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Local Banks and flood risk: the case of Germany

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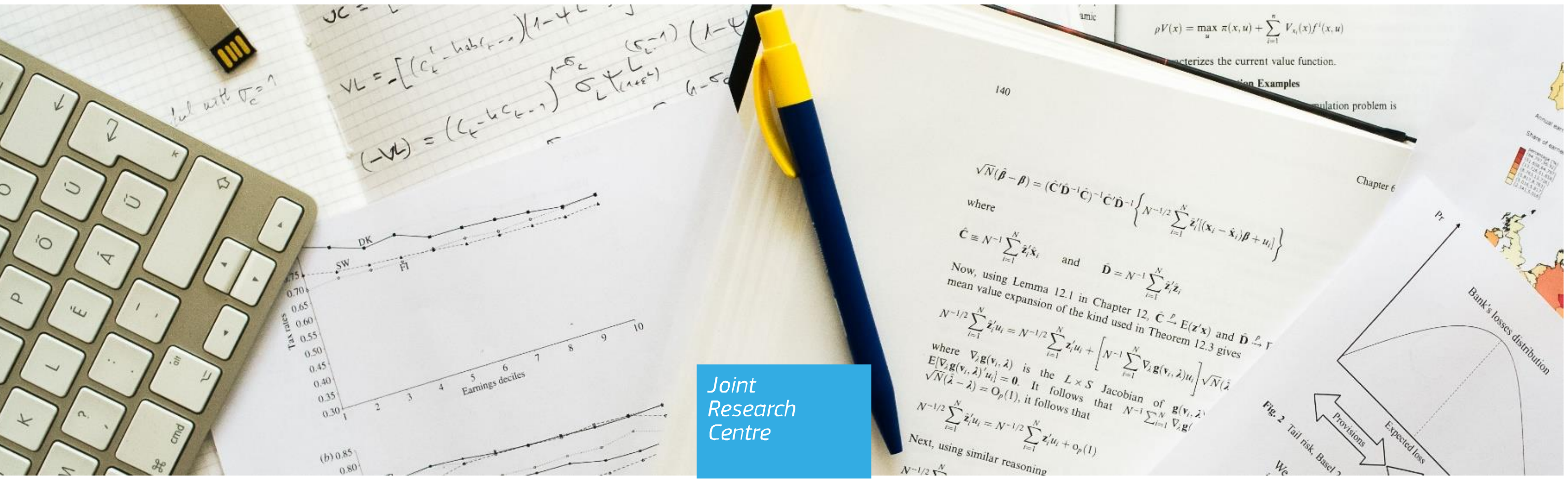

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Executive summary

The climate crisis has emerged as a significant threat to firms around the world, impacting not only their operations but also their debt repayment capacity. As extreme weather events become more frequent and severe, companies face an increased risk of being unable to meet their financial obligations with far-reaching repercussions on lending institutions.

Understanding and managing climate-related financial risks arising from the escalating frequency and intensity of catastrophic events, called physical risk, is crucial for maintaining financial stability. It requires assessing the vulnerabilities of financial institutions, integrating climate-related factors into risk management frameworks, and promoting climate resilience and adaptation measures.

Policymakers have taken several policy initiatives which require banks to assess and disclose risks arising from climate-related natural disasters, integrate these risks into their risk management frameworks, and align their investment portfolios and financial products with sustainability criteria. The specific requirements vary for each initiative, but the overall goal is to foster a more climate-resilient financial sector by considering and addressing climate physical risks. At the EU level, several policy actions require banks to assess, report and integrate climate-related risks into their risk management frameworks. The Sustainable Finance Strategy expects banks to conduct comprehensive risk assessments that consider the potential impacts of climate change on their business activities. As part of the Strategy, European Supervisory Authorities will work on climate stress testing of the financial system including a one-off Fit-for-55 climate risk scenario analysis in cooperation with the European Central Bank (ECB) and the European Systemic Risk Board. The Non-Financial Reporting Directive requires banks under its scope to disclose information on their policies, risks, and outcomes related to environmental matters, including climate change and physical risks. The EU Taxonomy, which provides criteria for determining which economic activities can be classified as environmentally sustainable, details how banks need to identify and report on investments or products that contribute to climate change adaptation or mitigate physical risks.

Against this background, the primary objective of this paper is to evaluate the effect of localized climate-related events, under various global warming scenarios, on regional banks in Germany. By doing so, it aims to shed light on potential vulnerabilities and risks in the German banking sector, paving the way for more informed decision-making, in particular on risk mitigation strategies.

Considering a static systemic financial crisis scenario, we show that climate-related risks would increase overall losses by 0.1% under the current temperature level and these could become even more significant with losses up to 0.9% with a 3°C temperature increase. However, banks in some regions would suffer much higher losses than in others. Moreover, we observe that, even in a normal economic situation, there are few banks defaulting because of climate risk. Should these defaults trigger disorderly market adjustments, subsequent dynamics would be negligible under the actual warming conditions, however, could lead to significant losses for the German regional banking system up to 1% of total assets if a 3°C temperature rise materialized. In both cases, the variability of losses across NUTS2 regions, is quite large, with some regions reaching 5% of total assets in case of an existing financial crisis, and even to 10% in a normal economic situation. This negative impact can be effectively tackled with the implementation of adaptation strategies. Therefore our findings support the idea that banks operating in regions prone to such geographic risks should take measures to safeguard themselves. One potential approach is to implement additional bank- specific capital add-ons, which would enhance the resilience of the banking sector against these natural-related shocks. This strategy would help mitigate the potential negative impacts on banks' financial stability and ensure their ability to withstand and recover from such events. Alternatively, banks can contribute to

the adaptation efforts aimed at reducing the vulnerability of the regions they operate in. By supporting adaptation initiatives, such as investing in climate-resilient infrastructure or providing financial services to support sustainable practices, banks can play a crucial role in building the resilience of the financial sector and reducing the overall impact on the economy.

Further research could investigate more in detail the overall impact of physical risk on the financial sector, as increasing attention is devoted both by policymakers and academics to the role of climate risk for financial stability and debt sustainability

Local Banks and flood risk: the case of Germany

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Abstract

This paper uses a simulation model to evaluate the effects of river flooding events occurring within Germany on *regional' banks*. Under a 1.5°C increase in temperature, the impact is overall rather small, even accounting for the devaluation of loans exposed to floods. However, under a 3°C increase, bank losses can reach 1% of total assets. We show that the implementation of adaptation solutions would be successful in keeping risks at the current level.

Keywords: Physical risk, river flood events, dynamic balance sheet, banking crisis.

J.E.L. classification: C15; G2; Q54.

1 Introduction

The climate crisis has emerged as a significant threat to firms around the world, impacting not only their operations but also their debt repayment capacity. As extreme weather events become more frequent and severe, companies face an increased risk of being unable to meet their financial obligations. A study from the Bank of Japan (Yamamoto et al., 2021) identifies a negative impact of flood damages on company profitability proxied by the ratio of profit to sales, especially in the manufacturing industry. Interestingly, the impact tends to be larger for firms located in places which do not frequently experience floods. Furthermore, flood events can have far-reaching, indirect impacts on companies' financial performance through the global supply chain network. Recently, the German car manufacturer Volkswagen announced production losses and suspension of operations for some of its factories in Portugal due to floods in Slovenia which affected some of its engine part suppliers (Reuters, 2023). In an earlier study, Haraguchi and Lall (2015) document declines in profitability of up to about 60 % in some Japanese automakers due to a flood which occurred in Thailand. Evidently, such substantial impact could negatively affect firms' debt repayment capacity with far-reaching repercussions on lending institutions.

Understanding and managing climate-related financial risks arising from the escalating frequency and intensity of catastrophic events, called physical risk, is crucial for maintaining financial stability. It requires assessing the vulnerabilities of financial institutions, integrating climate-related factors into risk management frameworks, and promoting climate resilience and adaptation measures. The nascent literature shows some mixed evidence on the impact of weather-related natural disasters on the financial sector. The study by Blickle et al. (2021) finds that large banks are barely affected by extreme weather-induced and their income even increases due to subsequently higher loan provision. The impact is more pronounced in local banks but still not large enough to cause solvency concerns. Similarly, Caloia and Jansen (2021) find that the Dutch banking sector is sufficiently capitalised to withstand floods in areas where the real estate exposure is low. However, the impact would be larger in case more severe floods hit the densely populated areas of the country. The analysis from Calice and Miguel (2021) also finds a small, yet statistically significant result of large-scale natural disasters on banks' credit portfolios. In particular, in Latin American and Caribbean (LAC) countries banks' NFC-related nonperforming loans increase by up to 2.5 percentage points post-disaster. Two studies focus on small, regional financial institutions and empirically examine the indirect impact of floods on them. They both document the adverse effects of floods on banks either by temporarily increasing their impaired loans (Shala and Schumacher, 2022) or by hindering their profitability (Pagliari, 2023).

Policymakers have taken several policy initiatives which require banks to assess and disclose risks arising from climate-related natural disasters, integrate these risks into their risk management frameworks, and align their investment portfolios and financial products with sustainability criteria. The specific requirements vary for each initiative, but the overall goal is to foster a more climate-resilient financial sector by considering and addressing climate physical risks. At the EU level, several policy actions require banks to assess, report and integrate climate-related risks into their risk management frameworks. The Sustainable Finance Strategy[1] expects banks to conduct comprehensive risk assessments that consider the potential impacts of climate change on their business activities. As part of the Strategy, European Supervisory Authorities will work on climate stress testing of the financial system including a one-off Fit-for-55 climate risk scenario analysis in cooperation with the European Central Bank (ECB) and the European Systemic Risk Board. The latter aims to assess the resilience of the financial sector and gain insights into its capacity to support the transition to a lower carbon economy even under conditions of stress. The Non-Financial Reporting Directive[2] requires banks under its scope to disclose information on their policies, risks, and outcomes related to environmental matters, including climate change and physical risks. The EU Taxonomy[3], which provides criteria for determining which economic activities can be classified as environmentally sustainable, details how banks need to identify and report on investments or products that contribute to climate change adaptation or mitigate physical risks.

Against this background, the primary objective of this paper is to evaluate the effect of localized climate-related events, under various global warming scenarios, on regional banks in Germany. By doing so, it aims to shed light on potential vulnerabilities and risks in the German banking sector, paving the way for more informed decision-making, in particular on risk mitigation strategies.

The study focuses on 677 cooperative banks, which are geographically more concentrated in their exposures, given their strong connection to the local economy compared to other types of banks. We assume that the lending activities of a cooperative bank are conducted at the NUTS2 level, which represents

[1] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Strategy for Financing the Transition to a Sustainable Economy, COM/2021/390 final

[2] Directive 2014/95/EU of the European Parliament and of the Council of 22 October 2014 amending Directive 2013/34/EU as regards disclosure of non-financial and diversity information by certain large undertakings and groups. OJ L 330, 15.11.2014, p. 1-9

[3] Commission Delegated Regulation (EU) 2021/2178 of 6 July 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by specifying the content and presentation of information to be disclosed by undertakings subject to Articles 19a or 29a of Directive 2013/34/EU concerning environmentally sustainable economic activities, and specifying the methodology to comply with that disclosure obligation (Text with EEA relevance)m C/2021/4987 OJ L 443, 10.12.2021, p. 9–67

relatively large regions in terms of area. While more detailed data at the NUTS3 level would provide more accurate estimates of the assets that may be at risk from acute physical factors, we are constrained by data limitations and thus maintain this assumption.[4]

Based on 2023 ECB analytical indicators on physical risks,[5] the size of German bank assets currently at risk due to river floods is 0.6% of their portfolios to non-financial corporations. As the exposure to floods varies within the country, we distribute the amount of assets across different NUTS2 regions, using the share of people exposed as obtained from the Risk Data Hub. To account for the strain on banks' loan portfolios that can arise from the impact of river flood events, we consider the assets at risk as non-performing loans. This is also one assumption of the model, since part of the losses from non-performing loans might be recovered due to collateral for instance. As global temperatures rise due to global warming, we assume that non-performing loans might increase in proportion to the economic losses caused by floods, as projected in PESETA IV (Feyen et al., 2022; Dottori et al., 2020).

A micro-simulation portfolio model based on individual bank balance sheet data is used to derive the loss distribution for the banking sector, considering a situation in which losses from physical risk come in addition to initial financial sector losses. Two cases are considered: (a) a normal economic situation where the impact on banks is only due to the physical risk, the materialization of which triggers a small devaluation of assets exposed modelled via a dynamic balance sheet; (b) a crisis type situation where the impact of physical risk is on top of existing financial/economic crisis. For a stable economic situation, we consider only banks whose defaults are due to their exposure to river flood events, and starting with a mild initial devaluation of climate-related loans for all banks, we investigate if, and how many, new banks fail. We keep increasing the level of loans' devaluation, until a new equilibrium is reached (i.e. no extra defaults). The specific impact is rather small and eventually becomes significant under an increase in global average temperature, with losses of around 0.2% of total assets under a 1.5℃ increase in temperature, and around 1% under a 3℃ increase. When climate risk materializes on top of an existing financial crisis, the magnitude of losses ranges from 0.4% to 0.9% of total assets, depending on the specific climate warming scenarios, and climate-related financial risks are concentrated in few regions particularly exposed to climate-related events (up to 5% of total assets). Finally, we investigate the impact of physical risks when adaptation strategies are implemented. The level of risk associated with a 3℃ increase in global warming can be mitigated to the extent that it becomes comparable to the current situation both in crisis

[4]It is worth noting that the business area of regional banks may be smaller than NUTS2 areas but larger than NUTS3 areas.

[5]https://www.ecb.europa.eu/pub/pdf/other/ecb.climate_change_indicators202301~47c4bbbc92.en.pdf

time and in normal times. The results indicate that banks operating in regions prone to river floods should take measures to safeguard themselves. One potential approach is to implement additional bank-specific capital add-ons, which would enhance the resilience of the banking sector against these natural-related shocks. This strategy would help mitigate the potential negative impacts on banks' financial stability and ensure their ability to withstand and recover from such events. Alternatively, banks can contribute to the adaptation efforts aimed at reducing the vulnerability of the regions they operate in. By supporting adaptation initiatives, such as investing in climate-resilient infrastructure or providing financial services to support sustainable practices, banks can play a crucial role, not just in building the resilience of the financial sector, but also in reducing the overall impact on the economy.

The paper is organized as follows. The next section explains how the inputs to the model are derived, notably the share of river floods-related non-performing assets. Section 3 provides an overview of the main modelling framework. Section 4 models a crisis triggered by physical risk, while Section 5 investigates the case of a systemic banking crisis not triggered by physical risk. Finally, Section 6 discusses the role of adaptation strategies in mitigating the risk for the financial sector and Section 7 concludes.

2 Data inputs

The analysis relies on individual balance sheet data for German banks retrieved from Orbis BankFocus as of end of 2020. Specifically, we use Total Assets (TA), Risk Weighted Assets (RWA) and Total Regulatory Capital (K).[6] By acknowledging their role in financing local economic activities, the study focuses on cooperative banks only. Hence, the final data set covers 677 entities, accounting for around 40% of the total assets in the German banking system. Being inherently more interconnected with local businesses and communities, cooperative banks demonstrate a higher degree of geographical concentration in their exposures and a strong connection to the local economy. This means that their lending activities and investments are focused on specific regions or localities, resulting in a more localized footprint compared to other types of banks.[7]

By comparing our sample with German commercial banks, it becomes evident that cooperative banks differ from other types of banks in terms of financial riskiness and performance. Notably, cooperative banks exhibit higher levels of risk compared to commercial banks (see Figure 1), as indicated by lower solvency,

[6] See Table A.1 in Appendix A for descriptive statistics on the representativeness of the sample by country.
[7] See Koetter et al. (2020) and Behr and Schmidt (2015).

and higher RWA density.[8] However, this higher risk is counterbalanced by a stronger capitalization with respect to total assets (leverage), suggesting that cooperative banks have a robust capital base to mitigate potential risks, but probably not sufficient with respect to RWAs (compare leverage and solvency in Figure 1). One of the key factors contributing to the unique risk profile of cooperative banks is their closer ties to the local economy and their focus on specific sectors or industries. This can expose them to risks associated with local economic downturns and concentration risks in their loan portfolios. Additionally, cooperative banks may face challenges in diversifying their operations beyond their local markets, which can further impact their risk exposure. As a matter of fact, the business model of cooperative banks differs from that of other banks (see Figure 2). Cooperative banks tend to have a stronger focus on lending activities and rely more heavily on customer deposits. This emphasis on lending and customer relationships aligns with their mission to support local economic activities. In terms of profitability (see Figure 3), our sample of cooperative banks outperforms commercial banks, as evidenced by higher Return on Assets and larger operating income.

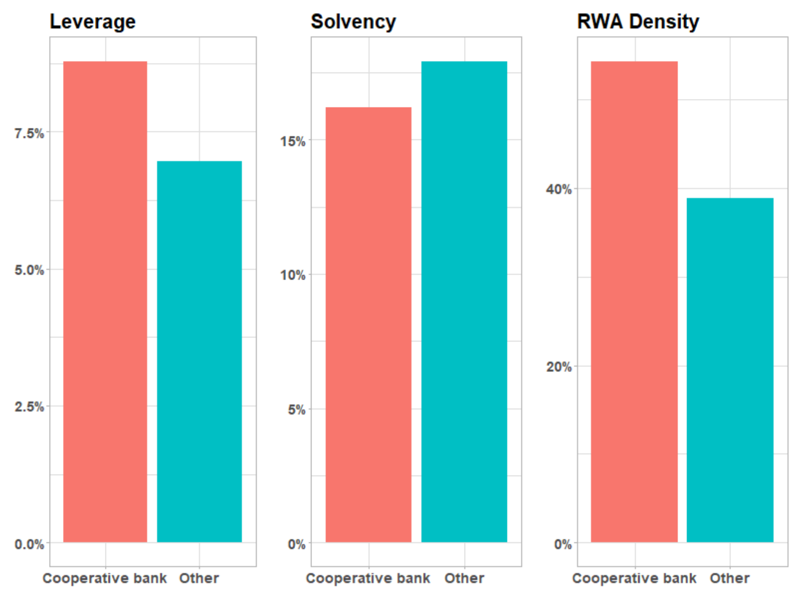

Figure 1: Risk indicators

[8]For bank i, RWA density$_i$ = $\frac{RWA_i}{TA_i}$; Solvency$_i$ = $\frac{RegulatoryK_i}{RWA_i}$; Leverage$_i$ = $\frac{RegulatoryK_i}{TA_i}$

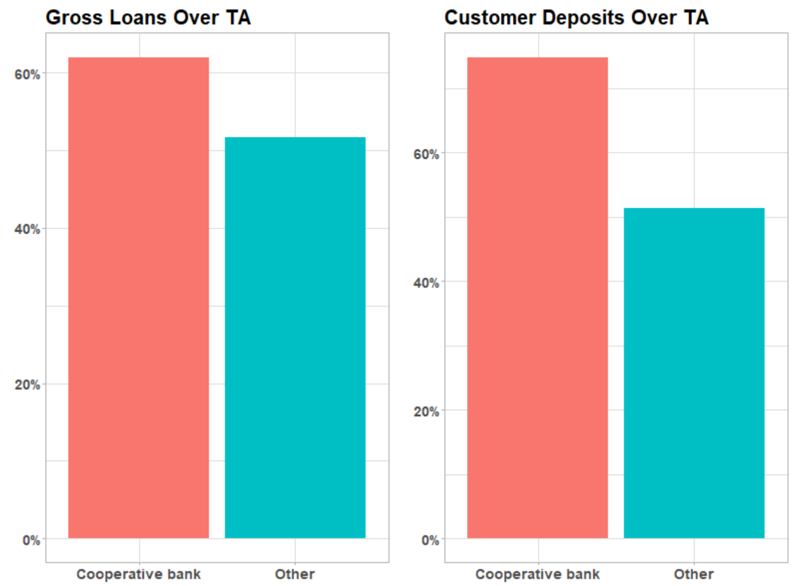

Figure 2: Business model indicators

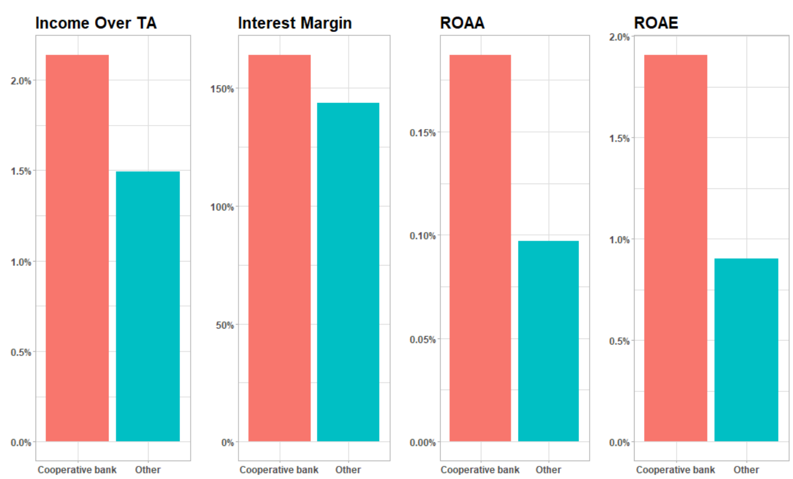

Figure 3: Profitability indicators

Together with balance sheet data, a key input to the model is the actual size of assets in banks' balance sheets that are exposed to non-financial corporations located in river flood-prone areas. The ECB assumes that 0.6% of German financial institutions' portfolios are at risk considering the intensity of the hazard, while 29.8% are exposed.[9] Leveraging the ECB's breakdowns of domestic and cross-border intra euro-area positions, we determine the proportion of assets held by non-financial institutions (ECB_{NMFI}). We then apply the ECB's estimated share of portfolio at risks (ECB_{FR}) to derive the amount of German assets that are vulnerable to flood events (TA^F):

[9]Indicators NEAR (Normalised exposure at risk) and PEAR (potential exposure at risk) and as published here: https://www.ecb.europa.eu/pub/pdf/other/ecb.climate_change_indicators202301~47c4bbbc92.en.pdf

$$TA^F = TA \cdot ECB_{NMFI} \cdot ECB_{FR}. \quad (1)$$

Specifically, TA is the total amount of assets for our sample, ECB_{NMFI} is equal to 59.8% and ECB_{FR} is set at 0.6%. Next, we allocate the German assets that are susceptible to flood events across different n NUTS2 regions, by taking into account the corresponding share of population exposed to river floods (P_n^F). This allows for a more accurate distribution of assets based on the level of vulnerability to flood events in each specific region. Essentially, regions with a higher proportion of the population exposed to these events will have a greater amount of assets at risk.

The total assets of all banks in region n at risk of floods are represented by TA_n^F in the following equation:

$$TA_n^F = TA^F \cdot P_n^F. \quad (2)$$

The share of population is obtained from the Risk Data Hub[10], an EU-wide web-based geographical information system platform developed by the Joint Research Centre of the European Commission. The platform provides geo-referenced exposure data over one year[11] for various assets (such as buildings, population, critical services, and the environment).[12] Figure 4 presents the map for Germany along with a relative score measuring the population exposed in case of natural catastrophes. The figure shows that the exposure to river floods in Germany varies across different regions. Some regions, such as the areas along major regions, are more susceptible to severe flooding than others. This is the case for Trier, Darmstadt, Niederbayern, Schwaben, Koblenz.

[10] https://drmkc.jrc.ec.europa.eu/risk-data-hub

[11] The exposure of each asset over one year is an average of the exposure under different return periods weighted using the probability of occurrence. The "return periods" are estimates of the interval of time between events. For example, a return time of 100 years indicates that the event will occur once in 100 years on average, therefore the probability a similar event could occur in the same interval of time is 1% (1/100).

[12] Each hazard is covered with a specific grid resolution (100m for river floods), and an aggregation at the level of local administrative units is also available.

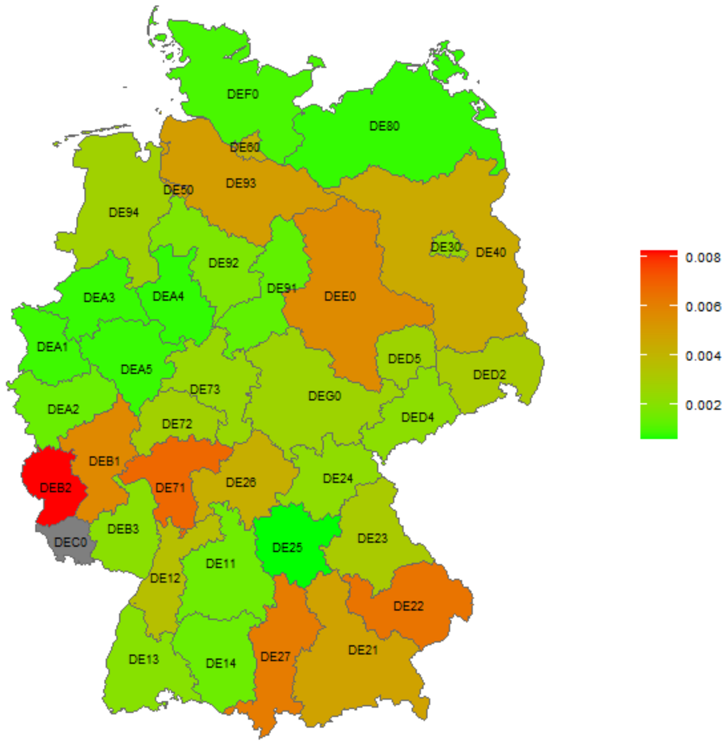

Figure 4: Map of the population exposed to floods in Germany (relative score). Source: JRC Calculation on JRC RDH data.

To account for the strain on banks' loan portfolios that can arise from the impact of river flood events, we consider the assets at risk of river flood-related risks as non-performing loans. All in all, when borrowers are affected by catastrophic events, which cause losses and damages to their businesses, the ability to honour their debt obligations becomes compromised, leading to a potential rise in unlikely-to-pay and non-performing loans. The total amount is thus distributed across each bank, denoted as i, based on their respective share of assets. Hence, we calculate the amount of bank assets at risk of becoming non-performing (NPL_i^F) as follow:

$$NPL_i^F = TA_n^F \cdot \frac{TA_i}{TA_n}, \tag{3}$$

where TA_i represents the assets of bank i, and TA_n represents the total assets of all banks in region n. Figure 5 provides insights into the distribution of non-performing loans across banks. The graph reveals that the density distribution of NPL^F is skewed, indicating that the majority of institutions have a relatively size of NPL^F lower than 10% compared to their equity. This skewness suggests most banks in the sample might be able to manage credit risk and minimize the impact of loan defaults on their overall financial health.

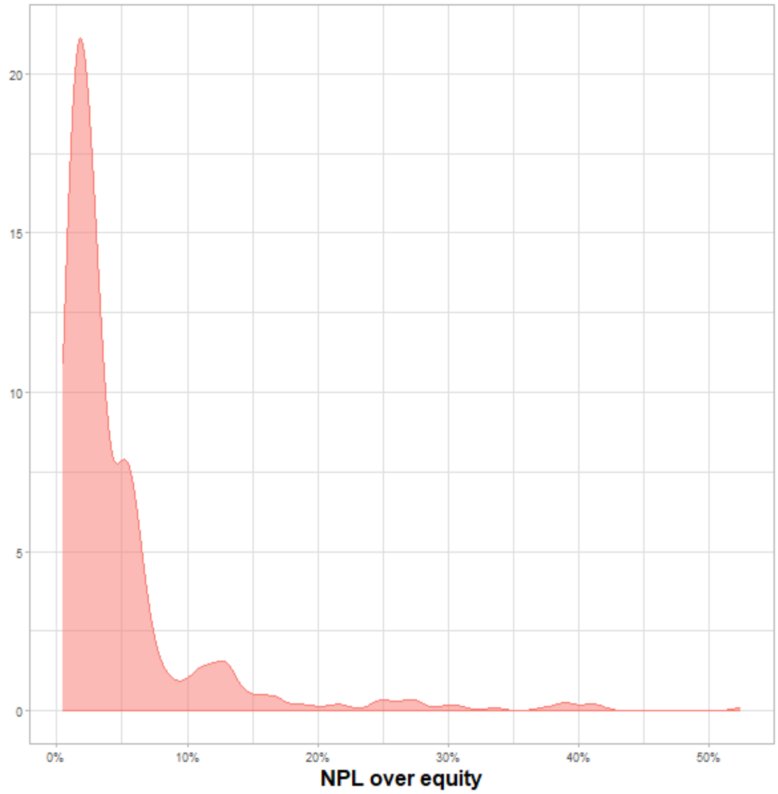

Figure 5: Density distribution of $NPLs^F$ over equity across banks in the sample (under the actual climate condition)

As the global temperature raises, economic losses from flood-related events are expected to rise, which could potentially affect the worth of assets held by financial institution. For example, we can think about damage to assets serving as collateral, as in the case of mortgages given for properties located in vulnerable areas. Though accurately predicting the impact of global warming on the financial assets is challenging, it is reasonable to assume that as economic losses increase, assets currently exposed to flood risks, but not yet at risk, are likely to become non-performing in the future due to worsening climate conditions. To incorporate this assumption into our modelling framework, we assume that the size of river flood-related non-performing loan, across NUTS2 German regions, will increase proportionally to the severity of the economic impact caused by the rise in temperature:

$$NPL^{F_i,t^{\circ}\mathrm{C}} = NPL^{F_i} \times \Delta L_{t^{\circ}\mathrm{C}}, \tag{4}$$

where

- NPL^{F_i} are losses due to physical risk in the current situation;

- t °C refers to the increase in global temperature of a specific global warming scenario (t = 1.5, 3.0);
- $\Delta L_{t°C}$ indicates the increase in economic losses under a t°C increase in temperature with respect to today;
- $NPL^{F_i,t°C}$ refers to the new flood-related losses under the warming scenario (1.5°C, 3.0 °C).

Using country data from the PESETA IV study (Feyen et al., 2022), we determine the expected increase in overall economic losses resulting from flood events under a 1.5°C and 3°C increase in temperature, with and without adaptation strategies. Based on this information, we project the size of river floods-related non-performing loans under four global warming scenarios: current climate conditions, 1.5°C increase without adaptation, 3°C increase without adaptation, and 3°C increase with adaptation strategies. These values are inputs to the model described in the next sections and their PESETA underlying values are reported in Table 1.

This assumption is a simplification that should be approached with caution. While it helps to address the complexity of the issue, it has the potential to oversimplify the situation, introducing uncertainty and potentially overlooking important factors. Specifically, we are assuming that the overall economy remains static, the structure of the banking system remains unchanged, and the risk appetite of financial institutions remains the same. It is important to recognize that in reality, these factors are subject to change and can significantly impact the relationship between economic losses and non-performing loans.

Table 1: Variation in economic losses under three temperature increases

Increase under 1.5 °C	**Increase under 3 °C**	**Decrease with adaptation under 3 °C**
95%	304%	80%

3 Simulation model

The modelling framework relies on the Systemic Model of Banking Originated Losses (SYMBOL, see De Lisa et al., 2011), a micro simulation portfolio model which uses bank-level data to simulate banking crisis scenarios. Specifically, individual banks may default based on their actual capital (K) and on the probability of default attached to their portfolio (PD). The bank's portfolio PD is calculated by inverting the Basel formula, which relates the minimum capital requirements to the PD of a bank's portfolio and its RWA as follow:

$$CR(PD) = LGD \cdot N\left[\frac{\sqrt{R}N^{-1}(\frac{0.08 \cdot RWA}{TA}) + N^{-1}(PD)}{\sqrt{1-R}}\right] - PD, \tag{5}$$

where R_i is the correlation among exposures in the portfolio, LGD is the loss given default equal to 0.45 as per regulation[13], N is the normal distribution function.

Bank-specific PDs are then used to generate losses for individual banks via a Monte Carlo simulation, where randomness is introduced by sampling the underlying shocks. While provisions and write-offs should cover expected losses on an ongoing basis, unexpected losses refer to seldom but potentially significant losses that should be covered by capital. The failure of a bank is determined by comparing the size of these unexpected losses to the actual regulatory capital available for absorbing them. In other words, banks fail when simulated unexpected losses exceed the total actual capital.[14] Some of the model iterations, particularly those where larger sampled shock, will likely result in at least one bank defaulting.

The output of the Monte Carlo simulation is an $I \times J$ matrix of unexpected losses $(\text{GL})_{ij}$, obtained as follows:

$$GL_{ij} = LGD \cdot N\left[\sqrt{\frac{1}{1-R_i}}N^{-1}(PD_i) + \sqrt{\frac{R_i}{1-R_i}}N^{-1}(\alpha_{ij})\right] - EL_i, \tag{6}$$

where the first term generates the total amount of losses and the second one (EL_i) approximates the expected losses.[15] Specifically, $i = 1, \ldots, I$ refers to the banks in the sample, $j = 1, \ldots, J = 10,000$ denotes the model iteration. $N^{-1}(\alpha_{ij})$ are correlated normal random shocks. The α_{ij} shocks are correlated as they are defined as the sum of a common shock Z_j and a bank-specific shock W_{ij}, as follows:

$$N^{-1}(\alpha_{ij}) = l \cdot Z_j + \sqrt{1-l^2} \cdot W_{ij}, \tag{7}$$

where l are the loadings, W_{ij} are the idiosyncratic shocks, and Z_j is a common shock which might be linked, for example, with overall economic developments. The standard version of the model, which is used in this paper, sets l so as to yield a fixed correlation of 0.5 across the α_{ij}.[16] The shocks Z_j and W_{ij} are drawn from a standardized normal distribution as in the Vasiceck model (see Vasicek (1977); De Lisa et al. (2011)).

In each iteration, the following three components are summed up for each bank: i) losses that cannot

[13] https://www.fdic.gov/analysis/cfr/working-papers/2006/2006-10.pdf
[14] See Benczur et al. (2017) for details.
[15] Expected loss is calculated as the product of PD, LGD, and total assets.
[16] See Di Girolamo et al. (2017) for a discussion on a more sophisticated correlation structure.

be absorbed by capital, and ii) recapitalization needed to bring the banks back to a viability status, i.e. a total regulatory capital ratio of 8% of RWAs and iii) climate-related financial losses (L^F) to assess the impact of climate change on the bank's balance sheet. The framework subsequently assesses whether the banks' capital is high enough to absorb losses and climate-related losses or if these could potentially lead to additional failures within the banking sector.

From here on, we then define as *losses* for each bank and each iteration, the unexpected losses in excess of capital plus recapitalization needs ($ExLR_{ji}$), as follows:

$$ExLR_{ij} = \max(GL_{ij} - K_i + 8\%RWA_i + L_i^F, 0), \tag{8}$$

of course, L_i^F are taken into consideration just when physical risk materializes. Excess losses plus recapitalization needs for individual banks yield the following aggregate loss distribution for each iteration:

$$L_j = \sum_{i=1}^{I} ExLR_{ij}. \tag{9}$$

Each point in the distribution (i.e. each iteration) is associated with a different level of financial/economic distress. Using individual banks' distribution, they can be aggregated at different scales (e.g. country, NUTS2, etc.).[17]

4 Physical risk as a trigger of a crisis

4.1 Modelling framework

In this application of the model, we investigate under which conditions river flood events could be the trigger of a crisis for cooperative banks in Germany even in the absence of a large economic shock. To do so, we start by comparing SYMBOL results with and without climate related financial losses to identify those banks that would fail due to a materialization of physical risk but would not fail otherwise. Essentially, based on the simulation results, we identify iterations where banks default when river-flood

[17] This modelling framework can accommodate different degrees of commonality by allowing for various shock correlation structures, while a contagion mechanism is not explicitly considered. We do not explicitly model contagion effects through the interbank market for three main reasons. First, contagion would introduce an additional layer of complexity, increasing the uncertainty around the results. Second, modelling contagion dynamics is quite challenging, as public data do not fit for the purpose of calibrating the network. Third, the comprehensive crisis management and deposit insurance framework put forward by the Commission after the last financial crisis (notably, the bail-in tools and the establishment of resolutions funds), is expected to prevent the spreading of contagion as distressed banks would be resolved, liquidated or recapitalised well before direct contagion effects could materialize (see, e.g. Benczur et al. (2017).

non-performing loans are taken into account but do not default without. Formally, these correspond to the runs satisfying the following condition:

$$\widetilde{j} := j \text{ such that } \begin{cases} ExLR_{ij} & = 0 \text{ without physical risk,} \\ \text{and} & \\ ExLR_{ij} & > 0 \text{ with physical risk.} \end{cases} \quad . \tag{10}$$

Then, we model a dynamic mechanism whereby, owing to these initial defaults, a devaluation of exposed assets takes place, leading to further failures and losses in the banking sector. In particular, we assume that initial bank defaults (only due to climate) may trigger a sequence of devaluation dynamics of assets exposed, which is reflected on the one hand, in a lower share of exposed assets on banks' balance sheets, and on the other hand, in lower market prices for those assets. The mechanism is modelled as follows. Initially, when physical risk from river-flood events emerges, there is an immediate devaluation of assets that are exposed to such risks. This devaluation is determined by the proportion of non-performing loans attributed to river floods in relation to the overall size of the exposed assets. The extent of devaluation at each round is directly linked to variations in climate-related losses. This means that the size of the devaluation is proportional to the changes observed in losses associated with climate-related events. The mechanism continues until the system reaches a new equilibrium, i.e. no more banks default.

Final loss (FL) due to physical risk is then computed by taking the expected value of aggregate bank losses (as defined in Equation 9) across the selected iterations. This corresponds to the Expected Shortfall concept:

$$FL = \mathbb{E}_j[(L)_j \mid j \text{ in } \widetilde{j}], \tag{11}$$

Climate-related losses, L^F (see Equation 8), take into account first and second-round effects from the devaluation of exposed assets (see Section 2):

$$L^F_{t_r} = \begin{cases} NPL^F \text{ if } t_r = 0 \\ FL_{t_r} + \frac{NPL^F}{TA^F_{e,0}} \times TA^F_{e,t_r} \text{ if } t_r = 1 \\ FL_{t_r} + \frac{FL_{t_r-1} - FL_{t_r-2}}{TA^F_{e,t_r-1}} \times TA^F_{e,t_r} \text{ if } t_r > 1, \end{cases} \tag{12}$$

where TA_e^F refers to the assets exposed to river flood:

$$TA^F_{e,t_r} = \begin{cases} 29.8\% \cdot TA \text{ if } t_r = 0 \text{ as estimated by the ECB} \\ TA^F_{e,t_r-1} - FL_{t_r-1} \text{ if } t_r > 0. \end{cases} \quad (13)$$

4.2 Results

Based on the SYMBOL simulation and considering climate-related losses from river-flood events, our findings suggest that the impact on German cooperative banks is negligible today. However, this could become a more significant concern if the temperature increases by 1.5 °C and even worse under a 3 °C increase.

Table 2 presents the percentage of banks that default at each step, while Table 3 shows the corresponding percentage of assets affected. At step 0, our results indicate that physical risk initially leads to a relatively small number of failures in the banking system. Specifically, 0.2% of the total number of banks in our sample are in default, which also corresponds to 0.2% of total German assets. Under the most severe climate conditions, the initial share of failed banks increases to 7% of the total number of banks, affecting 5% of total assets (see Table 2 and Table 3). The dynamic feature introduced to simulate the devaluation of exposed assets leads to more banks defaulting in the system. While the final number of defaults does not increase significantly under the current temperature level, the worst global warming scenario could result in the failure of 29% of banks, which hold approximately 24% of the total assets.

In terms of financial losses, the impact is relatively small under the current climate conditions but could become significant as temperatures increase up to 3°C. Specifically, aggregated losses amount to 0.02% of total assets at the present temperature level, 0.2% under a temperature increase of 1.5°C, and 1.1% under a 3°C increase (see Table 4).[18] These results show that should such risk materialises nowadays the recourse to public finances would be contained. However, an increase in temperature would pose challenges for the corporate sector that could destabilize the German regional banks, at least in some regions.

When examining specific NUTS2 regions, our results indicate that a few regions could be particularly strongly affected, with losses reaching up to 10% of total assets under a 1.5 °C temperature increase. Figure 6 shows that there are at least three regions with a share of losses over total assets larger than 5%,

[18] It is important to note that in reality, the impact would be much more contained due to bank recovery mechanisms and troubled asset purchase programs that would be triggered before a large number of banks become insolvent.

even under a 1.5°C temperature increase (and even higher under a 3 ℃ temperature increase). Comparing the two panels in Figure 6, one can see that there are just few NUTS2 regions contributing to the overall losses.

	Current	1.5 ℃ increase	3.0 ℃ increase
Step 0	0.2%	3%	7%
Step 1	3%	7%	17%
Step 2	3%	8%	23%
Step 3	3%	8%	25%
Step 4	3%	8%	27%
Step 5	3%	8%	27%
Step 6	3%	8%	28%
Step 7	3%	8%	28%
Step 8	3%	8%	29%

Table 2: Number of banks defaulted over the total number of banks in the sample (crisis triggered by physical risk)

	Current	1.5 ℃ increase	3.0 ℃ increase
Step 0	0.2%	1%	5%
Step 1	1%	4%	15%
Step 2	1%	5%	19%
Step 3	1%	5%	22%
Step 4	1%	5%	23%
Step 5	1%	5%	24%
Step 6	1%	5%	24%
Step 7	1%	5%	24%
Step 8	1%	5%	24%

Table 3: Assets of banks defaulted over the total amount of assets in the sample (crisis triggered by physical risk)

	Current	1.5 ℃ increase	3.0 ℃ increase
Step 0	0%	0%	0.1%
Step 1	0.02%	0.1%	0.6%
Step 2	0.02%	0.2%	0.9%
Step 3	0.02%	0.2%	1%
Step 4	0.02%	0.2%	1.1%
Step 5	0.02%	0.2%	1.1%
Step 6	0.02%	0.2%	1.1%
Step 7	0.02%	0.2%	1.1%
Step 8	0.02%	0.2%	1.1%

Table 4: Size of losses in the sample as share of TA (crisis triggered by physical risk)

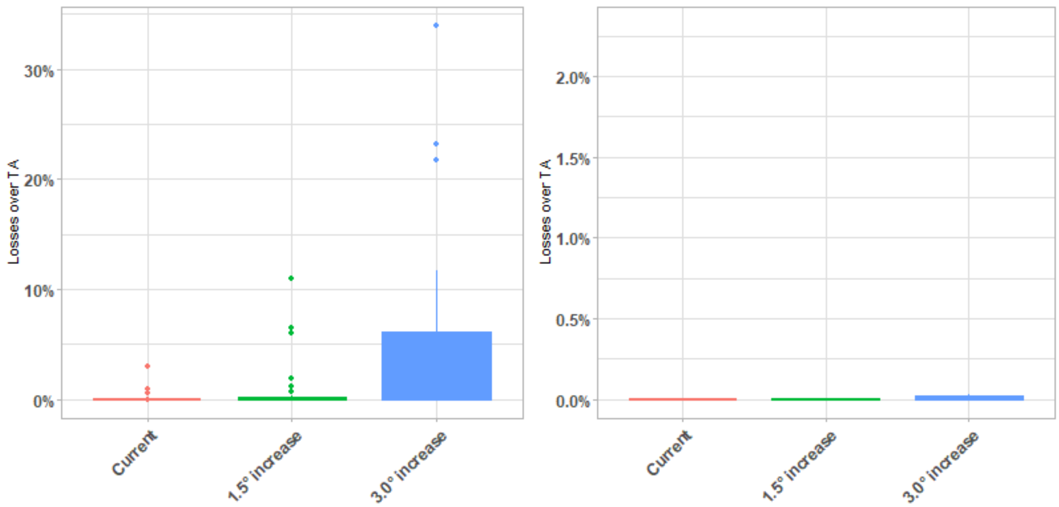

Figure 6: Losses over TA distributions across NUTS2 regions under different temperature levels (crisis triggered by physical risk). Left panel: full sample, right panel: with no outliers. Note: The middle line is the median, the observation separating the sample in two halves. The extremes of the box are the first and third quartile, half of the sample is included inside the box, and a quarter is outside on each side. The whiskers are the highest or lowest observation lying within 1.5 times the length of the box from the median.

5 A crisis not triggered by physical risk

5.1 Modelling framework

In this section, we use the model presented above to assess the impact of river-flood events, during a systemic banking crisis which is *not* triggered by climate crises. We do so by looking at the effect of including first-order climate-related losses (L^F) in Equation 8, without the amplification mechanism. Hence, L^F is equal to river floods-related non-performing loans (NPL^F).

We focus on the (very) right tail of the loss distribution, which is associated with a severe, but plausible, banking crisis. Technically, this part of the distribution corresponds to values of Z_j which are farther than 3 standard deviations from the mean.[19] This corresponds to the following iterations $\widetilde{j}$:

$$\widetilde{j} = \{j \text{ such that } Z_j > \mathbb{E}(Z_j) + 3\text{std}(Z_j)\}. \tag{14}$$

Final losses (FL) are then computed as in Equation 11 by taking the expected value of aggregate bank losses (as defined in 9) across the selected iterations. By comparing results with and without physical

[19] As Z_j may be seen as a negative economic shock, this calibration is representative of a recession comparable to those observed on the occasion of the global financial crisis and the Covid-19 pandemic.

risk one can derive the size of final losses when river flood events materialize.

5.2 Results

In a crisis situation, approximately 14% of banks (representing nearly 15% of total assets) default, resulting in losses of 0.3% of total assets in the German banking system. The inclusion of climate-related factors exacerbates the situation, as physical risk contributes to more losses and failures. While the contribution of additional physical risks to overall losses is relatively modest under the current climate conditions, it becomes significant under a climate warming scenario. In terms of number of banks involved, Tables 5 shows that flood events would cause a 4% increase in defaults among cooperative banks under the current climate situation, and a 17% increase under a temperature rise of up to 3 ℃. In terms of losses, for 1.5 ℃, aggregate losses, as a share of total assets, increase from 0.3% to 0.5% on average and up to 0.9% under a 3 ℃.

Figure 7 shows the increase in losses: the situation is quite heterogeneous across regions, with some NUTS2 subject to very mild (or almost zero) impacts and others where losses can increase substantially with respect to a situation with no climate risk. This is the case in particular for three regions, having a more than 5% increase for the 1.5 ℃ temperature increase scenario, and up to 30% in the 3 ℃ temperature increase scenario.

	Without physical risk	With physical risk		
	Current	Current	1.5 ℃ increase	3.0 ℃ increase
N.Banks	14%	18%	22%	31%
Assets	15%	18%	22%	30%

Table 5: Number of banks defaulted over the total number of banks in the sample and assets involved over the total amount of assets in the sample (systemic banking crisis)

	Without physical risk	With physical risk		
	Current	Current	1.5 ℃ increase	3.0 ℃ increase
Losses (%TA)	0.3%	0.4%	0.5%	0.9%

Table 6: Size of losses in the sample as share of TA (systemic banking crisis)

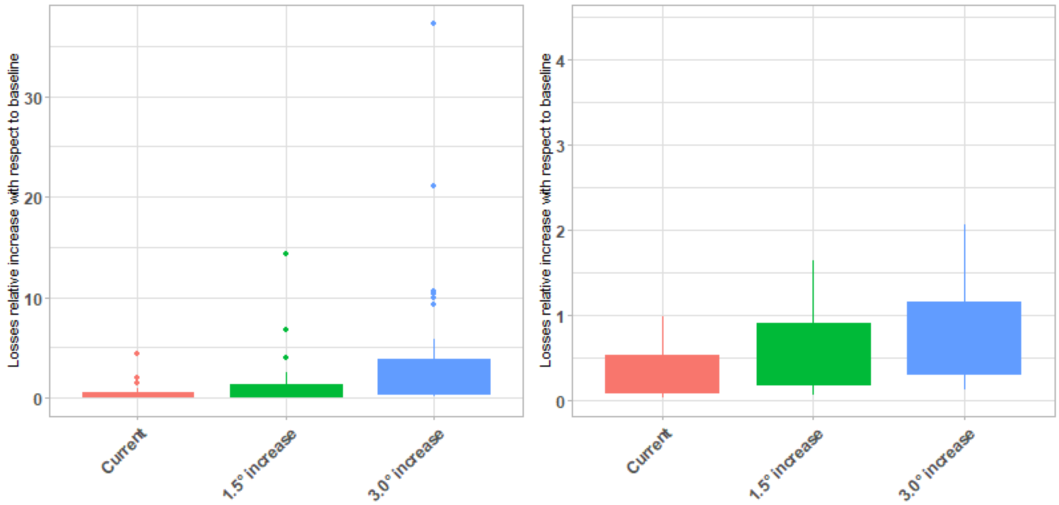

Figure 7: Losses' relative increase with respect to Baseline distributions across NUTS2 regions, under three temperature levels (systemic banking crisis). Left panel: full sample, right panel: with no outliers

6 Adaptation strategies and impact on the banking sector

PESETA IV study (Feyen et al., 2022) quantifies that, under a 3 ℃ global temperature increase by the end of the century, in the EU+UK, river floods related losses would increase by six times, with more than half a million people exposed every year.[20] The implementation of effective adaptation strategies plays a crucial role in mitigating economic losses and enhancing the resilience of firms to climate risks. By proactively implementing and integrating adaptation measures, businesses can minimize their vulnerability to climate-related events, thereby reducing the size of potential economic losses and enabling businesses to better anticipate or recover from climate-related shocks. The European Commission adopted its new EU Adaptation strategy on 24 February 2021. The four main principles of the strategy are a smarter adaptation, a systemic and faster set of actions, and international support for climate change adaptation and common policies.

Due to the uncertainty surrounding future scenarios, quantifying climate damages and determining effective adaptation strategies remains a difficult task. However, PESETA IV has taken an initial step by explicitly modeling adaptation strategies and estimating the potential reduction in losses. According to the report, adaptation measures would be very effective in reducing population exposed and potential economic losses, protecting citizens, preserving economic activities, and building a more resilient financial system. Among others, the reduction of flood peaks installing retention reservoirs could reduce by around

[20] If one compares these numbers with the present situation, losses move from 7.8 to 48 billion per year and people exposed go from 172000 to 4820000

EUR 40 billion the losses related to river floods, and around 400,000 fewer people would be exposed each year. Other adaptation measures such as the restoration of floodplain areas, strengthening the existing dyke system, and implementing building-based damage reduction measures are effective in further reducing the original impact. Overall, PESETA estimates point to a 80% reduction of the impact of climate-related events under a 3 °C (see Table 1).[21].

In our modelling framework, we apply this reduction to the estimated amount of river flood-related non-performing loans under a 3°C increase in temperature and we run our analysis to estimate the size of final losses under a normal economic situation and a banking crisis. Results show that the financial sector would benefit significantly, as the likelihood of either sudden asset devaluations and final losses driven by climate-related events diminishes to a point where they are comparable to the present circumstances, during a system crisis and in normal times (see Figure 8 and 9).

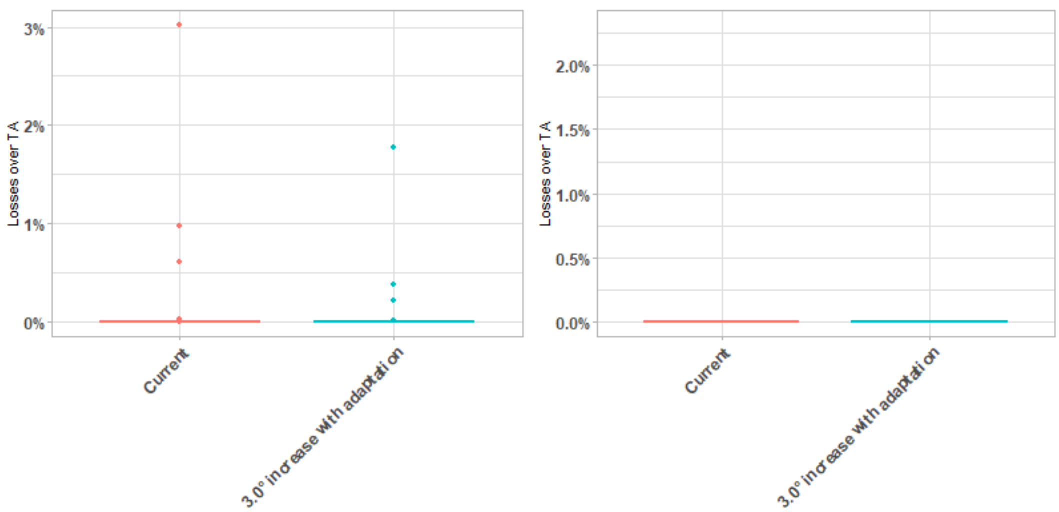

Figure 8: Losses' distribution (crisis triggered by physical risk) for Current and 3.0°C increase with adaptation. Left panel: full sample, right panel: with no outliers

[21]As a caveat, PESETA IV highlight that estimates are surrounded by relevant uncertainty and as such costs and benefit might be larger both in terms of economic losses and reductions due to adaptation strategies

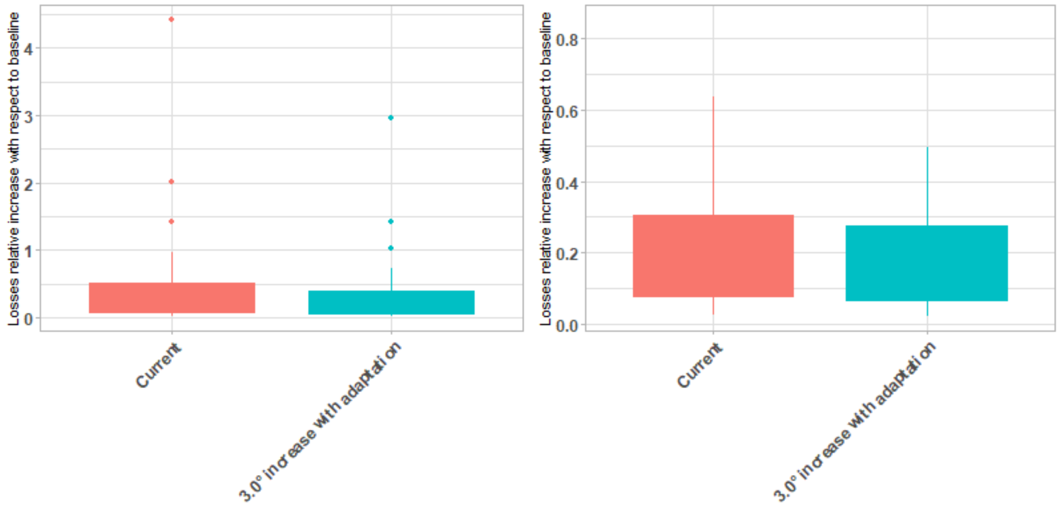

Figure 9: Losses' (systemic crisis) relative increase with respect to Baseline distributions across NUTS2 regions for Current and 3.0°C increase with adaptation. Left panel: full sample, right panel: with no outliers

7 Conclusions

In this paper, we propose a methodology to assess the effect of river-flood events occurring within Germany on *regional banks*. Considering a static systemic financial crisis scenario, we show that climate-related risks would increase overall losses by 0.1% under the current temperature level and these could become even more significant with losses up to 0.9% with a 3°C temperature increase. However, banks in some regions would suffer much higher losses than in others. Moreover, we observe that, even in a normal economic situation, there are few banks defaulting because of climate risk. Should these defaults trigger disorderly market adjustments, subsequent dynamics would be negligible under the actual warming conditions, however, could lead to significant losses for the German regional banking system up to 1% of total assets if a 3°C temperature rise materialized. In both cases, the variability of losses across NUTS2 regions, is quite large, with some regions reaching 5% of total assets in case of an existing financial crisis, and even to 10% in a normal economic situation.

This negative impact can be effectively tackled with the implementation of adaptation strategies. Therefore our findings support the idea that banks operating in regions prone to such geographic risks should take measures to safeguard themselves. One potential approach is to implement additional bank-specific capital add-ons, which would enhance the resilience of the banking sector against these natural-related shocks. This strategy would help mitigate the potential negative impacts on banks' financial stability and ensure their ability to withstand and recover from such events. Alternatively, banks can contribute to the adaptation efforts aimed at reducing the vulnerability of the regions they operate in. By supporting adaptation initiatives, such as investing in climate-resilient infrastructure or providing financial services to support sustainable practices, banks can play a crucial role in building the resilience of the financial sector and reducing the overall impact on the economy.

Further research could investigate more in detail the overall impact of physical risk on the financial sector, as increasing attention is devoted both by policymakers and academics to the role of climate risk for financial stability and debt sustainability.

Appendices

A Data inputs

	N banks	**TA, mn€**	**FL_{NPL}, mn€**
DE11	49	72,369	96
DE12	34	66,291	153
DE13	21	37,213	71
DE14	30	21,936	41
DE21	51	70,189	344
DE22	24	21,032	123
DE23	26	29,112	52
DE24	15	14,565	37
DE25	21	26,778	15
DE26	18	16,473	87
DE27	39	35,207	179
DE30	3	26,097	133
DE40	11	6,776	173
DE50	2	1,910	52
DE60	5	12,437	119
DE71	19	33,790	417
DE72	12	16,673	45
DE73	12	12,226	47
DE80	6	4,820	19
DE91	10	15,011	31
DE92	11	24,954	59
DE93	14	10,609	130
DE94	45	34,474	106
DEA1	20	113,655	67
DEA2	21	33,839	97
DEA3	22	36,000	32
DEA4	16	25,426	24
DEA5	24	48,948	44
DEB1	19	19,191	132
DEB2	6	5,220	67
DEB3	16	39,714	67
DED2	6	5,445	74
DED4	6	6,893	47
DED5	4	2,678	42
DEE0	9	5,111	190
DEF0	20	25,752	42
DEG0	10	7,600	87

Table A.1: Sample descriptive statistics

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