channels (Hammerstrøm et al. 2010; McAuley et al. 2000;

Hutchinson and Lucey 2024; Helmer et al. 2001; Rothstein and Hopewell 2009). Our decision to draw also on grey literature in this research field is motivated by its ability to capture nuances that are not yet fully reflected in academic publications. First, these risks are supranational in scope and have far-reaching systemic implications, as they transcend national borders and directly threaten financial stability. Second, they represent a relatively new category of risk, whose characteristics and long-term manifestations are not yet sufficiently defined in white literature. Third, their scale and urgency have prompted regulators and supervisors to take proactive measures, producing a large body of reports, guidelines, and technical documents to help the financial system, particularly the banking sector, manage climate risks and prevent spillovers to the real economy. Furthermore, supranational institutions such as the ECB, DNB, and BoE enjoy privileged access to highly granular data collected by national banks, which are rarely available to academic researchers. Thanks to their substantial computational capacity and expertise, these institutions are able to build sophisticated forecasting systems and climate-adjusted models that offer forward-looking perspectives on the possible consequences of such risks.

Furthermore, a second original aspect of this paper lies in using several methodological choices, including bibliometric techniques, topic modeling, Latent Dirichlet Allocation (LDA) analysis, and systematic literature review, encapsulated in a PRISMA workflow, ensuring a rigorous understanding of the climate drivers of credit risk. A further original feature compared to previous analyses, and a point of differentiation, lies in the study's strong focus on practicality, highlighting both the impact of climate-related risks on credit risk factors and the most effective methodologies currently available to address them. The presence of this updated and comprehensive review on the integration of climate risks into credit risk assessment is also justified in light of the rapid evolution of reporting standards, frameworks for climate stress testing, emerging methodologies based on artificial intelligence, machine learning, and climate data in risk modeling, and, ultimately, the proliferation of new data sources and metrics (e.g., satellite imagery, IoT-based sensors, next-generation ESG data).

Therefore, this review aims to answer the following research questions:

- RQ1: What are the annual trends in scientific production in this research field, and who are the leading contributors in terms of authors, journals, organizations, and countries?
- RQ2: What topics have been the focus of this research field?
- RQ3: What is the current knowledge on the influence of climate change on PD, LGD, EAD, and UL?
- RQ4: What future directions should be pursued in research to bridge the knowledge gaps regarding the impact of climate change on the main components of credit risk?

Sections 2 and 3 describe the methodology and data used in the study. Section 4 presents the results of the performance analysis. Section 5 covers scientific mapping and topic modeling. In Section 6, the content of the clusters is examined using content

analysis techniques. Section 7 provides a discussion and outlines a future research agenda. Finally, Section 8 offers concluding remarks.

2 | Methodology

We employed a systematic literature review, bibliometric analysis, and content analysis to address the research questions, utilizing a dataset comprising both white and grey literature. As outlined in the introduction, this bifocal approach primarily serves to mitigate biases arising from the selective visibility of academic outputs by incorporating forward-looking frameworks that are initially disseminated through policy-driven documents. The systematic review aims to gather all relevant evidence on a topic to answer a research question. A robust and rigorous methodological approach is the PRISMA model for systematic reviews and meta-analyses (Moher et al. 2009; Page et al. 2021), widely used in the most recent financial research (Galletta et al. 2024). This process involves selecting keywords and defining inclusion and exclusion criteria for extracting pertinent documents. Given the comprehensive nature of the review and the sizable dataset, a bibliometric analysis is subsequently carried out (Donthu et al. 2021; Liew and Cao 2025). In order to avoid analyzing research that the scientific landscape has not yet fully assimilated, both in terms of validity and soundness and in terms of citations, studies that are 12 months away from the start date of the analysis have been omitted, as required by the literature in this field (Cosma et al. 2024).

The bibliometric research technique applies quantitative and statistical methods to bibliographic data to better understand a field of study and the relationships between different publications (Costa and Forte 2022). This includes performance analysis, which allows for the analysis of scientific production, identifying the most relevant authors, sources, and countries (Donthu et al. 2021), and scientific mapping to identify knowledge clusters and the relationships between various scientific elements (McCain 1990). In conclusion, content analysis is employed to examine the content of the studied publications and synthesize the data resulting from the bibliometric and systematic analysis.

Specifically, in our review, we first analyzed the trends in scientific production, author, country, and institutional productivity and its impact using specific functions of Scopus, Web of Science (WOS), VOSviewer, and Scholarcy. We then employed a scientific mapping approach to uncover the main research areas and their evolution over time. This phase of the analysis combines two complementary methods to identify the thematic structures that define the theoretical foundations and key arguments of the field under investigation (Manesh et al. 2020). First, we conducted a network and overlay analysis of abstracts and author keywords using VOSviewer. This technique enabled the mapping of the most frequent terms and the assessment of their co-occurrence relationships (Aria and Cuccurullo 2017). The resulting network visualization illustrates how clusters of keywords are interlinked, helping to delineate the main areas of focus within the literature. Subsequently, we applied topic modeling using the LDA

algorithm to the full text of the selected articles. This probabilistic model enables the identification of latent thematic structures in large text corpora (Ligorio et al. 2022; Blei et al. 2003; Mustak et al. 2021; Hutchinson and Lucey 2024). According to Blei et al. (2003), LDA treats each document as a mixture of various topics, where each topic is in turn defined as a distribution over words. This method facilitates the unsupervised discovery of underlying semantic patterns and topic clusters through a hierarchical Bayesian framework.

3 | Data

The study, relying on a white and grey literature dataset, utilized Scopus, Web of Science (WOS), and Google Scholar as primary databases, covering a period from 1988 to the end of 2023. The WoS and Scopus databases were selected to ensure rigorous coverage of peer-reviewed literature, deliver standardised citation data, and enable cross-referencing to validate results and improve robustness (Ligorio et al. 2025). To complement these, Google Scholar was also added to access grey literature that is not systematically indexed elsewhere. While white literature includes scientific articles characterised by formal peer review and bibliographic identification, grey literature refers to documents that are not easily accessible through conventional academic channels and often do not meet strict editorial standards, such as technical reports, conference proceedings, working papers, and self-published materials. Although these unconventional documents have limited availability and poor bibliographic visibility, they retain considerable scientific relevance (Auger 2017).

This combined database strategy ensures both academic rigor and comprehensive literature coverage (Donthu et al. 2021; Khan et al. 2022; Merigó et al. 2016).

To extract the studies necessary to answer our research questions, we formulated the following search string, carefully selecting keywords:

(“climate” OR “climate change”) AND (“climate risk” OR “climate-related risk” OR “CRR” OR “physical risk” OR “transition risk” OR “extreme weather events” OR “green transition” OR “low carbon economy” OR “greenhouse gas” OR “GHG” OR “carbon emission” OR “carbon intensity” OR “CO2”) AND “credit risk” AND (“probability of default” OR “loss given default” OR “exposure at default” OR “VAR” OR “value at risk” OR “climate VaR” OR “climate Value-at-Risk”).

The first block ensures that the initial pool of articles under review focuses on climate-related issues by capturing studies that use the general term climate or explicitly refer to climate change. The OR operator allows for the inclusion of both formulations and prevents the exclusion of relevant studies (Shaffril et al. 2020).

The second block, which must be considered together with the first due to the AND operator, is structured to cover the two main categories of climate risk, physical risk and transition risk, together with the related factors. The OR operator broadens the search by incorporating different terminologies used in the literature (Alogoskoufis et al. 2021). In particular, terms such as extreme weather events, chronic climate risks and natural disasters capture physical risks. At the same time, green transition, carbon pricing and stranded assets reflect transition risks, which align with the classifications provided by the ECB (2020) and the BCBS (2021a).

The third block acts as a filter, ensuring that only studies that address the relationship between climate risk and credit risk are included in the final dataset.

The fourth block aims to focus research on studies analyzing the impact of climate risk on the fundamental components of credit risk. In particular, the PD, LGD, and EAD are widely recognized in the literature as key parameters for measuring EL, while value-at-risk (VaR) and its climate-adjusted version climate value-at-risk (Climate VaR) are essential tools for quantifying

TABLE 1 | Inclusion and exclusion criteria.

Criterion	Inclusion	Exclusion
Language	English	Non-English Studies
Year	All studies before 12/31/2023	All studies after 01/01/2024
Article type	Peer reviewed and non-peer reviewed articles	Book chapters, books, notes, reports, editorial, conference proceedings, etc.
Publication stage	Published and In-Press articles have been included.	—
Focus of the abstract/papers	Studies focusing on the impact of climate change on PD, LGD, EAD, and UL have been included.	Studies not focused on the impact of climate change on PD, LGD, and EAD have been excluded.
Article type: White literature	Articles ABS Journal Ranked have been included	Articles NON-ABS Journal-Ranked have been excluded
Article type: Grey literature	Articles published directly by central banks, banking regulators, banking supervisors, and on the SSRN database have been included.	Articles not published directly by central banks, banking regulators, banking supervisors, and on the SSRN database have been excluded

UL (Lando 2004; BCBS 2005; Jorion 2006). In order to build the final dataset, following the PRISMA model, we applied rigorous inclusion and exclusion criteria synthesized in Table 1 (Page et al. 2021; Redondo and Aracil 2024).

For nongrey literature, the search on the Scopus database resulted in 101 results within all research fields, 86 of which were written before 2023 and in English. The exact search on WOS returned 225 papers, of which 146 were compliant with the selection criteria.

For grey literature, we employed Google Scholar and Scholarcy, an AI-powered tool for abstract and reference list extraction (Latte 2024; Srivastava and Agarwal 2024; Gupta et al. 2020). We extracted abstracts and full texts using the above search string, resulting in 7140 hits. From these, 340 documents were identified with citations, of which 328 were in English.

After eliminating duplicates and manually screening the records by table of contents, titles, summaries, and abstracts, the total number of records identified as relevant was reduced to 256, consisting of 163 from white literature and 93 from grey literature. After downloading the 256 documents, we proceeded to full-text screening, reducing the total number of articles to 137. An additional three articles were included using the snowball technique, resulting in a final database of 140 papers, with 101 from white literature and 39 from grey literature. Figure 1 summarizes the whole methodological framework.

4 | Performance Analysis

Performance analysis is an analytical approach that utilizes activity indicators to evaluate the volume and impact of research through various techniques (Mingers and Leydesdorff 2015). In this study, we examine publication and citation trends, with publications serving as a proxy for research productivity and citations as an indicator of impact and influence (Donthu et al. 2021). This approach allows us to identify key authors, sources, and countries involved in the study of the effect of climate-related risk on financial risk within the banking sector. Regarding the performance analysis, publications on the topic have skyrocketed in recent years. Since 2019, there has been an almost exponential increase in literature addressing the lack of a clear and unified framework for assessing the impact of climate change risk on credit risk drivers (Figure 2).

Table 2 presents the most cited articles. The most cited article was published by Jung, J., Herbohn, K., and Clarkson, P., and the title is "Carbon Risk, Carbon Risk Awareness and the Cost of Debt Financing." This study examines the relationship between carbon risk awareness and the cost of debt for companies in Australia, finding that companies with higher carbon risk awareness face lower borrowing costs. In particular, the findings highlight that companies demonstrating awareness through actions such as participation in the Carbon Disclosure Project can mitigate the financial penalties associated with higher carbon emissions. The second most cited article, entitled "Climate risk and financial stability," written by Battiston S., Dafermos Y., and Monasterolo I., analyses the impact of climate risks on financial

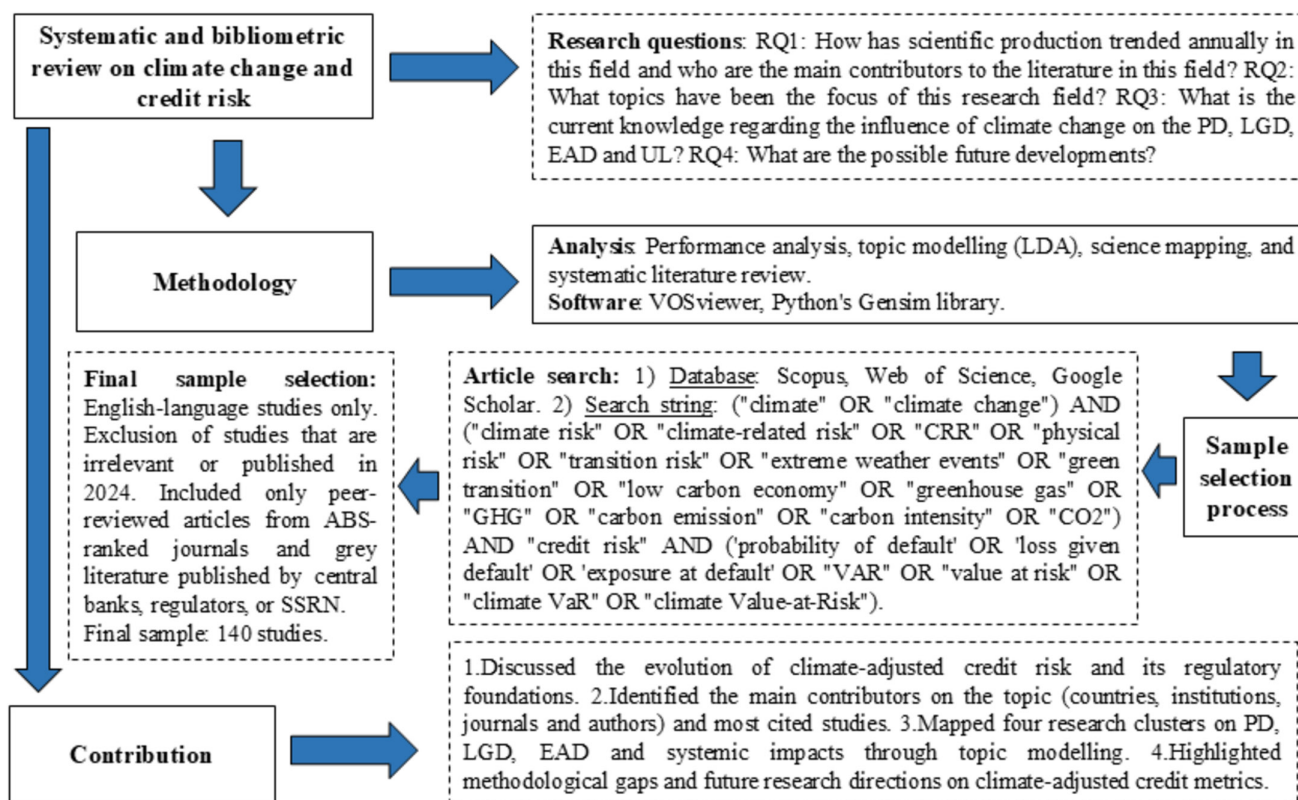


FIGURE 1 | Methodology flowchart.

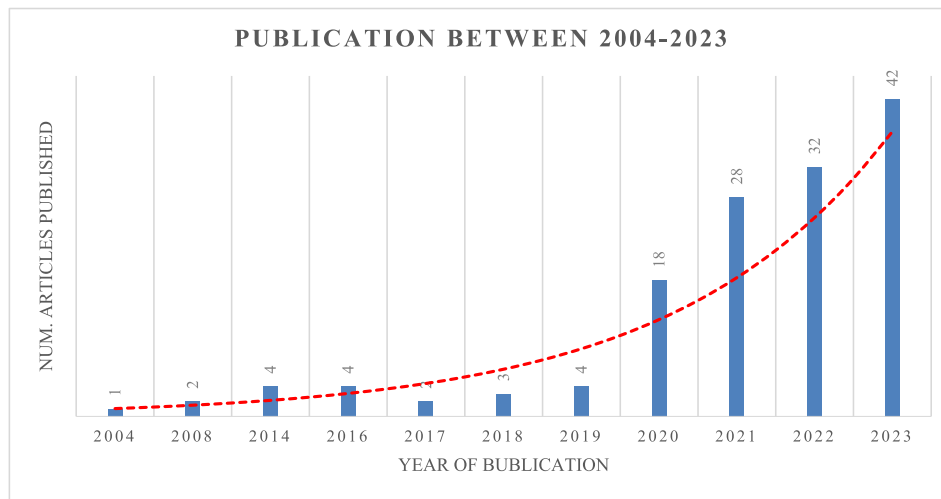


FIGURE 2 | Publications over time.

stability, highlighting the need for better methodologies to analyze these risks. It explores physical and transition risks and the role of climate policies in shaping financial outcomes, emphasizing the importance of integrating climate risk into financial assessments and policies.

The third most cited article by Capasso G., Gianfrate G., and Spinelli M. is titled “Climate change and credit risk.” It discusses how exposure to climate change affects firm credit risk, revealing that higher carbon emissions increase default risk and decrease creditworthiness, especially following policy shifts like the Paris Agreement.

Among the authors analyzed in the dataset, the most prolific are Nepomuk Dunz, Senior Economist at The World Bank, with five publications, followed by Irene Monasterolo, from Utrecht University, with four. Cristina Angelico from the Bank of Italy, Tina Emambakhsh from the ECB, Ivan Faiella, and Pierre Monnin have three published papers in this field. Several other authors have two publications, including Raffaella Calabrese, Louis Daumas, Ivan Diaz-Rainey, Duminda Kuruppuarachchi, Quyen Nguyen, Baofeng Shi, and Stuart M. Turnbull. In terms of country productivity, the leading contributors are China, followed by the United Kingdom, Italy, France, and the United States. The most prominent affiliations in this field include The University of Edinburgh, Duke University of Piraeus, Universität Zürich, Central University of Finance and Economics, University of Otago, University of Birmingham, and International Monetary Fund.

The journals with the highest presence are the International Review of Financial Analysis, Journal of Environmental Management, Agricultural Finance Review, and Finance Research Letters. For the grey literature, the most utilized platforms for publications are SSRN and central bank websites.

The leading affiliations in this area are the European Central Bank, followed by the Bank of Italy and the Bank of Canada. After noting this and examining the articles, we conclude that climate change and climate-related risks significantly impact credit risk assessments, driving the leading cited sources.

5 | Science Mapping and Topic Modeling

In this section, after collecting the articles that populate this field of research using the PRISMA technique, we first conducted a science mapping analysis with the bibliometric software VOSviewer. This analysis is further divided into two sub-analyses: the overlay analysis, discussed in Section 5.1, and the network analysis, presented in Section 5.2. Subsequently, to corroborate the findings from the previous analysis, we employed topic modeling to identify the possible number and content of topic groups that are likely to characterize the climate and credit risk literature. This combined approach allowed us to map the research field in more depth, identify emerging trends, and provide a clearer picture of the main areas of study in the field (Hutchinson and Lucey 2024).

5.1 | Overlay Analysis

The overlay analysis depicted in Figure 3 allows examination of the temporal distribution of keywords within each cluster. The illustration uses a combination of colors to represent the timeline, with blue indicating the oldest keywords, moving through green and fading to yellow for the most recent topics.

We can infer the evolution of specific research themes over time from the network map. In particular, the overlay analysis reveals that earlier studies, represented by darker shades of blue, focused on key concepts such as ‘global warming’ and the early recognition of climate change as a significant risk driver by central banks and international commissions. During this period, the first responses to this emerging risk also appeared, as reflected in terms such as “climate policy,” “metrics,” and efforts to link climate change to risk factors. In contrast, most recent studies, post-2022 and represented by shades of green and yellow, dive into particular topics like the analyses of the impact of climate change on market variables such as interest rates, credit default swaps, and broadly on credit risk. These analyses aim to quantify the cost of climate-related risks in terms of prices and counterparty risk. In parallel, increasing attention has been paid to the role of climate change in modeling LGD. In addition, recent studies also investigate the

TABLE 2 | The table shows the most cited studies regarding this topic by total citations.

TC	Title	Authors	Journal	Year
655	Carbon Risk, Carbon Risk Awareness and the Cost of Debt Financing	Jung, J., Herbohn, K., Clarkson, P.	Journal of Business Ethics	2018
404	Climate risks and financial stability	Battiston S., Dafermos Y, Monasterolo I.	Journal of Financial Stability	2021
321	Climate change and credit risk	Capasso G., Gianfrate G., Spinelli M.	Journal of Cleaner Production	2020
277	Carbon neutrality, bank lending, and credit risk: Evidence from the Eurozone	Umar M., Ji X., Mirza N., Naqvi B.	Journal of Environmental Management	2021
276	ESG scores and cost of debt	Apergis N., Poufinas T., Antonopoulos A.	Energy Economics	2022
173	Climate Change Risk and the Cost of Mortgage Credit	Nguyen D.D., Ongena S., Qi S., Sila V.	Review of Finance	2022
146	Carbon emissions and default risk: International evidence from firm-level data	Kabir M.N., Rahman S., Rahman M.A., Anwar M.	Economic Modeling	2021
136	A study on credit scoring modeling with different feature selection and machine learning approaches	Trivedi S.K.	Technology in Society	2020
136	Climate-related risks in financial assets	Campiglio E., Daumas L., Monnin P., von Jagow A.	Journal of Economic Surveys	2023
108	The impact of carbon emissions on country risk: Evidence from the G7 economies	Chaudhry, S.M., Ahmed, R., Shafiullah, M., Duc Huynh, T.L.	Journal of Environmental Management	2020
102	The bright side of carbon emission permits on supply chain financing and performance	Cao E., Yu M.	Omega	2019
100	A finance approach to climate stress testing	Reinders H.J., Schoenmaker D., van Dijk M.	Journal of International Money and Finance	2023
81	Banks, climate risk and financial stability	Nieto M.J.	Journal of Financial Regulation and Compliance	2019
69	The Low-Carbon Transition, Climate Commitments and Firm Credit Risk	Carbone S., Giuzio M., Kapadia S., Krüger J.S., Nyholm K., Vozian K.	SSRN	2021
67	Climate transition risk in U.S. loan portfolios: Are all banks the same?	Nguyen Q., Diaz-Rainey I., Kuruppuarachchi D., McCarten M., Tan E.K.M.	International Review of Financial Analysis	2023
62	The influence of green innovation on default risk: Evidence from Europe	Meles A., Salerno D., Sampagnaro G., Verdoliva V., Zhang J.	International Review of Economics and Finance	2023
54	Corporate environmental responsibility and default risk: Evidence from China	Shih Y.-C., Wang Y., Zhong R., Ma Y.-M.	Pacific Basin Finance Journal	2021
51	Credit Risk Sensitivity to Carbon Price	Bouchet V., Le Guenedal T.	SSRN	2020

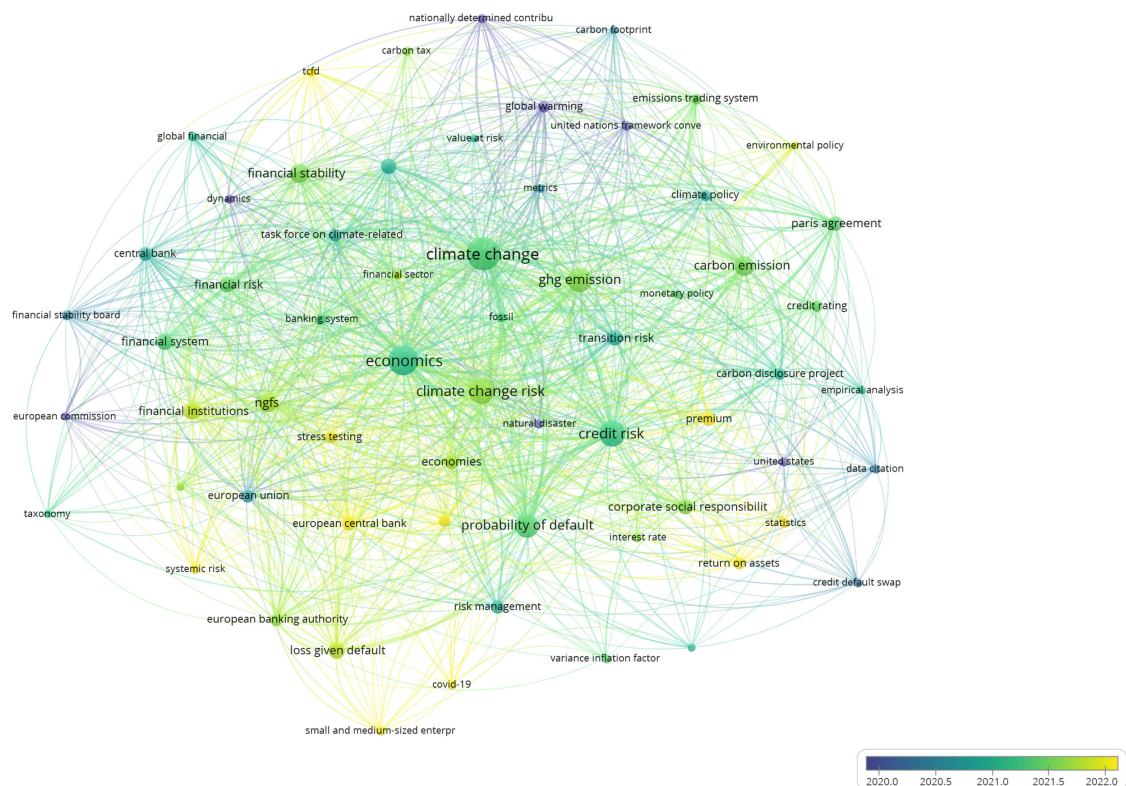


FIGURE 3 | Overlay analysis. Node size reflects keyword frequency, link thickness indicates co-occurrence strength, and node colors represent the average publication year, highlighting the temporal evolution of research themes.

broader implications of climate change on firm-level variables such as return on assets (ROA), and the resulting spillover effects on the banking and financial sectors.

The network diagram illustrates the growing attention to integrating and evaluating the impact of climate risk. In this sense, several frontier topics also emerge, including the analysis of these impacts on small and medium-sized enterprises (SMEs), as well as on credit default swaps and broader macroeconomic aspects, such as those associated with inflation variance.

5.2 | Network Analysis

The Network analysis identified the relationships between the studies in the sample through the authors' keywords (Cosma et al. 2024).

The keyword co-occurrence analysis is presented in a network diagram highlighting the interconnections among the keywords (Figure 4). The four distinct clusters can be interpreted as follows:

1. First cluster (green): examines how transition and physical risks affect financial stability. It emphasizes the role of regulatory policies and governance in mitigating economic and financial disruptions, highlighting the central role of banks in this context.
2. Second cluster (red): examines the relationship between carbon emissions and credit risk, focusing on PD and

transition costs. It also explores climate-adjusted risk models and innovative approaches to integrating climate factors into credit risk assessments.

3. Third cluster (blue): investigates how climate risks reshape economic conditions, influencing capital allocation and asset valuation. It also includes forward-looking exposure assessment measures, such as Climate VaR, as a tool to measure uncertainty and market volatility caused by climate-related financial disruptions, as well as CLIMAFIN framework.
4. Fourth cluster (yellow): examines the impact of climate risks on credit post default exposures, including collateral devaluation and postdefault losses, with a particular focus on LGD and EAD.

Based on the five most prominent words in each cluster, reported in Table 3, we have assigned descriptive names to them: Climate Risks and Financial Stability (green), Emissions and Credit Risk (red), Climate Scenarios and Climate Risk Impact Assessment (blue) and Climate Risk and Collateral Loss of Value (yellow).

5.3 | Topic Modeling

In a bibliometric analysis, the number and composition of the clusters may be sensitive to the selection of VOSviewer's specific parameters, such as the minimum occurrence threshold and the resolution setting, which are often determined through qualitative judgment (Marzi et al. 2025). To corroborate our findings,

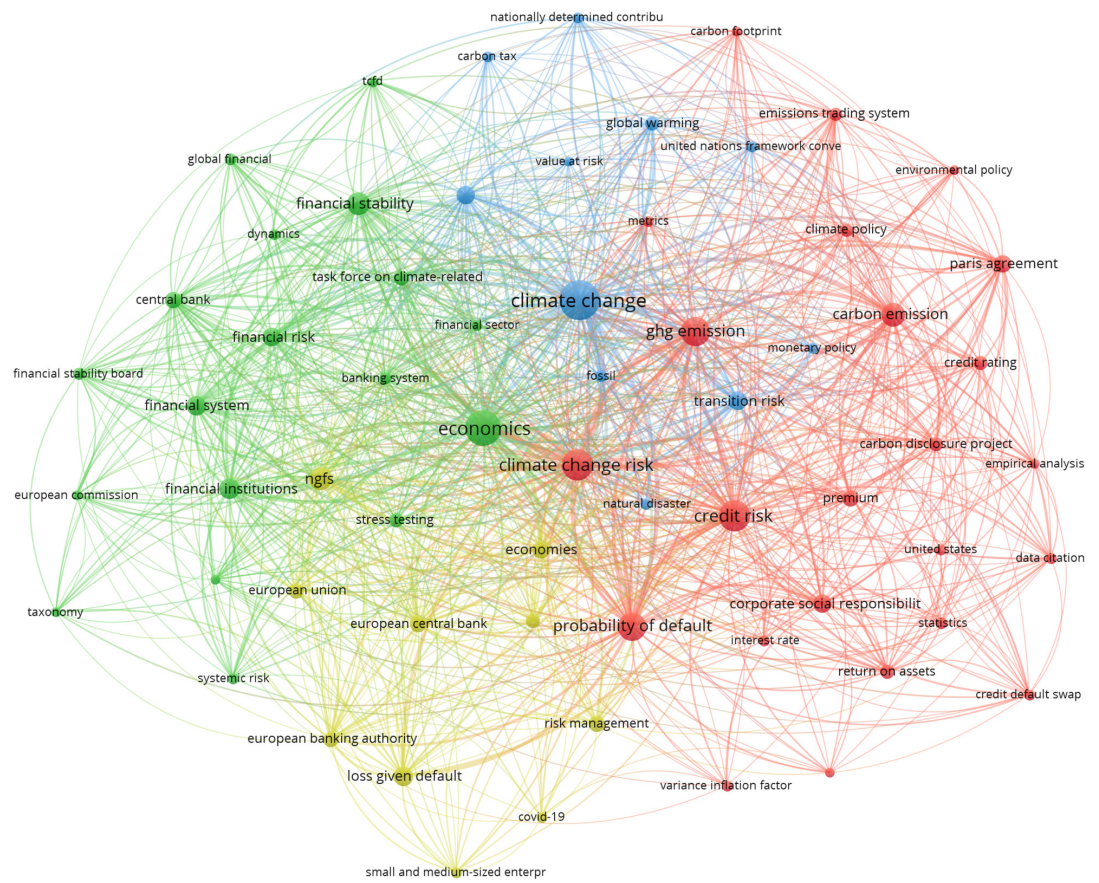


FIGURE 4 | Network diagram of the co-occurrence of keywords. Node size reflects keyword frequency, link thickness indicates co-occurrence strength, and colors denote thematic clusters.

TABLE 3 | The table displays the top five words in each cluster, ranked by total link strength, derived from the abstract and title of the corpus.

Cluster 1		Cluster 2	
Keyword	Total link strength	Keyword	Total link strength
Economics	472	Climate change risk	374
Financial stability	206	Credit risk	328
Financial institution	183	Ghg emission	315
Financial system	152	Probability of default	283
Financial risk	140	Carbon emission	223
Cluster 3		Cluster 4	
Keyword	Total link strength	Keyword	Total link strength
Climate change	572	NGFS	201
IPCC	170	Loss given default	133
Transition risk	147	ECB	119
Global warming	87	Economies	110
Value at risk	40	EBA	98

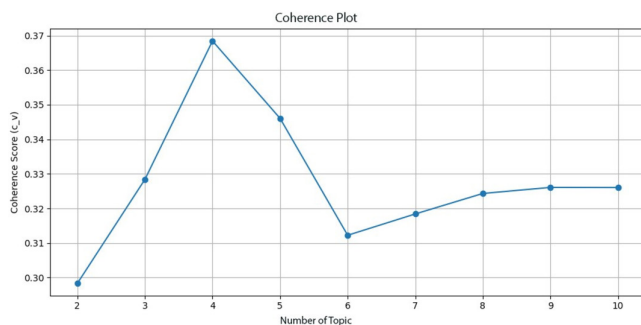


FIGURE 5 | Coherence score by topics' graphs. The graph shows coherence values for different topic numbers, where higher scores indicate greater semantic consistency.

we complemented the VOSviewer-based clustering with a validation step using LDA, one of the most widely used unsupervised topic modeling techniques in computational social science and bibliometric research (Blei et al. 2003; Hutchinson and Lucey 2024), which identifies latent topics across documents.

In order to assess the thematic consistency of the corpus from an independent analytical perspective, we ran multiple LDA models, each with a different number of topics. For each model, we calculated the *coherence score*, a metric that quantifies the semantic similarity among the most representative terms within each topic. This measure has been shown to correlate strongly with human assessments of topic interpretability.

The resulting *coherence plot* (Figure 5) illustrates how semantic coherence varies across different topic configurations. The peak observed at four topics supports the internal consistency of this thematic structure and aligns with the clustering obtained through the VOSviewer-based bibliometric mapping, thereby reinforcing the overall robustness of our classification framework.

6 | Thematic Clusters: Content Analysis

6.1 | First Cluster (Green): Climate Risks and Financial Stability

The Green Cluster, which is in turn divided into two subthematic areas, investigates the relationship between climate change and the financial system's stability. The first emphasizes the role of regulatory policies, institutional governance, and banking supervision in mitigating systemic vulnerabilities. The second focuses on the use of climate stress tests as a tool to assess the financial system's exposure to climate-related shocks.

In this field, the first thematic area's quantitative studies offer clear evidence of how climate risks affect financial stability. Le et al. (2023) analyze 6433 banks in 109 countries between 2005 and 2019. They find that smaller and less capitalized banks are more exposed, while strong governance, supervision, and regulation reduce vulnerability.

Nieto (2019) and also Noth and Schüwer (2023) confirmed this systemic relevance, estimating on one side a significant

exposure of the banking systems of the major global economies amounting to \$1.6 trillion and on the other side documenting that borrowers' financial conditions deteriorate significantly in regions of the United States affected by natural disasters (Noth and Schüwer 2023). Daumas (2023) adds to this systemic perspective by examining the impact of transition risks on financial stability. He emphasizes how market changes triggered by policy measures can pose a significant threat to financial institutions, particularly when these measures are implemented in a fragmented manner by regulators and policymakers. Concluding, Roncoroni et al. (2021) simultaneously simulate disorderly transition shocks and analyze loss propagation through direct and indirect contagion, considering forced liquidation effects, market volatility, and endogenous recovery rates (RRs).

The second analytical strand of this group focuses on the use of climate stress testing methodologies, which have become essential tools for quantifying potential asset devaluations, loan portfolio risks, and financial stability challenges stemming from direct and indirect exposure to climate change (Alogoskoufis et al. 2021; Allen et al. 2020; Vermeulen et al. 2019; Daniëls et al. 2017; BoE 2022; Ferrer et al. 2021). These methods rely on IPCC and NGFS scenarios, which convert scientific projections into financial risk metrics and classify pathways as orderly, disorderly, or hot-world (ECB 2020; AIFIRM 2020; BCBS 2021a). Among the most comprehensive assessments, the European Central Bank (ECB) conducted a top-down climate stress test to analyze the impact of micro- and macroeconomic climate drivers on the financial stability of the entire credit system, considering both the direct and indirect effects of exposure to these factors. The results indicate that an increase in transition risk due to a rise in the carbon tax could compromise the system's overall stability by up to 10% by 2030.

Focusing on sectoral resilience, De Nederlandsche Bank (DNB) in 2021 adopted a top-down approach, developed by Vermeulen et al. (2019) and Daniëls et al. (2017), to assess the financial stability risks associated with transition dynamics across 56 NACE 2 sectors. The study reveals that a strict carbon tax regime combined with high technological barriers in carbon-intensive sectors can lead to systemic financial imbalances, which are further amplified when political interventions and changes in investor sentiment coincide, highlighting the need for targeted risk management strategies.

A complementary firm-level study by Allen et al. (2020) uses the Banque de France's internal credit assessment system (ICAS) to assess how corporate financial structures respond to transition risks. The result from a sample of 260,000 companies suggests that increased regulatory pressure weakens credit fundamentals, disproportionately affecting high-emission companies. A broader system-wide assessment was conducted by the Bank of England (BoE) through its Climate Biennial Exploratory Scenario (CBES) (BoE 2022), applying a macroprudential top-down stress-testing framework to evaluate the financial stability implications of climate risks within the UK financial system. Also, this study states a significant sectoral disparity in climate risk exposure, particularly among institutions dependent on carbon-intensive industries.

A different perspective emerges from Banco de España (BdE), which conducted a sector-specific top-down stress test through its Forward-Looking Exercise on Spanish Banks (FLESB) (Ferrer et al. 2021). Findings indicate that local banks, heavily reliant on domestic carbon-intensive firms, are more financially vulnerable than internationally diversified institutions. So, evaluating carbon-intensive business models under new climate policies could intensify systemic financial pressures, underscoring the need for adaptive regulatory frameworks to mitigate risks and enhance banking sector resilience.

6.2 | Second Cluster (Red): Emissions and Credit Risk

The Red Cluster investigates the crucial relationship between greenhouse gas (GHG) emissions, credit risk, and PD, highlighting the direct impacts of emissions on credit parameters and the evolution of techniques for estimating climate-adjusted PD. This connection represents a central challenge for the financial sector, which is called upon to integrate climate variables into risk management models in light of regulatory pressures and the transition to a sustainable economy.

Broadening the scope, Kabir et al. (2021) explore the impact of carbon emissions on corporate credit risk in 2785 companies in 42 economies from 2004 to 2018. The study uses the distance-to-default (DD) metric derived from Merton's and finds that an increase of one standard deviation in emissions reduces the DD by 10%, with the most significant effects observed in energy-intensive sectors. Further evidence is provided by Gutiérrez-López et al. (2022), demonstrating how companies' improvements in carbon efficiency, measured as emissions/sales ratios, enhance companies' Altman Z scores.

The post-Paris Agreement era has intensified regulatory pressures, as demonstrated by Capasso et al. (2020). Capasso et al. analyze 458 publicly traded companies, revealing a 17.2% decrease in solvency for carbon-intensive firms post-agreement. Political uncertainty also plays a fundamental role, as evidenced by Liu et al. (2023). They analyzed 1874 Chinese companies and measured climate policy uncertainty (CPU) through a social media-based index. The study demonstrated a link between CPU and higher PD, with effects exacerbated by reduced investment in research and development and weaker ESG performance. On the other hand, Meles et al. (2023) illustrate the advantages of green innovation using Expected Default Frequencies (EDF). The authors demonstrate that ecological practices reduce the risk of insolvency by up to 67.14%, mainly thanks to greater profitability rather than a reduction in financial leverage. In addition, Bouchet et al. (2020) and Bell and van Vuuren (2022) contribute to this cluster, investigating the correlation between credit risk and climate risk using climate stress scenarios. Bouchet et al. (2020) analyze 795 MSCI World firms with a Merton model, linking Scope 1 emissions to carbon price scenarios. They find extreme vulnerability in utilities, materials, and energy, with PDs above 99% under long-term stress. On the contrary, Bell and van Vuuren (2022) apply a geometric Brownian motion with the KMV model to A-rated firms. Their simulations show that severe meteorological shocks increase volatility and can raise PDs up to fourfold.

Finally, Faralli and Ruggiero (2022) analyze 1841 companies from the United States, the United Kingdom, the Eurozone, and Japan between 2008 and 2019, using carbon emissions as a proxy for transition risk and Moody's Expected Default Frequencies for credit risk. The study shows that, after the Paris Agreement, the credit risk for high-emission companies increased significantly in Europe, mainly due to increased volatility and a decline in asset values. In contrast, US companies show relative resilience thanks to a less rigid market and regulatory environment.

Reply (2022) proposes a structured methodology for integrating physical climate and transition risks into credit risk models. Their three-phase approach develops climate scenarios, estimates their impact on cash flows and balance sheets, and translates these into PD and LGD metrics. By adopting the Merton model adjusted to incorporate climate-related costs and introducing the Climate Credit Quality Index (CCQI), they create a tool sensitive to sectoral and geographical climate vulnerabilities. The study combines bottom-up granularity with top-down scalability, extending the time horizon of risk assessments beyond the typical 1–3 years to better capture the nuances of climate-adjusted PD. AIFIRM (2020) contributes a comprehensive framework for integrating physical and transition risks into bank risk management metrics. AIFIRM (2020) builds on Merton-type models, introducing the Transition Vulnerability Factor (TVF) and the CCQI to capture sectoral and geographical variations in PD. This framework integrates granular data and scenario-specific changes, aligning risk metrics more closely with climatic realities. Jung et al. (2025) introduce an innovative market-based measure, CRISK, to quantify banks' capital shortfall under climate stress. CRISK combines climate beta, a measure of banks' sensitivity to climate risks, with forward-looking scenarios involving stranded assets, carbon emissions and transition policies. During the 2020 stress events, CRISK for major US banks rose by \$260 billion, showing its ability to capture systemic vulnerabilities and refine PD estimates. Concluding, Garnier et al. (2022) develop the Climate Extended Risk Model (CERM), a multifactor extension of Merton-type credit risk models that integrates climate variables. The model employs Monte Carlo simulations to estimate PD, capturing sector-specific vulnerabilities and geographical climate exposures. Based on NGFS and IEA climate pathways, scenario analysis reveals that transition-sensitive industries face elevated default risks. The findings underscore the systemic implications of climate-related financial risks, highlighting the necessity for climate-adjusted capital requirements and enhanced regulatory stress testing frameworks.

6.3 | Third Cluster (Blue): Climate Scenarios and Future Climate Risk Impact

The Blue Cluster is composed of two macro-themes. The first examines climate change, its components and characteristics, and the mechanisms through which it interacts with the economic and financial system, shaping its dynamics. It explores how physical and transition factors translate into economic and financial implications. The second line of analysis exploits the stress test methodologies introduced in the Green Cluster

to develop innovative techniques for evaluating how climate change translates into unexpected losses in terms of credit risk.

The first research approach, based mainly on grey literature, examines how climate change and its components influence economic and financial conditions. Reports from the Basel Committee on Banking Supervision (BCBS) and the European Central Bank (ECB) highlight how physical risks related to extreme weather events and long-term climate change and transition risks arising from regulatory, technological, and market adjustments alter economic trajectories and capital flows, leading to structural changes in the allocation of resources.

The most important study in this field is the ECB Guide on climate-related and environmental risks (2020), which provides a structured taxonomy of climate-related risks, distinguishing between physical and transition risks (ECB 2020). The IPCC also emphasizes the role of adaptation strategies, such as flood defenses, which have been shown to mitigate economic pressures in vulnerable areas by up to 30% (Allan et al. 2023). Regarding the mechanisms through which climate change shapes economic and financial conditions, Medina-Olivares et al. (2022) analyze how climate variability influences capital distribution and sectoral economic adjustments. They demonstrate that fluctuations in environmental conditions affect investment strategies and economic activity. Also, Castro and Garcia (2014) examine the economic consequences of temperature and precipitation anomalies, demonstrating that climatic conditions change influences capital allocation and sectoral productivity, particularly in agriculture and climate-sensitive industries. Furthermore, Correa et al. (2022) explore how climate-related disasters influence financial mechanisms, finding that hurricanes and extreme weather events trigger adjustments in capital prices and cost structures. They find a 19 basis point increase in loan spreads in highly exposed areas, demonstrating how climate shocks reshape financial interactions and market expectations.

The second line of analysis focuses on forward-looking methodologies to quantify exposure to climate risk, expanding the use of Climate VaR to assess the financial implications of transition and physical risks. This research integrates stress tests based on scenarios and probabilistic models to refine risk quantification techniques, improving the ability to measure uncertainty in financial markets based on different climate pathways.

Desnos et al. (2023) use a probabilistic Monte Carlo approach to simulate transition risk scenarios to assess the macroeconomic effects of carbon price dynamics, cost transmission mechanisms, and sectoral emissions. Their framework highlights how uncertainty in transition pathways translates into market volatility, particularly for industries with significant exposure to carbon-intensive activities. It shows that integrating stress tests with VaR provides a more resilient approach to risk assessment, capturing a wider range of potential disruptions than conventional models.

Building on this foundation, MSCI (2019) extends the framework of Climate VaR. MSCI (2019) introduces Climate VaR as a forward-looking metric, quantifying transition and physical risks by assessing financial exposure under NGFS climate scenarios. The model captures the effects of policy change, green

technology adoption, and extreme weather on asset valuation. Empirical results indicate that carbon-intensive industries exhibit a higher downside risk, while companies investing in low-carbon solutions demonstrate greater resilience and upside potential.

One of the most significant contributions within this cluster is the framework initially proposed by Battiston and later validated by Monasterolo (Battiston and Monasterolo 2019; Monasterolo 2020). In particular, Monasterolo (2020) introduces CLIMAFIN, an integrated model designed to assess the impact of climate-related risks on financial instruments and portfolios. The framework combines forward-looking climate scenarios with indicators such as Climate VaR and climate spread, while accounting for nonlinearity, deep uncertainty, and contagion dynamics. It draws on IPCC and NGFS scenario narratives, distinguishing between orderly transition, disorderly transition, and “hot house world” pathways. The results show that portfolios highly exposed to carbon-intensive sectors are particularly vulnerable under disorderly transition scenarios, whereas timely and coordinated climate policy planning can substantially mitigate the associated risks.

Extending the Climate VaR approach further, Yang and Xu (2021) apply this framework to the Bitcoin market, an asset class with high energy consumption and significant carbon emissions. By integrating the Climate Expected Shortfall with VaR, and using parametric (GARCH) and semiparametric models, they show that traditional carbon pricing fails to capture environmental externalities.

6.4 | Fourth Cluster (Yellow): Climate Risk and Collateral Loss of Value

The Yellow Cluster examines how climate risk impacts the valuation of credit exposures and the severity of postdefault losses, mainly through its effects on LGD and EAD.

As indicated in the ECB Guide on climate-related and environmental risks (2020), climate-related risks devalue collateral, altering postdefault RRs and amplifying LGD, particularly in carbon-intensive sectors. Similarly, the ECB Economy-wide Climate Stress Test (2021) demonstrates that in a disruptive transition, the decline in the value of credit exposures contributes to increased postdefault losses, amplifying LGD effects. The role of climate stress tests in risk modeling is further explored by Banque de France, which emphasizes the importance of adapting LGD models to consider the devaluation of financial assets due to climate (Allen et al. 2020). The Banco de España, using the FLESB framework, finds that an accelerated transition weakens postdefault RRs by up to 30%, intensifying LGD effects, particularly for high-emitting industries (Ferrer et al. 2021).

In addition to influencing the severity of losses, climate risks also affect the level of exposure of credit portfolios, particularly through their impact on the value of collateral and on the ability of companies to refinance their debt. The deterioration of physical assets due to extreme weather events and the stranding of carbon-intensive assets under transition policies alters the valuation of secured exposures, changing EAD estimates.

Advanced quantitative modeling has further expanded the understanding of the climate adjustment of LGD and EAD. Garnier et al. (2022) introduce the CERM, which integrates climate-related risks into postdefault loss estimates. CERM goes beyond Basel models by using a multifactorial approach that integrates carbon prices, asset devaluation, and collateral deterioration. Monte Carlo simulations capture climate shocks to LGD across sectors and geographies, providing a more detailed view of portfolio exposure.

CERM also updates EAD metrics by adjusting collateral values under NGFS scenarios, accounting for physical deterioration, transition costs, and liquidity constraints.

The combined effect of physical and transition risks translates into changes in EAD, reflecting the erosion of asset values and the reduced ability of firms to refinance debt or access additional credit.

Similarly, Grundmann et al. (2023) examine the impact of carbon pricing mechanisms on corporate LGD, revealing that increased emission costs reduce asset values, significantly increasing LGD in bank portfolios. Further insights from Belloni et al. (2022) demonstrate that delayed climate policies contribute to asset devaluation and significant increases in LGD, particularly in the energy and industrial sectors.

Calice and Reinders (2022) empirically find a strong correlation between increased LGD and climate-related financial risks, particularly in carbon-intensive sectors. In support of these findings, the ECB/DNB (ESRB 2020) pilot exercise makes a significant methodological contribution by integrating climate-related factors into LGD estimation techniques. The study combines BEAST transition rate equations model (Budnik et al. 2020) with a SUR-logit framework to estimate LGDs at the NACE 2 sectoral level. The results indicate that institutions with high exposure to carbon-intensive industries experience a significant increase in LGD, emphasizing the importance of better estimation of RR and exposure in risk modeling.

7 | Discussion and Research Agenda

The potential effects of climate-related risks on financial stability, influenced by physical and transition risks, have acquired considerable significance and attention within the last few years (BCBS 2021b; TCFD 2017; NGFS 2019). This comprehensive literature review examines existing knowledge on the impact of climate change risk on credit risk, distinguishing between its expected (EL) and unexpected (UL) components. Specifically, it analyzes how its key parameters, PD, LGD, and EAD, are affected by climate risk drivers while highlighting the role of VaR as a key model for measuring unexpected losses. Considering the first research question (RQ1: What are the annual trends in scientific production in this research field, and who are the leading contributors in terms of authors, journals, organizations, and countries?), the investigation, using bibliometric analysis, finds a pronounced increase in the amount of research on the topic since 2018, suggesting an increasing acknowledgement of the importance of this subject. Concerning the second aspect of

this research question, a key contribution was published by Jung et al. (2018), titled “Carbon Risk, Carbon Risk Awareness and the Cost of Debt Financing” finding that companies with higher carbon risk awareness face lower borrowing costs. Other influential works include Capasso et al.’s study on climate change and credit risk and Cao and Yu’s research on carbon emission permits in supply chain financing. The most prolific author in this field is Nepomuk Dunz, who has five publications. China is the dominant country in terms of productivity, followed by the United Kingdom, Italy, France, and the United States. Prominent affiliations include the University of Edinburgh, Duke University, the University of Piraeus, the Universität Zürich, the Central University of Finance and Economics, the University of Otago, the University of Birmingham, and the International Monetary Fund. All these results were obtained through performance analysis within the bibliometric approach.

Considering the second research question (RQ2: What topics have been the focus of their research?), our bibliometric analysis and topic modeling evidenced four primary research clusters. The Green Cluster focuses on the systemic impact of climate risks on markets and financial institutions, examining stress testing and regulatory frameworks. The Red Cluster explores the link between corporate carbon emissions and credit risk, mainly default probabilities and transition costs. The Blue Cluster assesses climate scenario modeling for credit risk, integrating IPCC and NGFS methodologies to evaluate financial vulnerabilities. Lastly, the Yellow Cluster examines how climate risks affect expected credit losses, focusing on LGD, collateral devaluation, sectoral risks, and advanced modeling techniques for risk estimation.

To answer the third research question (RQ3: What is the current knowledge on the influence of climate change on PD, LGD, EAD, and UL?), a content analysis of the 140 articles under study was conducted. According to this analysis, the literature focuses on studying the effects of climate risk, particularly its transition component, on the primary metrics of expected credit risk. Among these, PD appears to be the most investigated element, receiving significantly more attention than LGD and EAD. This evidence derives from topic modeling and content analysis of the selected articles.

Figure 6, included as a visual summary of Sections 6.1–6.4, brings together the common thread linking the thematic clusters and shows how climate change risk permeates these dimensions according to empirical research, influencing the components of expected credit risk (PD, LGD, EAD) and unexpected credit risk (UL).

Another insight of the review is that the financial system, while recognizing the growing importance of the issue, has not yet identified the need to establish new ad hoc risk categories. Instead, the prevailing trend seems to be oriented towards adapting the existing risk categories, which are considered adequate to capture the effects of climate change. This orientation is supported by evidence provided by regulatory bodies and supervisory institutions such as BCBS (2021a), Banque de France in 2020, and the ECB/DNB in 2020 (ESRB 2020; Allen et al. 2020).

In the first searching for a correlation between climate risk and credit risk, the prevailing methodological approach is based on

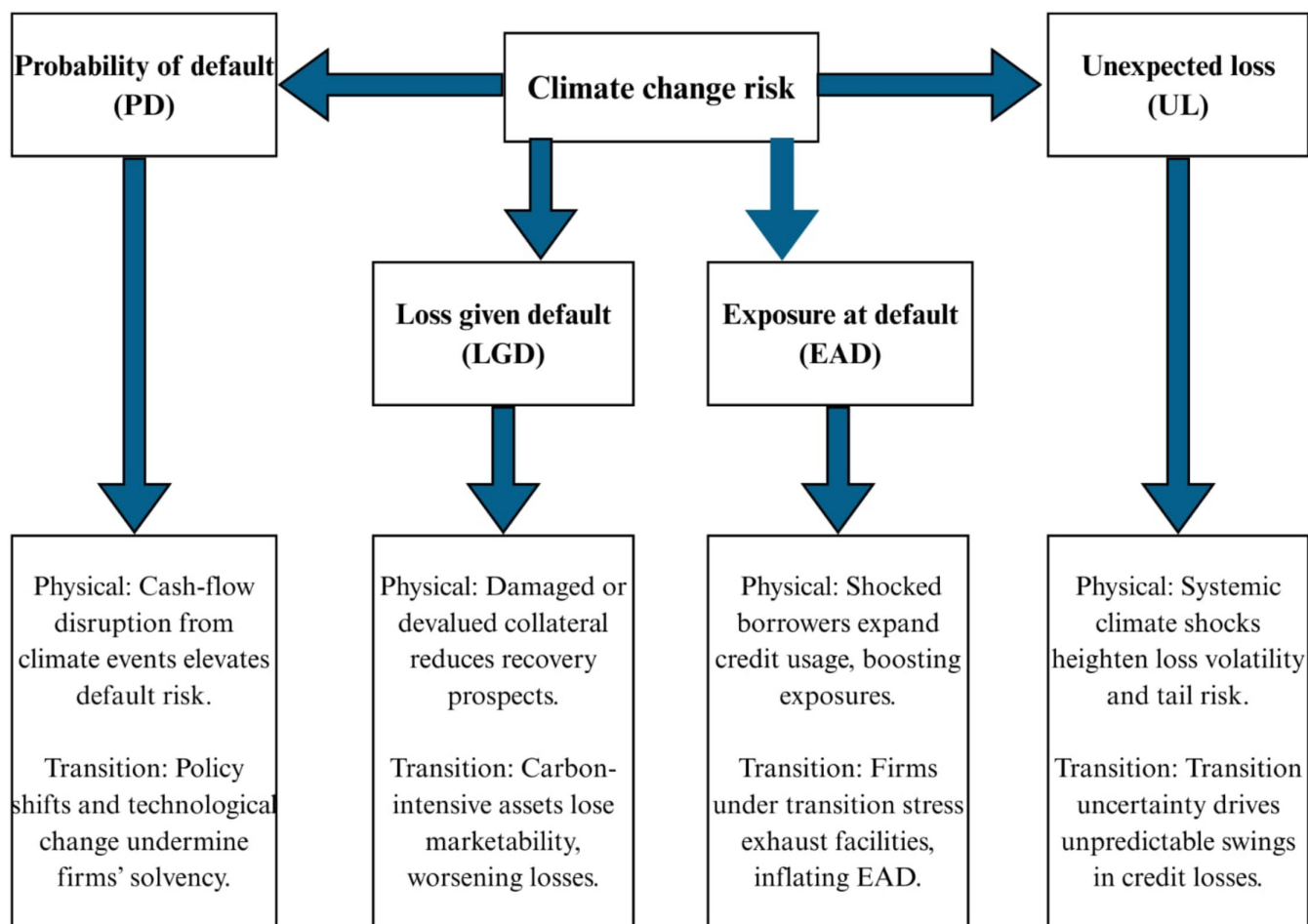


FIGURE 6 | Climate risk and credit risk components. The diagram shows how physical and transition drivers propagate through credit risk dimensions.

traditional models that do not explicitly incorporate climate factors. In particular, PD is generally estimated using consolidated methods, such as the KMV framework of Merton or Moody.

Only a limited number of studies, mainly from the grey literature, have attempted to overcome this limitation by adopting more advanced formulations, trying to develop methodological innovations for the integration of climate risk in the calculations of PD and LGD. Table 4 provides a structured overview of the most advanced models identified, distinguishing between those that modify core credit risk factors through climate-adjusted variables and those that apply such adjustments in practice through top-down or bottom-up stress-testing frameworks. These models also differ in terms of whether they address transition risks, physical risks, or both.

Table 4 reports adjusted versions of the Merton model have been developed, introducing the Climate Credit Quality Index (CCQI) and the Transition Vulnerability Factor (TVF), which allow for the calibration of the PD according to sectoral vulnerability to decarbonization (Avantage Reply 2022; AIFIRM 2020; ESRB 2020). On a systemic level, the CRISK Model (Jung et al. 2018) introduces Climate Beta, estimating banks' exposure to transition risks, while the CERM (Garnier et al. 2022) incorporates Monte Carlo simulations into Merton models to assess the effect of climate policies on PD. Central

banks have also integrated transition risk into their climate stress tests. The ECB's Macro-financial Climate Stress Test (2021) links corporate PDs to climate variables, demonstrating how an increase in carbon price can exacerbate credit risk in the most exposed sectors. Finally, the Banque de France ICAS-based Climate Stress Test (Allen et al. 2020) applies a logistic model to evaluate the evolution of corporate PD in transition scenarios.

The assessment of LGD considering climate risks has favored the development of advanced models capable of quantifying expected losses from financial shocks related to climate change. Among these, the CERM (Garnier et al. 2022) represents a methodological innovation to include the effects of climate policies and environmental conditions on the severity of post-default losses. Unlike the Basel ASRF models, which are based on a single systemic risk factor, the CERM adopts a multi-factor approach, integrating physical and transition risks to estimate how asset depreciation, increased emission costs, and deterioration of RRs influence LGD. Also, the ECB/DNB pilot exercise (ESRB 2020) further refines the LGD estimate, integrating Transition Vulnerability Factors (TVF) and introducing an adjustment factor to capture the effects of climate shocks. The results indicate a significant increase in LGD in carbon-intensive sectors, highlighting systemic exposure to physical and transition risks. In this sense, a further contribution comes from

TABLE 4 | The table shows a comprehensive list of advanced models for climate-adjusted credit risk assessment.

Model name	Description	Climate risks considered	Main references	Adopted in supervisory exercises (yes/no)
Climate-adjusting factors				
TVF (Transition Vulnerability Factor)	Sector-level adjustment factor used in top-down credit risk models to modify PDs based on a sector's vulnerability to transition scenarios; can also inform LGD via PD-LGD Frye-Jacobs model.	Transition, Physical	AIFIRM (2020); ESRB (2020)	Yes
CCQI (Climate Credit Quality Index)	Firm-level index applied in bottom-up assessments to adjust PDs based on company-specific climate risk indicators; supports indirect estimation of LGD via systemic dependency.	Transition, Physical	Avantage Reply (2022); AIFIRM (2020)	No
CERM (Climate Extended Risk Model)	Climate-extended structural credit model that simulates PD, LGD, and EAD jointly using Monte Carlo methods and climate scenarios (e.g., NGFS), integrating financial deterioration under stress.	Transition, Physical	Garnier et al. (2022)	No
CRISK	Systemic risk model that quantifies the expected capital shortfall of banks under climate transition scenarios by combining climate beta, leverage, and market impact.	Transition	Jung et al. (2025)	No
Climate VaR	Extension of traditional value-at-risk that estimates the potential financial loss of a portfolio under climate-stressed scenarios (e.g., NGFS or IPCC), using probabilistic or scenario-based modeling.	Transition, Physical	Desnos et al. (2023); Dietz et al. (2016); MSCI (2019)	No
CLIMAFIN	Integrated framework linking forward-looking climate scenarios, IPCC and NGFS, to financial metrics (e.g., Climate VaR and climate spread), accounting for nonlinearity, uncertainty, and contagion across instruments and portfolios.	Transition, Physical	Monasterolo (2020); Battiston and Monasterolo (2019)	No
Climate Contagion Module	Network-based stress testing model combining asset repricing, liquidity effects, and contagion between banks and funds to assess systemic exposures under disorderly transition scenarios.	Transition	Roncoroni et al. (2021)	No

(Continues)

TABLE 4 | (Continued)

Model name	Description	Climate risks considered	Main references	Adopted in supervisory exercises (yes/no)
Climate-adjustments in practice				
DNB top-down PD stress model	Transforms bank-reported through-the-cycle PDs into point-in-time stressed PDs via macroeconomic shocks (e.g., GDP, equity) and sectoral sensitivities using Transition Vulnerability Factors (TVFs).	Transition	Vermeulen et al. (2019); Daniëls et al. (2017)	Yes
ECB/DNB IFRS9 transition model (BEAST + TVF)	Integrates the BEAST model with TVFs to estimate IFRS9 stage transition probabilities, incorporating macro-financial drivers and sector-level exposure.	Transition	Budnik et al. (2020); Vermeulen et al. (2019); ESRB (2020)	Yes
ECB top-down PD model (2021)	Uses firm-level data and climate-macroeconomic variables (e.g., emissions, energy prices, and insurance costs) in a Z-score regression to estimate PDs under climate scenarios.	Transition & Physical	European Central Bank (2021)	Yes
Banque de France ICAS PD model	Applies the ICAS rating system to firms, aggregating theme-based financial indicators (profitability, liquidity, etc.) with sectoral shocks to assess transition-linked PDs.	Transition	Allen et al. (2020)	Yes
ECB/DNB LGD extension model	Extends LGD estimation via a SUR-logit framework with macro and scenario adjustments; includes TVF- and equity-linked adjustments to reflect transition shocks.	Transition	Budnik et al. (2020); Vermeulen et al. (2019); ESRB (2020)	Yes

Calice and Reinders (2022), who analyze the relationship between energy transition, financial instability, and credit risk, highlighting how LGD is particularly sensitive to the carbon intensity of economic sectors.

Despite EAD being essential for calculating expected loss, almost no methodologies provide a climate-adjusted assessment. The only significant contribution is that of the CERM, developed by Garnier et al. (2022), which, in addition to adapting PD and LGD to climate risks, modifies the EAD evaluation metrics to integrate the impacts of climate change. CERM also adjusts EAD by modulating credit exposure based on NGFS climate scenarios, integrating micro-correlations related to GHG emissions, which influence repayment capacity and credit risk over time. The combined effect of physical and transition risks translates into a variation in EAD, reflecting the deterioration of assets and the reduced ability to access credit.

Lastly, we also found studies that integrate physical and transition risks into VaR to improve financial vulnerability assessment (Desnos et al. 2023; MSCI 2019; Yang and Xu 2021). A prominent example is the CLIMAFIN framework (Monasterolo 2020; Battiston and Monasterolo 2019), which extends traditional risk assessment by linking forward-looking climate scenarios (e.g., IPCC and NGFS) to financial indicators such as climate VaR and climate spread. The model accounts for uncertainty, non-linearity, and contagion effects across instruments and portfolios, offering an integrated approach to quantify financial risk across a variety of climate transition pathways.

The literature review highlights significant methodological gaps in integrating climate risks into credit metrics. Although research on climate-adjusted PD is expanding, its application is still limited. Studies such as those by Capasso et al. (2020) and Kabir et al. (2021) confirm that exposure to climate risk affects creditworthiness, presenting a correlation between carbon emissions and default risk. However, the literature has not yet developed consolidated models incorporating these effects in assessing credit risk, thus highlighting future research directions that we have carefully compiled in a research agenda.

7.1 | Research Agenda

To answer the fourth research question (RQ4: What future directions should be pursued in research to bridge the knowledge gaps regarding the impact of climate change on the main components of credit risk?), we formalize a research agenda framed around three dimensions: methodological innovations, empirical validation needs, and the implications for sustainability reporting and financial regulation.

The very first dimension concerns methodological innovation. Despite recent progress, most contributions still rely on traditional credit risk models that fail to capture the complexity of climate dynamics. Developing climate-adjusted approaches for PD, LGD, and EAD, and doing so in an integrated way, is essential to reflect the joint nature of expected loss. Greater attention should also be devoted to the effects of transition and physical risks, including the role of carbon pricing mechanisms and regulatory changes in shaping corporate behavior (Battiston

et al. 2021; Capasso et al. 2020). Expanding scenario analysis and stress testing, and exploring the potential of artificial intelligence and machine learning, while ensuring their responsible and ethical use (Doumpos et al. 2023), would further enrich this line of research.

Methodological progress alone, however, will not be sufficient unless it is accompanied by robust empirical validation. The shortage of reliable, granular, and standardized data on emissions and climate impacts continues to be the most significant barrier. Strengthening data infrastructures and promoting harmonized disclosure frameworks will therefore be critical steps. Empirical applications based on firm-level and bank-level datasets are needed to test the robustness of climate-adjusted models across different institutional contexts and jurisdictions, and to ensure their practical relevance.

Finally, these developments inevitably carry implications for sustainability reporting and financial regulation. Operationalizing climate-adjusted PD, LGD, and EAD would enhance the transparency of corporate disclosures, allowing investors to assess climate vulnerabilities more accurately. At the same time, their integration into supervisory frameworks would provide regulators with more reliable tools to align prudential requirements with climate objectives, refine stress-testing practices, and calibrate capital buffers.

To conclude this research agenda and provide forward-looking guidance, three elements are strongly recommended as priorities for operationalizing climate-adjusted PD, LGD, EAD, and Climate VaR. The first concerns the role of academics, who should begin systematically using the innovative formulas already developed in the grey literature, such as TVF, CCQI, CERM, CLIMAFIN, and Climate VaR. These models have remained largely at the conceptual or supervisory level and have not been validated in peer-reviewed research. By applying them to granular datasets across sectors, geographies, and institutions, scholars can test their robustness and comparability, turning preliminary formulations into academically validated frameworks and helping to establish more consistent standards for climate-adjusted credit risk assessment. The second element relates to the alignment with expectations and recommendations already articulated by regulators and supervisors, such as those contained in the ECB Climate Guide (2020). These guidelines call on banks to integrate climate-related drivers into ICAAP, credit granting and monitoring, collateral valuation, and stress testing. Within this framework, the risk management function in banks should progressively embed climate-adjusted metrics into existing models. PDs can be recalibrated by embedding climate variables in internal rating systems. LGDs valuation can be reshaped to reflect the devaluation of collateral exposed to floods or stranded assets. EADs can capture the reduced refinancing capacity of firms under transition or physical stress. Climate VaR can be reported as part of prudential assessments to account for unexpected losses. The third element is the need to strengthen cooperation among regulators, supervisors, scholars, and practitioners. Each of these actors can provide a unique contribution: regulators and supervisors can supply guidance and access to data, academics can test and refine methodologies, and practitioners can bring operational expertise from credit processes.

8 | Concluding Remarks

This research reviews the available literature on climate risks and their effect on credit risk and presents important directions for future researchers in promising fields of investigation, considering jointly white and grey literature and pointing out the impact of climate on several parameters and components of credit risk. The evidence indicates that effective climate risk management requires joint efforts by academia, financial institutions, governments, and policymakers (Nicolò et al. 2024). It depends on advanced models, reliable data, training frameworks ensuring the resilience of the financial system, and stronger governance (Aibar-Guzmán et al. 2024). Existing literature has mainly concentrated on transition risks and on isolated parameters. It has often neglected the direct effects of physical climate events on financial stability. Consequently, a more holistic approach is needed, one that also takes into consideration physical risks and incorporates them into the most important elements of credit risk, such as PD, LGD, and EAD. The constantly developing economic and climatic conditions require dynamic and adaptable models that respond rapidly to external changes, reduce the consequent risks, and comply with regulatory requirements for model validation. The challenges connected to climate risk management will require creativity, resources, and diverse quantitative and qualitative abilities. Incorporating climate risks is fundamental for risk reduction and represents an opportunity to restructure finance toward sustainability. Looking ahead, the main contribution of this study lies in consolidating and systematizing the available frameworks and, by using both white and grey literature, providing a structured starting point for moving from conceptual discussion to practical experimentation, with broad coverage and practical relevance. First, it encourages public bodies to actively test and apply the climate-appropriate formulations identified in the literature in order to assess their usability and promote their gradual validation within the white literature. Second, it can provide a basis for guiding the refinement of prudential and regulatory policies and can support the development of coordinated rules to protect financial stability from climate-related risks.

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Conflicts of Interest

The authors declare no conflicts of interest.

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