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The effects of climate change-related risks on banks: a literature review

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THE EFFECTS OF CLIMATE CHANGE-RELATED RISKS ON BANKS: A LITERATURE REVIEW

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The effects of climate change-related risks on banks: a literature review

Abstract: This literature review describes the recent empirical literature in economics and finance focusing on how climate change-related risks affect banks, with a particular emphasis on microeconomic evidence. The comparison of empirical estimates shows that banks and bond markets perception of climate change-related risks, assessed through the lens of variations on banks' loan and bond spreads, as well as loan supply, is limited. Indeed, for both loan and bond spreads, most estimates obtained from banks and bond markets of the effect of climate change are below 50 bp. In comparison, studies on stock markets document responses that are more substantial. In real estate markets, there is evidence of price effects notably for flood risks associated with sea level rise. However, some studies indicate that climate risks could be underestimated. We note challenges related to the measurement of adaptation potential, non-linear changes in hazards and responses, and the aggregation of effects across studies, markets, and bank portfolios.

Keywords: climate change, banks, bond spreads, loan spreads, equity returns.

JEL Classification: Q54, Q52, Q51, G21.

Les effets des risques liés au changement climatique sur les banques: une revue de la littérature

Résumé : Cette revue de la littérature décrit les travaux empiriques récents, en économie et finance, qui ont étudiés les effets des risques liés au changement climatique sur les banques, avec un accent particulier pour les données microéconomiques. La comparaison des estimations empiriques montre que la perception par les banques et les marchés obligataires des risques liés au changement climatique, évalués au travers du prisme des variations des écarts de taux sur prêts et obligations bancaires, ainsi que de l'offre de crédit, est limitée. En effet, tant pour les spreads de prêts que pour les spreads obligataires, la plupart des estimations de l'effet du changement climatique obtenues auprès des banques et des marchés obligataires sont inférieures à 50 pb. En comparaison, les analyses empiriques qui se sont focalisées sur les marchés boursiers documentent des réponses plus substantielles. Sur les marchés immobiliers, des effets prix ont été observés, notamment en ce qui concerne les risques d'inondation associés à la hausse du niveau de la mer. Toutefois, certaines études indiquent que les risques climatiques pourraient être sous-estimés. Nous notons des difficultés d'évaluation liées à la mesure du potentiel d'adaptation, aux changements non linéaires des aléas et des réactions, ainsi qu'à l'agrégation des effets entre les études, les marchés et les portefeuilles bancaires.

Mots-clés : changement climatique, banques, écart de taux sur obligations, écart de taux sur prêts bancaires, rendements actionnaires.

JEL Classification: Q54, Q52, Q51, G21.

The effects of climate change-related risks on banks: a literature review

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Abstract

This literature review describes the recent empirical literature in economics and finance focusing on how climate change-related risks affect banks, with a particular emphasis on microeconomic evidence. The comparison of empirical estimates shows that banks and bond markets perception of climate change-related risks, assessed through the lens of variations on banks' loan and bond spreads, as well as loan supply, is limited. Indeed, for both loan and bond spreads, most estimates obtained from banks and bond markets of the effect of climate change are below 50 bp. In comparison, studies on stock markets document responses that are more substantial. In real estate markets, there is evidence of price effects notably for flood risks associated with sea level rise. However, some studies indicate that climate risks could be underestimated. We note challenges related to the measurement of adaptation potential, non-linear changes in hazards and responses, and the aggregation of effects across studies, markets, and bank portfolios.

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Introduction

According to the Intergovernmental Panel for Climate Change (IPCC) reports, the average earth surface temperature is expected to increase linearly with accumulated emissions (IPCC, 2022, 6th Report). In accordance with these projections, experts agree on the urgency of policy action to mitigate the effects of climate change (see Campiglio and van der Ploeg,2022, and European Central Bank, 2022).[2] Yet, global emissions keep accelerating. In an attempt to understand the financial impact of these projections, the economic and financial literature has grown exponentially, encompassing studies on a variety of relevant outcomes for the risk assessment for banks.

To provide an overview, within a contained scope, this literature review surveys the empirical literature published since 2010 in economics, finance, sustainable finance, climate, energy and environmental economics journals and selected working papers series. It examines how both physical climate risks and the risks associated with the transition to a low carbon economy affect banks. Overall, the review is based on more than 230 papers and covers the effects on both credit risk and market risk.[3] In contrast, the paper does not address the definition of new regulatory tools to limit banks' exposure to climate change.

An important contribution of the paper is to provide, based on a critical assessment of the literature, a distribution of impact of climate change across the papers under review, considering credit spreads, bond spreads, expected returns on non-financial corporate equity, and real estate prices. They provide the basis for future Meta-analysis.

The amount of research covered by this review is large, but it is important to note at the start that there remain large climate blind spots for banks. For example, the quality of data on carbon emissions is generally a challenge when trying to measure transition risk, in particular in the case of scope 3 emissions. Alogoskoufis et al. (2021) argue that this can lead to a significant underestimation of transition risk. In the case of real estate exposures of banks, Clayton et al. (2021) argue that evidence is more plentiful for residential, as compared to commercial, real estate. Indeed, there are few rigorous and data informed studies of the climate risks associated with commercial real estate. Another blind spot arises because most studies focus on advanced economies, but developing countries are arguably more exposed to climate change: they are more dependent on agriculture; conduct more of their activities outdoors; and have more limited resources to pay for defensive measures.[4] Finally, banks will eventually adjust their exposures in response to climate change, potentially taking on new risks. Arguably, this will include exposures to new energy firms. As noted by Zhang et al. (2022), lending to these firms could in fact be riskier than lending

[2] It is important to mention that Schmidt (2014), Campiglio (2016) and Edenhofer et al. (2017) already highlighted the need for (new) climate policy actions, and the associated challenges to be addressed (lack of attractive conditions for low-carbon investments, market failures, risk of stranded assets).

[3] This includes, notably Nature Climate Change, the Journal of Environmental Economics and Management, the Journal of the Association of Environmental and Resource Economists, Climate policy, Environmental and Resource Economics, Ecological Economics, Climatic changes, the Journal of sustainable finance and investment. We cover working papers published by the NBER, the Bank for International Settlements, the Board of Governors of the Federal Reserve System, the Federal Reserve Bank of New York, the European Central Bank, the Deutsche Bundesbank, the Banque de France, and the CEPR. We also reviewed the recent papers available on Web of Science, as well as RePEc. We searched for articles and working papers through the heading of "climate change" and "bank" from 2021 to March 2024 and selected manually the resulting papers based on their abstract to keep only quantitative and empirical papers. Reports from policy institutions, practitioners, and the industry are not covered.

[4] On the other hand, Mandel et al. (2021) argue that, because of climate change, advanced economies can generate more international financial instability than less developed countries. This is because the financial sectors of advanced economies are more highly leveraged and more central to the global economy, in part because they are more connected with the financial sectors of other countries.

to the traditional energy sector, but this new source of risk is generally not explored, creating another blind spot.

Despite notable progress in terms of the quantity and quality of studies published in recent years, the cumulative impact of physical and transition risks on banks' exposures remains difficult to quantify for several reasons. First, many studies aim to extrapolate various effects based on historical data and events; however, the most severe facets of climate-related risks have not yet materialized, so this approach leads to an underestimation of climate risks. For instance, empirical analyses based on historical data are challenged with the assessment of tipping points and outcomes such as climate-induced migration and aggravations of political conflict (Möller et al, 2024). These aspects are obviously difficult to model, but their omission is likely to lead to an underestimation of the impact of climate change on economies (e.g., Stern, 2013) and the banking system.

Second, the indirect nature of climate-related risks for banks through the exposure of borrowers is further complicated by, e.g., dependencies on customers and suppliers in supply chains arising from climate physical risks, as well as the unpredictability of transition risks associated with political measures to mitigate climate change.

Third, it remains difficult to quantify the impact of climate change due to the underlying uncertainty. For example, as noted by Lenton et al. (2019), there is a lot of uncertainty about how much ice sheets will melt, given any assumed amount of global temperature rise. In addition, as noted by Pindyck (2020), considerable uncertainty remains about how much average temperatures will rise given any assumed path for greenhouse-gas emissions. Consequently, the extent of coastal flooding from future sea level rise (SLR), while likely to be substantial, is highly uncertain, making it difficult to estimate damages to coastal real estate from future SLR with precision.[5] At the same time, probabilities associated with various levels of SLR are required for standard risk analyses.

Fourth, long-term forecasting horizons complicate the task of estimating the impact of climate-related risks on economies and asset prices. Indeed, researchers find it challenging to identify the effects of climate change on credit and market risks. In many cases, there are no clear benchmarks that quantify climate risks and their fair pricing, complicating the question of whether investors fully anticipate the range of possible adverse outcomes. In line with these considerations, Eren et al. (2022) note growing concerns that current financial asset prices do not sufficiently reflect climate risks. If future corrections in asset prices are sufficiently large and sudden, climate risks could exacerbate into financial stability risks.

It thus appears that climate risk in banks' exposures might not yet be well understood; this paper attempts to offer a critical summary of the existing research in order to identify possible gaps in the literature. The paper is organized as follows. Part 1 discusses the effects of climate change on credit risk, market risk and lending standards. Part 2 investigates the specific impacts on real estate prices, both residential and corporate real estate, as well as more generally the effects of climate change on corporates as well as central and local governments (states and municipalities). Part 3 broadens the perspective by considering macroeconomic interactions. Part 4 summarizes the main conclusions of the review and makes suggestions for future research.

[5] Previous research highlights the importance of differentiating between risk and Knightian uncertainty in the context of climate change (Stern, 2007 and 2013). For example, the uncertainty associated with SLR is arguably Knightian in nature, meaning that the probability distribution of future SLR is quasi-unknowable due to variation across climate models, uncertainty related to the level of emissions, as well as the translation of emissions into temperature increases.

Part 1: Transmission channels of climate change on regulatory and lending standards

This part focuses on general issues related to the effects of climate change on credit risk and market risk, as well as lending standards. Credit risk includes risk of default on loan and bond exposures. Market risk mainly concentrates on equities and other non-bond exposures traded in securities markets (see also European Systemic Risk Board, 2021 and 2022).

1.1 Credit risk

Physical and transition risks associated with climate change have the potential to increase the credit risk faced by banks which is determined by both the type and average maturity of exposures. Yet banks might not experience an increase in credit risk if loan portfolios can be reshuffled before significant climate risks materialize. However, there are important caveats. First, even if most commercial loans are provided over short horizons, banks hold assets displaying long-term maturities especially through real estate loans, which we discuss in more detail in section 2.1. Second, banks' franchise values could be affected if their traditional customers, and notably non-financial companies, are threatened by climate change, as discussed in section 2.2. Of course, even if the majority of climate physical risks will materialize over a longer horizon than the maturity of the typical bank loan, climate transition risks may materialize at any time. Transition risk may thus be a more immediate source of risk and may have broader financial stability implications if the findings of D'Orazio et al. (2024) for Germany generalize to other countries. They find that exposure to transition risk is over-proportional for the biggest German banks while smaller banks tend to be more exposed to physical risk by way of loans to the agricultural sector.

In this section, we focus on credit risk. First, we cover physical risk (1.1.1), then transition risk (1.1.2). To visually illustrate the distribution of the documented estimates on loan spreads (Figure 1) and bond spreads (Figure 2), we gather evidence from around 30 papers. Within each figure, we differentiate between physical and transition risk. The figures report the impact arising from a unit climate risk shock, i.e., $\Delta y/\Delta x$, where y is the credit or lending spread, measured in basis points, and Δx is a one unit increase in the exposure to the underlying types of climate risk. For transition risk, unit changes are often studied in the cross section (e.g., difference in carbon emissions). For physical risk, studies usually adopt statistical methodologies or climate change scenarios, and exploit historical data and time series (event studies) to assess the variation over time of relevant variables (e.g., profitability, solvency, liquidity or borrowers' default risk; see Lamperti et al. (2019) and Zhou et al. (2023) and the literature cited there).

1.1.1 Impact on lending spreads due to acute and chronic physical climate risk

1.1.1.1 Floods

Physical risks not only destroy property and harvests, but also impact the probability of repayment of retail loans. In the case of a U.S. flood event, Kousky et al. (2020a, 2020b) find that the probability of default of a non-insured moderately priced property increases by 2.6 times in the two years following the event. However, studies in other geographies find effects that are more limited. For example, Garbarino and Guin (2021) study how lenders react after a flood event using UK data for the mid-2010s and find that lenders do not adjust interest rates or loan amounts. The absence of effects of floods in their analysis may be explained by public flood relief subsidizing high-income households, and high-income households self-selecting into areas with high flood risk. Following extreme rainfall events observed from 2014 and 2018, Bayangos et al. (2021) find evidence of a deterioration in branch-level (small banking units) loan growth and loan quality of the Philippine banking sector. Meucci and Rinaldi (2022) provide an assessment of Italian banks' exposure to physical risk in relation to lending to non-financial corporations. Two sources of information are adopted to measure physical risk: the National Plan of Adaptation to Climate Change

(NPACC) and hydrogeological risk. The analysis shows that this exposure is limited, given that a majority of risky loans is secured by collateral. Nevertheless, the authors highlight that the exposure through loans is highly correlated with the exposure to collateral, with a positive correlation between the probability of default and the loss given default of exposure. Johnston et al. (2023) also reported that the direct damages of flooding have modest impacts on residential real estate secured lending portfolios using current and projected flooding by extreme weather events in Canada with caveat that the lack of granular flood data may have led to an underestimation and smoothing of financial risks across households.

In addition to possible direct effects, some studies show that the costs of borrowing in the face of climate risk can increase indirectly for unaffected borrowers. Following climate change-related disasters, Correa et al. (2023) find that banks charge higher spreads on loans to indirectly affected borrowers with recently high exposure to these types of disasters. This effect varies from 19 basis points for hurricanes to about 8 basis points for wildfires and floods. The effects are economically sizable, as they represent between 5% and 10% of the unconditional spread charged on loans included in the sample.

1.1.1.2 Heat and droughts

For droughts, Do et al. (2021) show that banks charge higher interest rates to borrowers located in drought-located areas. The authors find more pronounced effects for borrowers in the food industry; a one standard deviation increase in their drought measure induces an increase of 11 bp on their interest rates.

Acharya et al. (2022) show that heat stress affects U.S. bond spreads and equity returns. A one standard deviation increase in the cross-sectional exposure to heat stress leads to a 15 bp per annum increase in municipal bond yield spreads. The authors find larger effects for longer-term, revenue-only and lower-rated bonds and hypothesize that these increases could be driven by increases in energy expenditures and decreases in labor productivity. For sub-investment grade corporate bonds, they find that a one standard deviation increase in heat stress is associated with yield spread increases of about 43 bp while S&P 500 companies experience a 45 bp increase in their annual expected return on their equity.

Similarly, Javadi and Masum (2021) show that firms in regions exposed to droughts pay significantly higher spreads on their bank loans: loan spreads of firms in the top quartile of climate risk exposure are about 4.4% larger than those of firms in the bottom quartile. They conclude that the interest rate spread on loans is significantly higher for firms when their customers are more exposed to climate risk. Like Archarya et al. (2022), the authors also conclude that the effects are even more pronounced for long-term loans of borrowers with poor credit ratings. For these borrowers, they find that loan spreads are 5.8% higher for firms in the top quartile of climate risk than those in the bottom quartile. Pinto-Gutiérrez (2023) empirically assess the impact of drought risk on loan contracts provided to mining-industry-based borrowers. The proposed empirical analysis finds that mining companies exposed to droughts face significantly higher loan spreads, and the relationship is more pronounced for larger and longer-term loans.

Using a granular data set of loans provided by commercial banks to private firms in Mexico, Aguilar-Gomez et al. (2024) examine the relationship between extreme temperatures and credit performance. They find that, given a positive temperature shock, firms pay higher loan rates and provide more collateral.

On the other hand, Kurowski and Sokal (2023) reported credit risk of Polish households associated with the physical risks of climate change based on interviews with borrowers. The interviews reveal that some borrowers would not be able to repay their insured loans in wildfire or storm but they observe limited concern on drought.

1.1.1.3 Sea Level Rise (SLR)

As far as SLR risk is concerned, there is evidence on the effects on loans and municipal bonds. For loans, Nguyen et al. (2022) show in the cross-section that lenders charge higher interest rates for mortgages on residential real estate exposed to more SLR. Interest rate spreads for mortgages in a zip code with all residential real estate exposed to SLR risk are approximately 7.5 bp higher compared to mortgages in areas in which none of the properties are exposed to SLR risk.

For bonds, Goldsmith-Pinkham et al. (2021) show that chronic SLR risk as well as acute flood risk impact the price of municipal bonds of the affected counties. In general, the premium seems to be driven by the uncertainty of the impact of the SLR risk and not by a reduction in asset values. In addition, Auh et al. (2022) analyze whether the increase of frequency or intensity of natural disasters impacts the riskiness of the municipal bonds of the affected issuer-county. The authors find that the bondholder losses account for half of the estimated physical damage induced by the relevant natural disaster with 31 bp in the weeks after a disaster.

1.1.1.4 Common challenges

Whereas the literature has covered different aspects of physical climate change, many of the studies have three challenges in common. First, measuring physical climate exposures of borrowers is challenging, as corporations operate in various locations, and have incentives to keep the details of their production sites and networks private. Therefore, investors and researchers have to work with incomplete information in tracking firms' geographic exposure. In this setting, many studies rely on subsets of firm locations. For instance, Huynh et al. (2020) use the location of firms' headquarters to measure their exposure to climate risk and include information on other sites such as the locations of customers and suppliers. Billings et al. (2023) reported the heterogeneous impact of flood losses for households with differing access to insurance and credit in Hurricane Harvey in August 2017. Second, studying both physical and transition risk is challenging in the cross-section as both physical risk exposures and emissions are likely to be highly correlated with confounding factors or concentrated in specific industries. Third, when it comes to physical risks, the effects of climate change are likely to be highly heterogeneous across industries. At the same time, it is challenging to study the heterogeneous effects across industries and firm types in enough detail to understand the effects of climate change on financial institutions and markets. Gramlich et al. (2023) reported that accounting measures of solvency are more sensitive to the impact of natural disasters than are regulatory measures. Gasparini et al. (2024), analyzing data from the European Banking Authority, suggest that existing financial accounting measures might be providing disincentives for investments in low-carbon assets. The agricultural sector might be a particularly striking example in terms of a sector that is substantially affected by physical climate risks. Brar et al. (2021) conclude that not accounting for climate change-related risks in agricultural loans leads to an underestimation of the riskiness of these loans. Kraemer and Negrilla (2014) find that poorer countries are more exposed to climate risk, because agriculture sectors account for a larger share of GDP in these countries (see also de Bandt, Jacolin and Lemaire, 2021).

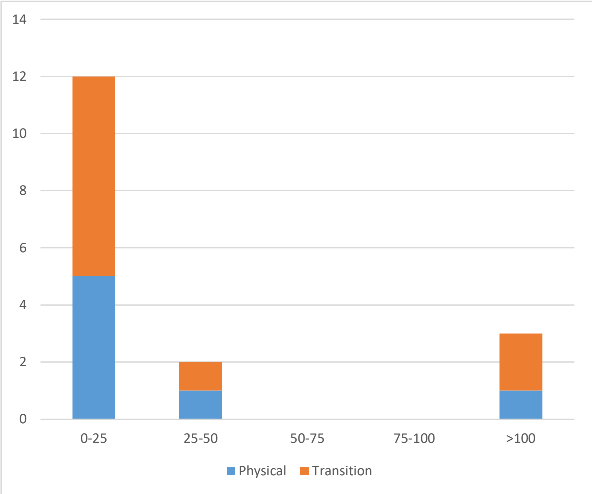
1.1.2 Impact of the transition to a low-carbon economy on lending and bond spreads

The recent literature analyses the effects of transition risk both when it comes to corporate loans and mortgage markets and studies possible effects on the probabilities of default as well as supply-side adjustments to higher risks, e.g., in terms of loan spreads and maturities.

Estimates of the effects of climate change on loan spreads

17 entries

Figure 1

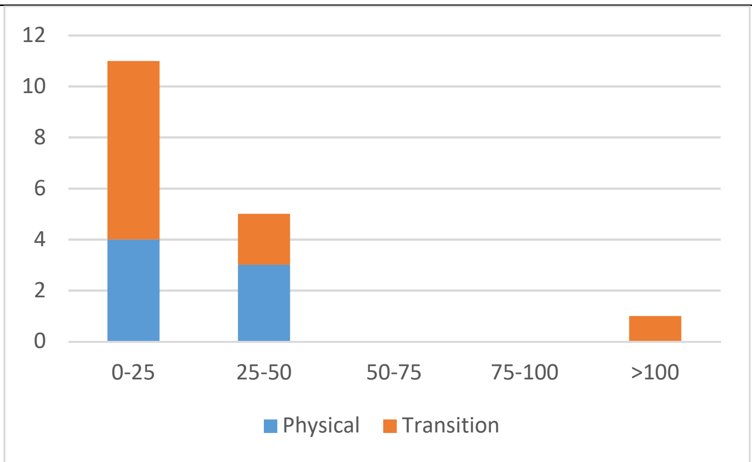


Source: Authors' calculations based on a review of 17 estimates provided by the academic literature: number of entries (vertical axis) providing an estimate of yield spreads of bank loans, in basis points (horizontal axis). A limited number of studies provide more than one estimate. The estimates usually capture the response of loan spreads to a one standard deviation increase in exposure to different measures of climate risk or exposures. The data points are from: Altavilla et al. (2023); Beyene et al. (2022); Chava (2014); Correa et al. (2023); Degryse et al. (2023); Delis et al. (2021); Do et al. (2021); Ehlers et al. (2022); Fuchs et al. (2023); Garbarino and Guin (2021); Huang et al. (2021)*; Ivanov et al. (2024)* ; Javadi and Masum (2021); Kleimeier and Viehs (2018); Nguyen et al. (2022); and Pinto-Guttierez (2023)*. The data points for physical risk are depicted in blue, transition risk in red. The references for the observations above 100 bp appear with a * in the list.

Estimates of the effects of climate change on bond spreads

17 studies

Figure 2



Source: Authors' calculations based on a review of 17 estimates provided by the academic literature: number of entries (vertical axis) providing an estimate of yield spreads of corporate or sovereign bonds in basis points (horizontal axis). A limited number of studies provide more than one estimate. See Figure 1 for details. The articles are: Acharya et al. (2022 a,b); Auh et al. (2022); Baker et al. (2018); Cevik and TJalles (2020); Fatica et al. (2021); Goldsmith-Pinkham et al. (2021); Höck et al. (2020); Kim and Pouget (2023) - 2 entries; Lau et al. (2022); Painter (2020) - 2 entries; Pastor (2022); Seltzer et al. (2022); Xia and Zulaica (2022); Zerbib (2019). The studies investigating shocks in terms of physical risk are depicted in blue, transition risk in red. The reference above 100 bp is Höck et al. (2020).

a) Bank loans

It can be a challenge to measure transition risk empirically. Reflecting this obstacle, the recent literature adopts a variety of approaches. Delis et al. (2023) hand-collect data on fossil fuel reserves to measure the amount of potential "stranded assets" on borrowers' balance sheets.[6] Using this data, they analyze whether U.S. banks price borrowers' climate policy risk exposure. In particular, they estimate whether banks charge higher rates when borrowers have larger reserves in interaction with information on the climate policy stringency in borrowers' home countries. The authors find that borrowing firms with high fossil fuel reserves pay a higher loan rate, and the effect is more pronounced for firms in countries with stringent policy as well as in countries within close costal proximity. In addition, the authors document that fossil fuel firms obtain larger loans compared to non-fossil fuel firms and that the rates charged by banks are higher when banks are labeled as "green banks". Therefore, their results support the view that banks scrutinize the fossil fuel industry. Consistent with this idea, Degryse et al. (2023) show that green firms borrow at a significantly lower spread in the international syndicated loan market after the Paris Agreement, especially when the lender consortium can be classified as "green". Nguyen et al. (2023) assess banks' exposure to climate transition risk, by matching machine-learning evaluation of corporate carbon footprints to syndicated loans initiated in the US economy in 2010-2018. They find that banks have a large exposure to the energy sectors, and that their vulnerabilities are also driven by the ex-ante financial risk of their borrowers, thus highlighting that climate risk is not independent from conventional risks.

An alternative approach is to use emissions as a proxy for transition risk. Following this approach, Ehlers et al. (2022) investigate whether a higher carbon intensity drives the associated risk premium a company has to pay. The authors find that, when narrowly measured and strictly related to the firm's activity, higher emissions are associated with slightly higher loan spreads, but the broader carbon footprint of the firm (i.e. indirect emissions related to energy consumption and production inputs) has no effect on loan spreads. In addition, while "green banks" may lend less to high carbon emitters than other banks, they do not appear to charge a higher carbon premium. Altavilla et al. (2023) study the European credit market and find similar results, documenting that banks charge higher loan spreads for firms with higher current carbon emission. The authors show that for the period from September 2018 to December 2022 rates charged to firms in the highest quartile of emissions is 14 bp higher than for those in the first quartile and the difference rises to 20bp for firms that commit to decarbonize their activity.

As a third strategy, researchers have used national and international climate policy events to study banks' and borrowers' responses to transition risk. For instance, Ivanov et al. (2024) study the effect of the introduction of a cap and trade policy in California in 2011. They find that affected firms with higher emissions, which are privately owned, obtain loans with shorter maturities by 5 months (to be compared to an average of 30 months) and higher interest rates. Huang et al. (2021) investigate the impact of the Clean Air Action that the Chinese province of Jiangsu implemented in January 2014 as a quasi-natural experiment. Based on a sample of 1.3 billion loans they show that the lending spread to polluting firms significantly increased by 130 bp, which is equivalent to 5.5% of the mean lending spread. Aiello and Angelico (2023) assess the short-term (one-year horizon) potential impact of alternative carbon taxes on Italian banks' default rate, using the micro-founded climate stress approach of Faiella et al. (2022). The authors observe that, during a period of low default rates, the rise in the credit risk level, induced by the introduction of the carbon tax, is modest. Nevertheless, the impact could be more severe during periods with higher (baseline) default rates. In the case of the Polish economy (among the European countries with the highest intensity of CO_2 emissions), Nehrebecka (2021) finds that the introduction of a carbon tax (of 75 euros per ton of CO_2) in brown sectors would induce a rise (over a one-year horizon) of the default

[6] Mercure et al. (2018) find that, if contrary to investors' expectations (International Energy Agency (IEA) scenario), policies to achieve the 2C° target are adopted and low-cost producers (some OPEC countries) maintain their level of production despite declining demand, the potential cumulative (from 2015 to 2035) global loss in value of stranded fossil-fuel assets would be close to $12tn (in 2016 USD). This is equivalent to 15% of global GDP in 2016 ($75tn).

probability from 3.6% in the baseline scenario, to a value between 6.3% and 10.1% in alternative scenarios. This result seems to suggest an associated relevant rise in banks' capital requirements. In the same vein, Fuchs et al. (2024) investigate the impact of the 2021 stress test run by the ACPR, the French supervisor: interest spreads on loans to high carbon emitters increased by 16 bp.

Beyond commercial bank loans to companies, Kaza et al. (2014) find that mortgages on energy-efficient homes have significantly lower risks than those on less efficient homes. The risk of default is about one third lower compared to the control group. In addition, the more energy efficient, the lower the mortgage risk. An increase in the energy efficiency by 1 point decreases the probability of a default by 4% and decreases the chance of prepayment by 2%, measuring the higher performance of energy-efficient projects from the lenders' perspective. However, the authors do not consider the potential endogeneity of the results in the sense that more affluent (hence less risky) borrowers can more easily afford more efficient housing.

Guin et al. (2022) improve upon the previous methodologies and examine the relative riskiness of residential mortgages depending on the energy efficiency of the underlying real estate as well as borrowers' risk characteristics. For a data sample collected in the United Kingdom, the analysis concludes that the energy efficiency of residential real estate reduces the frequency of mortgage payment arrears. This finding is unaffected when controlling for other relevant determinants of mortgage default, like borrower income and loan-to-value (LTV).

However, Bell et al. (2023), studying pre-2018 loans, find "no evidence of lenders charging higher rates on riskier mortgages against energy-inefficient properties".

b) Bond spreads

Several studies explore a carbon premium – the extra yield investors demand to buy bonds issued by firms with more greenhouse gas emissions – in the U.S. corporate bond market. Studying a sample of US companies that issued investment grade fixed-rate corporate bonds from December 2007 to December 2017, Capasso et al. (2020), show that distance-to-default, is negatively correlated with of a firm's carbon emissions and carbon intensity, measured by Scope 1. Seltzer, Starks, and Zhu (2022) find that high emitters have lower credit ratings and higher yield spreads, particularly in states with stricter regulatory enforcement. Further, they find that the composition of bondholders changed after the Paris Agreement. Xia and Zulaica (2022) study two potential mechanisms behind the carbon premium in corporate bonds and find evidence consistent with both: one is the "preference channel", under which the premium reflects investors' preference for firms that they perceive as being more environmentally responsible. The other channel is the "risk channel", where investors perceive more carbon-intensive firms as more prone to default. Further, the authors find that the premium is larger for firms in more energy-intensive sectors. Kim and Pouget (2023) study the relation of carbon emissions and yield spreads both in the primary and secondary corporate bond market. They find that firms with higher emissions have larger yields than firms with low emissions on the primary market, implying a higher cost of capital of 4 bp. However, the premium in the primary market accounts for less than 15% of the one prevailing on the secondary market and is measured to be 27.4 bp. Underpinned by a theoretical framework, the authors document support for both the uncertainty about future climate preferences of investors and limited competition among primary market dealers as drivers of this difference. Conversely, Wilson and Caldecott (2023), looking at portfolio holdings for corporate bonds by investment funds over the 2016 to 2021 period in the US, document passive ETF flows have channelled capital to carbon-intensive assets through primary markets, undermining the carbon premium.

In addition, there is an abundant literature on green bonds (i.e., bonds for which issuance proceeds are required to be invested in green projects). Zerbib (2019) measures a small negative premium for the period from July 2013 to December 2017: the yield on a green bond is lower than that on a conventional bond. On average, the premium is -2 basis points both for the entire sample and euro and U.S. dollar bonds separately. Baker et al. (2018) study a sample of more than 2,000 municipal and corporate green bonds and find that green bonds trade at lower yields than bonds with similar characteristics but without a green label. Fatica (2021) studies bonds issued from 2007 to 2018 and show that the greenium for bonds (i.e., lower interest rates on green than brown bonds), is only significant for supranational entities and corporates and reaches 22 bp in the latter case. Lau et al. (2022) identify that the greenium consists of the environmental benefit as received by the investor of the green bond and the effective costs incurred by issuing the bond. Based on their global green bond data set, they estimate a mean greenium of only 1 bp. In a next step, they decompose the greenium into a market and an idiosyncratic component to analyse the marginal size of the greenium. Their findings point to the fact that investors are not willing to pay to preserve the environment. Following the authors, this might be caused by investors' "fear of greenwashing" so that the risk premium for greenwashing offsets the greenium. Pastor et al. (2022) predict that similarly to the existence of a "greenium" for bonds, green stocks have lower expected returns, but show that ex post, based on realized returns, green stocks outperform brown due to positive surprises over the sample period. These market reactions provide further evidence that the effects of climate change are not fully anticipated. Nevertheless, the "greenium" is not very substantial overall. Further research would need to explain why green and brown bonds issued by the same company might have different ratings.

The study by Pastor et al. (2022) also highlights the overlap of concerns about climate-related risk and environmental, social and governance (ESG) performance. As borrower and lender ESG disclosures can contain relevant information for climate risk management, there is a growing literature on the impact of ESG criteria on credit risk and lending (see de Bandt et al. (2023) and Billio et al. (2024)). The perspective of risk for equities is discussed in section 1.2.

1.2 Market risk

In addition to credit risk, banks could be exposed to climate change through market risk from shocks associated with sudden changes in stock prices, interest rates, exchange rates, and commodity prices (see Campiglio et al., 2023).[7] In this section, we focus on equity markets, as bond markets were discussed in section 1.1. As Giglio et al. (2021a) stress, research on market risk is complicated by the fact that investors may have recently started to pay more attention to climate change-related risks.

As for credit risk, physical and transition risks have different implications for market risk and are discussed separately. Figure 3 summarizes the estimates in the empirical literature. Also, note that the risk premium is not comparable to lending and bond spreads, as indicators for market risk measure the expected return differential from a brown versus a green portfolio.

1.2.1 Physical risk

For physical risk, Acharya et al. (2022) conclude that S&P 500 corporations with a one standard deviation higher heat stress exposure have a 45 bp higher (unlevered) expected return per annum, with the effect being observed robustly since 2013. Furukawa et al. (2020) show that the prices of corporate bonds and equities reflect the impact of climate change related physical risk. However, investors tend to assess the impact of climate change-related risks based on "memorable" events rather than all available events. For example, Hong et al. (2019) demonstrate that drought risk is not priced in food companies' equity prices in regions/countries that have not suffered from severe damage of drought for 20–30 years, although drought risk indicators are globally available. Alok, Kumar, and Wermers (2019) document that professional money managers overreact to large climatic disasters that happen close to them, underweighting disaster-zone stocks to a much greater degree than distant mutual fund managers do. They also document that this overreaction can be costly to fund investor performance. In contrast, Choi et

[7] Dietz et al (2016) estimate that the expected climate value at risk (VaR) of global financial assets in 2016 is 1.8% along a business-as-usual emissions path, amounting to $2.5 trillion. Cutting emissions to limit warming to no more than 2°C reduces the climate VaR by an expected 0.6 percentage points.

al. (2020) find that in abnormally warm weather, stocks of carbon-intensive firms underperform those of low-emission firms. An increase of one standard deviation in abnormal temperature corresponds to a decrease of 16 bp in return. For firms in the United States, Addoum et al. (2023) show that firm profitability is influenced by extreme temperatures, but stock prices do not immediately respond to temperature shocks. For firms outside of the United States, Pankratz et al. (2023) reach similar conclusions. They find that heat reduces revenues and operating income. However, analysts and investors do not appear to fully anticipate these effects. Moreover, the deviation in analyst estimates from actual financial performance and the earnings announcement returns become more negative when firms' heat exposure increases. These findings indicate that investors do not fully anticipate the economic repercussions of heat as a first-order physical climate risk.

A possible explanation for this mixed evidence of pricing for climate risks is that it is challenging investors to make decisions under deep uncertainty regarding climate change-related risks. Barnett, Brock and Hansen (2020, 2022) document that even supervisory authorities and central banks suffer from shortages in information in policy decision making (see also Campiglio et al. (2018)). Such uncertainty can lead to loss in economic welfare and biases in resource allocation (ACPR, 2021).

1.2.2 Transition risk

There are three hypotheses on potential transmission mechanisms of transition risk into market risk (Bolton and Kacperczyk, 2021a). First, the profitability of firms with high emissions could decline due to a carbon tax, pricing and other regulatory interventions to limit emissions. Then, forward-looking investors would seek compensation for holding the stock of these firms ("carbon premium hypothesis").

Second, the prices of securities might not reflect climate transition risk properly and efficiently as climate change-related financial risks are unconventional. Consequently, conventional methodologies of market risk measurement (e.g., value-at-risk and expected shortfall) are not directly applicable to risk management and measurement of climate change-related risks under limited availability of historical data ("market inefficiency hypothesis" or "carbon alpha hypothesis").

Third, the number of institutional investors that commit to socially responsible investment could continue to increase. These investors pledge to request firms to commit to the reduction in their emissions and to reduce their investment in firms that are reluctant to reduce their emissions ("divestment hypothesis").

Regarding the carbon premium hypothesis, Bolton and Kacperczyk (2021a and 2021b) document a broad range of evidence that investors require a higher expected excess return for investing in the securities of firms with higher GHG emissions. This is true for the United States as well as from a cross-border perspective. They conclude that the pricing is uneven across countries, depending on the likelihood of transition policies, with little effect in Africa, Australia and South America. They also provide robust evidence (also confirmed by Bolton and Kacperczyk (2022)), that the level of emissions matters more than the intensity (emissions/value of sales), highlighting the importance of industry fixed effects. There is a carbon premium for firms within the same industry, which is growing with the size of firms, as bigger firms are more likely to be concerned with transition policies. They also stress that the premium of high emissions emerged after the Paris Agreement in COP21 in 2015. This indicates that policy initiatives and international agreements on greenhouse gas emission reduction can send a signal of risk in transition to a low carbon society. Antoniuk and Leirvik (2024) confirm that market participants price climate-related policy events in terms of risk and growth expectation about sectors. Their event studies including the Paris Agreement show a positive impact of those events on the clean energy sector. In addition, they show that events weakening climate change policy lead to abnormal positive returns for the fossil fuel sector. Kruse et al (2021) find that, following the Paris Agreement, firms with a significant share of their revenues from green goods and services significantly outperformed the market. Aljughainman et al. (2024) show that after the Paris Agreement high emitting firms (GHG emission) are more prone to tail risk in terms of extremely negative returns in general market downturns. Consistently, Bauer et al. (2023) find that, using carbon intensity, from 2010 to 2021, a green portfolio outperforms a brown portfolio for six of the G7 countries (Italy being an exception) ranging from 23% for Canada to 110% for France. However, it is also noteworthy that other studies find no significant differences in ex ante return of securities in terms of firms' GHG emissions (Dai, 2020). As trigger events of transition risk, the implementation of comprehensive carbon tax/pricing have materialized in only a limited number of jurisdictions, it is still challenging to identify the source of excess returns of high emission firms. In particular, Bolton and Kacperczyk (2022) do not uncover a carbon premium for banks.

Similarly, Hsu, Li, and Tsou (2023) find that highly polluting firms are more exposed to environmental regulation risk and command higher average returns of 4.42% for the United States in the period 1994–2017, measured by the return of a long-short portfolio from firms with high versus low toxic emission intensity within an industry. Emissions, not limited to GHGs, are measured by plant-level chemical pollutants data from the Toxic Release Inventory (TRI) database constructed and maintained by the U.S. Environmental Protection Agency (EPA). Martini et al. (2024), working on the syndicated loan portfolios of U.S. banks, find that the banks more exposed to transition risks have returns that co-vary more with stocks predisposed to lose value when transition risks materialize.

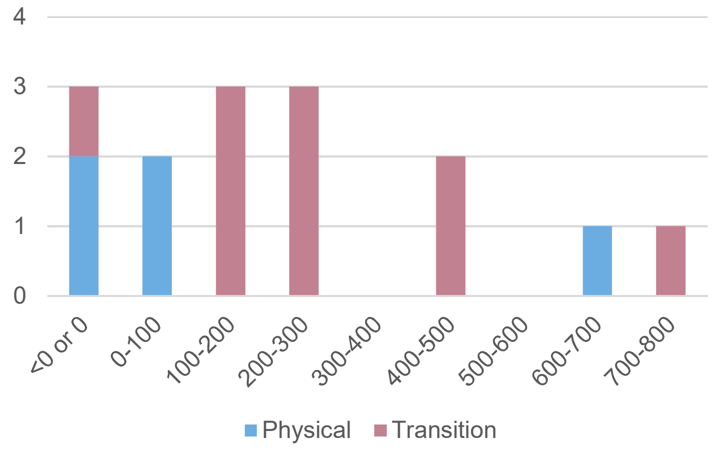
Bua et al. (2022) investigate the climate risk premium on European equity markets. Using a low-minus-high transition (physical) climate beta portfolio, they identify positive excess returns, measuring a climate risk premium 7.05% and 6.14% on average per-year after 2015, for transition and physical risk, respectively.

The quality of information on firms' carbon emissions is a common challenge for studies on transition risk. Aswani et al. (2024) find no statistically significant excess return from the data of firms' actual disclosure while they find supporting evidence of excess returns from the dataset complemented by financial data vendors. This finding is consistent with the assessment of financial institutions' preparedness to conduct scenario analysis of climate change-related risks by the European Central Bank (2022). The majority of banks participating in the exercise conduct their analysis based not on borrowers' disclosure of emission data but on the estimated emission data provided by third party data vendors. Similarly, Krueger et al. (2020) show that the majority of institutional investors expect that equity prices do not fully reflect climate related risks.

Impact of climate change on risk premium for stocks

15 entries

Figure 3



Source: authors' calculations, based on a review of 15 estimates provided by the academic literature: number of entries (vertical axis) providing an estimate of risk premium on non-green, or carbon-intensive, or non-ESG stocks, in basis points (horizontal axis); a limited number of studies provide more than one estimate. The studies are: Acharya et al. (2022); Addoum et al. (2023); Bua et al. (2022) - 2 entries; Bolton et Kacperczyk (2021 a and b) – 6 entries; Choi et al. (2020); Hong et al. (2019); Hsu et al. (2023); Giglio et al. (2023); Monasterolo and De Angelis (2020). The studies investigating shocks in terms of physical risk are depicted in blue, transition risk in red. Note that the risk premium is not comparable to lending and bond spreads.

There are two additional strands of the literature that need to be mentioned: the impact of disclosures and ESG investments in financial market.

First, the disclosure of exposures also has an impact on the equity risk premium. As discussed by Bolton and Kacperczyk (2022), disclosures reduce uncertainty, leading to a lower premium. Krueger (2015) studies the effect of mandatory GHG emissions disclosure passed into law in 2013 in the United Kingdom. His research shows that firms most heavily affected by the regulation experience a significant increase in Tobin's Q, as compared to a matched sample of European firms, providing evidence of positive valuation gains. He further finds that investors value carbon transparency more in carbon intensive sectors: basic materials (mining) as well as oil and gas production. Kennett et al. (2023) show that firm assets, profitability, and firm age determine climate disclosure of New Zealand firms. With a four factor model extended by carbon price returns and its volatility, the authors conclude that carbon risk is only priced in the stock prices in terms of volatility and extreme price movements. Suggesting that in light of limited disclosure and low carbon prices transition risk is not likely to be fully priced in stock values. In an international context, Krueger et al. (2023) find that ESG disclosure mandates positively affect firm-level stock liquidity. The effects are stronger for binding mandates compared to comply-or-explain policies and increase under stringent enforcement. Using survey methods, Ilhan et al. (2023) show that investors value and demand climate risk disclosures. Further, the authors use the introduction of a law on the energy transition in France (Article 173) to show that climate-conscious institutional ownership drives better firm-level climate risk disclosure.

Bolton and Kacperczyk (2021c) report the asymmetric reaction of investors in transition risk pricing in a response to companies' new disclosure of GHG emissions. This indicates that firms' disclosure of their GHG emissions and exposure to climate change-related risks is helpful to reduce investors' uncertainty in terms of both transition and physical risks. Panjwani et al. (2023) find that firms that disclose scope 3 emissions have a cost of borrowing that is 20 basis points lower, on average (scope 3 disclosure premium). At the same time, controlling for scope 1 and 2 emissions that lead to higher lending spreads, higher scope 3 emissions are not associated with a higher cost of borrowing.

That said, some studies challenged the usefulness of disclosure. Ameli et al (2021) pointed out that disclosure is not necessarily increasing transparency and driving disinvestment from high carbon assets. They argue that the effectiveness of disclosure is undermined by the voluntary nature of disclosure requirements, the lack of reporting standards and comparable measures on climate risks. In a similar vein, Scatigna et al (2021) argue that mandatory and standardized disclosures would be essential for investors to respond to environmental signals.

Second, and more generally, the literature has also extensively studied the connection between ESG indicators and market risk, the conclusions of which matter for banks. On the one hand, banks report increasing attention by investors and a strong demand for ESG investments. On the other hand, the literature offers conflicting results on ESG performance at this stage. Friede et al. (2015) combine the findings of about 2200 individual studies and report that 90% of studies find a nonnegative ESG–Corporate Financial Performance (CFP) relation, and that most studies report positive findings. Further, the positive ESG impact on CFP appears stable over time, but rather more apparent for bonds than equities. However, recent papers continue to find heterogeneous effects. Some studies indicate that there is no ultimate consensus. For instance, Giglio et al. (2023a) find that the average retail investor anticipates negative excess returns on ESG. They document an average expected 10-year annualized return that is lower by 1.4% for ESG investments than the overall stock market. They also highlight the heterogeneity of investors' return expectations – additional evidence of an absence of definite conclusions – with 25% of investors having ethical motives, 22% with hedging objectives.

1.3 Lending standards

After lending prices, it is important to study lending volumes; banks would be expected to adjust credit supply in response to changes in risks and expected rewards. Climate change-related factors could affect how banks perceive these risks and rewards.[8] Banks can in principle play a role in making investments in high polluting or other exposed sectors more expensive and can provide more (and/or cheaper) credit to potential green sectors. However, papers differ in terms of ability to effectively identify exposures to climate change-related risks at a granular level. Syndicated loans offer detailed information on the financing of large corporations, especially for large energy producing projects such as power plants. Loan registers provide detailed bank loan level data to assess transition risk for a broader set of exposures (Schubert, 2023), including SMEs. For assessing physical risk, where information is required at the granular plant level, bank level data are also used by some authors, but at the cost of a few identifying assumptions (Blickle et al., 2022). To address these issues, Pagliari (2023) focuses on so-called territorial banks, which are more likely to lend to local firms. Territorial banks are considered less significant institutions,[9] but may be more concentrated and located in areas that are more prone to flooding and more susceptible to suffer from climate change-related shocks.

1.3.1 Banks' supply of credit / credit rationing to sectors affected by physical risks

In the area of physical risk, some papers concentrate on the effects of floods and natural disasters. To the best of our knowledge, no paper investigates the impact of drought and heat stress. Meisenzahl (2023)

[8] Demand effects by corporates are discussed in section 2.2.

[9] Banks that are under indirect ECB supervision (i.e. supervised by national supervision authorities), which are smaller than the ones under direct ECB supervision.

uses supervisory data for the largest U.S. banks and finds that after 2015 banks significantly reduced lending to areas more impacted by floods and wildfires. A one standard deviation increase in climate risk reduces county-level balances in banks' portfolios by up to 4.7 percent in counties with large loan balances. However, the reductions are concentrated among borrowers and products with high credit risk, and low-risk borrowers received more funding even in heavily affected areas.

Chavaz (2016) investigates the mortgage lending market's reaction to the 2005 hurricane season – the costliest natural disaster recorded in U.S. history, where together, Hurricanes Katrina, Rita, Wilma, and Dennis damaged 1.2 million housing units. The author studies changes in banks' mortgage lending in affected counties compared to elsewhere and before the shock – depending on their geographic diversification. It appears that the "financial capacity channel" (whereby local banks have a smaller financial capacity after the shock as they are less diversified) is dominated by the "relative loan profitability channel" (local banks have better technology or higher incentives to lend in affected areas). According to the paper, local banks increase the share of new mortgages and small business loans in affected areas, but, at the same time, sell more of the new mortgages in the secondary market.

A small part of the literature tries to link the effects of physical events to bank behavior. Gallagher and Hartley (2017) investigate the impact of flooding on household finance using Hurricane Katrina. Spikes in credit card borrowing and overall delinquency rates for the most flooded residents are modest in size and short-lived. Greater flooding results in larger reductions in total debt. Lower debt levels are driven by homeowners using flood insurance to repay their mortgages, instead of rebuilding. Mortgage reductions are larger in areas where reconstruction costs exceeded pre-Katrina home values and where mortgages were likely to be originated by nonlocal lenders.

Garbarino and Guin (2021) look at how lenders react after a flood event using U.K. data. As mentioned above in 1.1.1.2, they find that banks do not offset the change in valuation by adjusting interest rates or loan amounts.

One should stress, however, that extra lending post natural disasters (see also Koetter et al, 2020 for flooding of the river Elbe in Germany in May 2013.) may offset reluctance to lend to risky borrowers: Blickle et al. (2022) find that disasters increase the demand for loans; new loans after a natural disaster offset losses on loans on the books. Bos et al. (2022) examine how banks adjust their asset structure in response to changes in loan demand following natural disasters. The empirical analysis shows that U.S commercial banks increase real estate lending after disasters, notably after floods and storms, and sell government bonds to finance this credit surge driven by natural disasters. This is consistent with Cortés and Strahan (2017) who show that banks reallocate credit from less exposed to more exposed areas

1.3.2 Banks' supply of credit / credit rationing to energy-inefficient real estate or industries with high emissions (brown and black sectors)

Several papers investigate banks' credit allocation across sectors, and its interactions with monetary policy.

a) Regarding banks' allocation across sectors and companies, Reghezza et al. (2022) find that, following the Paris Agreement, European banks reduced credit to polluting firms; the same is observed after the withdrawal of the United States from the Paris Agreement; lending by European banks to U.S. firms decreased. For U.S. banks, Jung, Santos and Seltzer (2023) document a downward trend in exposures to the riskiest industries, at least partially explained by a reduction in banks' funding to these industries. Using the estimated sectoral effects of climate transition policies from the general equilibrium models of Jorgenson et al. (2018), Chen, Goulder and Hafstead (2018), and NGFS (2022), the authors find that bank exposures appear overall to be manageable. The largest projected exposures of the average bank reach 9 percent under the NGFS disorderly transition scenario.

Takahashi and Shino (2023) argue that the levels of scope 1 and 3 emissions have a negative impact on lending for Japanese banks, but this was already visible before the Paris Agreement. They also show that banks with greater leverage and a lower return on assets are more likely to decrease loans to firms with high GHG emissions.

Ghosh (2023) shows on the basis of a diff-in-diff analysis for a sample of banks from Middle East and North African countries that the implementation of national legislations to address climate change led to lower lending by 3% with respect to countries without such legislation, and a substitution towards bond and equity investment.

Miguel et al. (2024) study banks' response to the implementation of the 2017 ICAAP in Brazil when banks were requested to embed environmental risk in their framework. They show that large banks decreased lending to small firms by close to 3%, but this was offset by an expansion of credit by small banks.

b) Monetary policy may also affect credit allocation as shown by Altavilla et al. (2023). The authors provide evidence that banks respond to the risk channel of monetary policy, in the sense that banks restrict credit more to brown firms in case of restrictive monetary policy.

1.3.3 Banks supply of credit to green industries

Whereas only a few papers explicitly investigate the financing of green sectors, a slightly larger set of papers considers the issue of financing the transition to low-GHG emission economies, taking into account differences between advanced countries and developing countries.

1.3.3.1 Limited evidence on the financing of green sectors

Very few papers directly address the issue of financing green sectors. As mentioned above in 1.1.2 for lending spreads, Chava (2014) provides seminal analysis about the impact of environmental concerns on loan availability in the syndicated loan market. Degryse et al. (2023) use international syndicated loans to investigate whether banks create obstacles to the transition given the legacy of brown loans. They actually show that it is not the case for green firms which receive a lower spread on loan volume when the lender consortium can also be classified as green, especially after the Paris Agreement.

Accetturo et al. (2022) measure the ability of banks to finance the green transition in Italy by estimating the likelihood of firms to start green projects conditional on bank lending. This leads eventually to a less risky bank portfolio. However, the approach raises the issue of the implications of such findings regarding the broader and more relevant issue of financing the transition.

1.3.3.2 Impact of commitment

The impact of bank commitments in favor of the transition is mixed. Ehlers et al. (2022), working on the syndicated loan market, conclude that self-identified green banks may lend less to high carbon emitters. Kacperczyk and Peydró (2021) measure a cut in bank lending after banks' commitment to reduce GHGs, but find no effect on brown firms' environmental score. Mésonnier (2022) shows that lending to small and medium-sized enterprises across more or less carbon-intensive industries is unaffected by banks' commitment to green their portfolio. Altavilla et al. (2023) find that banks determine their loans (also) based on firms' commitments to reduce future emissions.

Elliot and Löfgren (2021) find that even in banks that state a strong commitment to reduce climate impacts, this does not seem to be reflected as a reduction in exposure to the fossil fuel industry. Gianetti et al. (2023), analyzing euro area banks, conclude that banks with extensive environmental disclosure lend more to brown borrowers. Furthermore, this is not offset by lending for green projects or for financing the transition. However, banks are less likely to start new lending relationships with brown companies. The divergence between green commitments and lending appears to be higher for low capitalized banks.

1.3.3.3 *Ability to finance the transition*

Offering the proper funding for the energy and climate transition is a difficult issue to address empirically. Mueller and Sfrappini (2022) show that European banks extend their exposure to "green" corporates after the Paris Agreement and this might turn out beneficial with a future environmental-friendly regulation. This is not the case for U.S. banks, which appear to create an obstacle to the transition. Banks lend relatively more to firms that are likely to lose from future regulation. The authors find "no evidence that lending in the United States is directed to firms that have a higher likelihood of transition; moreover, low-capitalized banks exploit lending to this group of firms to boost profits". In contrast, for Europe, they conclude that "banks shift credit supply to European firms that consider themselves likely to benefit from future regulation; hence, banks' credit allocation seems to facilitate the transformation of the economy". Nevertheless, they also study the effect of banks' indirect exposure via their loan portfolios and find that "banks' exposure appears to be a hindering factor in Europe: larger exposures to brown sectors limit the transition".

Interestingly, Cohen et al. (2020) find that oil, gas, and energy firms are particularly important in the production of green assets, complicating questions about the funding of the low carbon economy. Damar (2024) shows that financial deregulation in the United States triggered an increase in credit supply which enabled low income households to buy newer energy-saving durable goods.

1.3.3.4 *Green washing or regulatory arbitrage*

Regulatory arbitrage in response to climate change policy may take different forms. Several studies point to the role of cross-border lending and regulatory arbitrage in response to a tightening of the regulation, notably Benincasa, Kabas and Ongena (2021) and Laeven and Popov (2023).

Captive banks belonging to car manufacturers may face wrong incentives in the face of a tightening of regulation on GHG emissions. Beyene et al. (2022) show that captive banks have stronger incentives to support the manufacturer's sales of high emission cars.

Part 2: Sector-specific channels of transmission

2.1 Climate impact on the pricing of property

We now consider the issue of the impact of climate change on real estate prices. Property is the most important source of collateral in the banking system. Buildings are also a major source for energy use, and they are highly vulnerable to many of the consequences of climate change – like increased risk of flooding, rising sea levels and more frequent extreme weather events. Property exposed to climate risk can be a major contributor to volatility in the financial system. At the same time, many of the risks are to some extent foreseeable, and with proper risk assessment banks can reduce exposure to climate risk significantly.

The transmission to banks obviously depends on the nature of the loan contract (whether it is a recourse or a non-recourse loan), which depends on the jurisdiction, but to our knowledge this dimension has so far not been fully investigated. It also depends on the existence of insurance guarantees (see de Bandt et al, 2023).

A large literature has evolved on how climate-related effects might affect property. The literature looks at possible price effects, with implications for collateral values. It also looks at how credit quality is related to exposure to different climate-related issues. We will first discuss the substantial literature on physical risk and then look at the much smaller literature on transition risk, especially related to energy efficiency.

2.1.1 Effects of physical risks

Property is directly exposed to physical risks associated with climate change, both chronic and acute physical risks, which of course can impact property values. Chronic physical risks, like sea level rise (SLR), occur over a long time horizon. In contrast, acute physical risks are event-driven phenomena, like storms, floods and forest fires, which may become more frequent with rising global temperatures. It is important to note that chronic and acute physical risks need not be independent. For example, rising sea levels can lead to more damaging storms from oceans. A fall in collateral values can affect banks both directly through increased losses and indirectly through less market growth or higher financing costs due to lower collateral values. Uncertainty about insurance payments and future property values can also reduce debtors' willingness to service their mortgage loans.

Using data from Florida, Calabrese et al. (2024) find that incorporating weather-related information significantly improves mortgage default models. This is particularly evident in coastal areas with high flood risk. Dennis (2023), focusing on the property market in Miami, argues that potential bank losses following weather-related events such as hurricanes are closely related to both insurance coverage and the extent of property devaluation.

In OECD countries, many such risks tend to be well known and mapped by authorities. It is possible to identify if a building is in a risk zone or not. However, the awareness of this information has been slow to disseminate in some regions. So far, most papers have investigated the effect of flood risk and rising sea levels, as these are the risks best documented. Some event studies look at the effect of hurricanes and storms.

Many countries, that are very significantly exposed to acute physical risks, are located outside the OECD. These countries tend to have less resources to prevent damage or to map potential risk zones. However, with a few exceptions the papers reviewed only cover industrialized countries.

2.1.1.1 Price effects of exposure to flood risk

A large literature has evolved on the question of price effects for property exposed to flood risk and SLR. Flood risk can arise either because the building is on a flood plain or at the coast and exposed to higher probability of water damage with rising sea levels. The results are summarized in Figure 4.

Numerous studies find that properties in potential flood areas sell at a discount. Bernstein et al. (2019) report that "homes exposed to sea level rise (SLR) sell for approximately 7% less than observably equivalent unexposed properties equidistant from the beach." Keys and Mulder (2020) observe that transaction volumes for exposed properties in Florida declined by 16–20% from 2018 to 2020, while prices decreased by 5%. Gourevitch et al. (2023) conduct a comprehensive study of flood risk across the United States. They find that properties located in a flood zone sell at a 2.8% discount, with larger discounts in areas where flood zones are disclosed compared to counties without disclosure requirements. Properties in the 100-year flood zone can be overvalued by more than 8.5%, even before adjusting for potential climate change.

Mirone and Poeschel (2021) find that properties in Denmark with expected future flood risk sell at a 3–4% discount. The discount for flood risk tends to increase after flooding events. Fuerst and Warren-Myers (2021) find a discount between 1 and 3% for properties and between 2 and 5% discount in land value in a flood risk area identified through the statutory authority planning overlays, looking at floodplains and SLR from Melbourne, Australia. Reeken and Phlippen (2022) find a more modest negative price effect of 2.5% in the Netherlands, but the paper notes a number of methodological issues identifying comparable properties. Giglio et al. (2021a) argue that flooded areas may indeed benefit from a premium, due to various amenities.

Beltrán et al. (2018), in a meta-analysis, find that “for inland flooding the price discount associated with location in the 100-year floodplain is -4.6% in the United States”. Hino and Burke (2020) estimate that full pricing of presence in a floodplain in the United States should reduce property values by 5.1% to 10.7%. Garbarino and Guin (2021) look at how lenders react after a flood event, using U.K. data. Properties in flooded areas decrease in selling price between 2.6 and 4.2%.

Estimated discount or overvaluation of house prices in high flood risk areas

12 studies

Figure 4

Source: authors’ calculations, based on a review of 12 papers in the academic literature, number of studies (vertical axis) providing an estimate of the impact of exposure to flood risk for property valuation. Studies finding an observed price discount in blue, studies indicating an estimated overvaluation due to lack of valuation of flood risk in red. Studies are: Bakkensen and Barrage (2021), Baldauf et al. (2020), Beltrán et al. (2018), Bernstein et al. (2019), Fuerst and Warren-Myers (2021), Garbarino and Guin (2021), Giglio et al. (2021a), Gourevitch et al. (2023), Hino and Burke (2020), Keys and Mulder (2020), Mirone and Poeschel (2021), Murfin and Spiegel (2020), Reeken and Phlippen (2022).

It should be noted that some papers also find smaller effects. Murfin and Spiegel (2020) find no price effect. They put forward two plausible interpretations of this finding. One is that home buyers have a limited understanding of relative SLR risk. The other is that homebuyers have sophisticated expectations of relative SLR risk but believe mitigation efforts will be largely successful. Bakkensen and Barrage (2021) find that prices are not always adjusted for risk and argue that that coastal prices in Rhode Island exceed fundamentals by 6–13%.

2.1.1.2 Perception and information is important for price impact

Many papers note that perceptions of risk can differ across locations, and that this can have a major impact on the price effect. Keys and Mulder (2020) find that sellers remain optimistic about the value of exposed property, while buyers are more and more suspicious. As a result, as is typical in case of adverse selection, volumes fall before prices begin to fall. Bakkensen and Barrage (2021) argue that belief heterogeneity can reconcile prior mixed evidence on flood risk capitalization. Bernstein et al. (2019) find that the discount has grown over time and is driven by sophisticated buyers and communities worried about global warming.

Information dissemination is also crucial. Baldauf et al. (2020) and Hino and Burke (2020) find that "the price penalty for flood risk is larger for commercial buyers and in states where sellers must disclose information about flood risk to potential buyers." This suggests that policies aimed at improving risk communication could influence market outcomes. Thompson et al. (2023) argue that "privileged access to knowledge" can exacerbate disparities; groups with less information may face higher financial burdens as their risk increases and property values decline. They find that climate gentrification – defined as the upscaling of areas less exposed to climate risks traditionally populated by lower-income households – could explain significant differences in price growth between exposed and unexposed areas.

Gourevich et al. (2023) argue that there is a "housing bubble by unpriced flood risk". Overpriced properties are concentrated along the coast, in areas with no flood risk disclosure laws and less concern about climate change. Overvaluation is especially widespread among low-income households. The authors estimate that U.S. residential properties are overvalued between USD 121–USD 237 billion, depending on the choice of discount rate (hence an average overvaluation of 0.5%, according to estimates based on data from the real estate company Zillow; total US residential value in 2021 was around USD 36.2 trillion).

2.1.1.3 Price effects of natural disasters

Another strand of the literature looks at how property prices are affected by natural disasters. While flood risk is a potentially recurring event, a natural disaster could be interpreted as a one off.

Often houses are built back better, making comparison of prices before and after difficult. Instead, the risk of future disasters might affect demography and housing supply. Zivin et al. (2020), using a detailed data set with housing characteristics from Florida, find that usually supply falls after a hurricane, but demand seems unaffected. This induces an increase in equilibrium prices and a decrease in transactions in affected areas, both lasting up to three years. The authors control for property characteristics, seasonality and differential economic growth across counties. As a result, incoming homebuyers during recovery have higher income, conditional on the characteristics of transacted homes, resulting in an enduring increase in the distribution of income.

Similarly, Apergis (2020), in a study that covers 117 countries from 2000–2018, finds floods cause an immediate fall in prices, but prices recover as repairs are completed. Only when floods occur very frequently do they find a permanent impact on prices, as there is no time to conduct full repairs. In a similar pattern, Kivedal (2023) uses payments from the Norwegian natural disaster insurance pool to identify exposed properties. The paper finds a positive effect in the short run for flood surges and damages related to extreme weather, indicating creative destruction in that homes are rebuilt with a higher quality than previously.

Clayton et al. (2021), survey the literature on effects on commercial real estate (CRE). The drop in prices after climate events has been modest and short-lived in locations that historically have been most exposed to extreme weather events like flooding and hurricanes. In such areas climate risk might already be capitalized into property values. However, some recent evidence finds that an increase in the frequency of climate related risks can lead to a long-lasting decline in CRE prices or reduce market liquidity. It can be reasonable to see this as a correction to previous under-acceptance or under-awareness of risk.

Rodríguez et al. (2023) look at a special case of ecological deterioration. A beach area in Spain located at a saltwater lagoon has since 2015 been struck by increased algal bloom. The authors find that in the 6 years after 2015 return on housing in the affected area was 43 percent lower than in similar neighborhoods outside the affected lagoon, indicating that environmental degradation can have large effect on housing value.

Non-climate related events can have a larger effect than climate-related events. Apergis (2020) highlights that geological disasters exert the strongest (negative) impact on house prices. Kivedal (2023) finds evidence of a negative effect on house prices from natural disasters at a longer horizon.

2.1.1.4 *Investment in climate risk adaptation*

The potential cost of future flooding raises the question of the social cost of adaptation. Hovekamp and Wagner (2023) look at the possibility of elevating houses as a private defense against flooding. Undertaking adaptation is socially optimal in the highest risk areas over a house's lifetime, but individual homeowners may underinvest in flood protection because the benefits do not accrue over their average tenure. The wedge between the perceived private benefits and the social value of adaptation is exacerbated by any undervaluation of flood protection while living on the coast, and the full benefits of adaptation also are not internalized by homeowners purchasing better than actuarially fair public flood insurance. The results underline the importance of public standards for new construction to ensure that minimum elevation standards are met in order to encourage efficient outcomes in areas at high risk of catastrophic flooding.

Benetton et al. (2022) look at the sea wall constructed around Venice to provide new evidence on the capitalization of infrastructure investment in climate change adaptation into housing values. They exploit the quasi-experimental temporal discontinuity in the exposure to sea floods from the first activation of the sea wall. They find that the sea wall increased house prices by 3% for properties above the sea wall activation threshold and by an additional 7% for ground-floor properties. Overall, one year after its inception, the sea wall generated an estimated 4.5% increase in the value of the total residential housing stock in Venice, which is a lower bound of the total welfare gains potentially generated by this infrastructure.

Giglio et al. (2021a) look at the housing market to determine appropriate discount rates for valuing investments in climate change abatements. The paper seeks to identify a term structure of discount rates for real estate over a horizon of hundreds of years – the horizon most relevant for investments in climate change abatements. Looking at data from the U.S. East Coast, they identify climate risk by linking geo-code addresses to identify properties that will be flooded with a six feet increase in sea levels. They find that, if real estate is affected by climate risk, the real estates' term structure of discount rates is downward sloping and reaches 2.6% for payoffs beyond 100 years.

Clayton et al. (2021) find that good governance and public investments might abate negative price effects and help explain the modest and short-term nature of price reductions; however, lack of governance or proactive investment may be harming prices. There is some evidence that investors put higher risk premiums on properties in areas exposed to negative climate events. This is regardless of whether their individual properties have been directly affected. This might even extend to areas with similar climate risk profiles, where events have yet to occur. On the other hand, there is so far little evidence that owners' investment in resilience improves financial performance or insurance pricing on the asset level.

2.1.2 Transition risk to property prices

Buildings account for about 40% of Europe's total energy consumption (Zancanella et al., 2018). Heating of homes made up over 60% of households' total energy use in the European Union in 2020 (Eurostat, 2022).[10] Median housing-related energy costs accounted for 7.2% of a household's weekly expenditure in Great Britain (Griffiths et al., 2015). Changing the sources of energy and making energy use in properties more efficient, will be a major factor in the transition to a low carbon society. Energy transition might increase energy prices. New requirements for energy efficiency will make it obligatory with investments today but can reduce expected energy costs in the long run.

With more volatile energy prices, energy costs can become a major risk factor for both households and commercial businesses. It is becoming increasingly clear that energy efficiency can reduce the risks associated with a property investment. This is motivating increasing action by financial regulators

[10] See Eurostat: Energy consumption in households - Statistics Explained (europa.eu).

and governments to require banks to incorporate these factors into risk management and pricing decisions.

For banks and other financial institutions, energy efficiency might be an indicator of lower financial risk since the property has lower costs and a lower exposure to volatile energy prices. This should be reflected in lending requirements.

Beyond the effects identified above of lending spreads on transition sensitive real estate assets (see 1.1.2), energy-saving improvements have a direct price impact. Zancanella et al. (2018), doing a broad literature review, find that residential assets tend to increase by 3–8% in price because of energy efficiency improvements. For commercial buildings the premium seems higher, over 10% and in some studies even over 20%. Rental prices of commercial real estate tend to increase by 2–5%. On the other hand, Ferentinos et al. (2023) conclude that the implementation of the Minimum Energy Efficiency Standard (MEES) that fined landlords in England and Wales if their rented properties did not meet minimum efficiency standard, was rapidly incorporated into a lower price on affected houses and flats. However, the study only provides a lower bound of the effect so that it is not possible to know the full extent of the decline in house prices.

In addition, many jurisdictions impose requirements of energy efficiency disclosure. Myers et al. (2022) looking at disclosure requirements imposed in Austin, Texas, find that disclosure has a positive impact on price premiums for energy efficiency. Cassidy (2023), looking at the same area, argue that the price effect seems to be most pronounced for factors that are less observable by buyers. Energy efficiency calculations based on observable factors make little difference. By focusing on less observable factors, policy makers can reduce administrative burdens.

2.2 Climate impact on non-financial firms

Businesses face increasing regulatory and economic pressure to address their operational exposure to physical and transition risk. This demand and their responses could affect their financial health and quality as borrowers, their demand for credit, and their behavior as depositors. Therefore, the magnitude of potential repercussions of physical hazards and regulatory shocks for borrowing firms is important to understand from the perspective of banks and financial institutions.

2.2.1 Physical risk

When it comes to physical risks, many studies examine damages from the perspective of equity holders as residual claimants. A common challenge for this type of research is the requirement of granular information on firm locations. However, for competitive reasons and complicated production processes, firms face incentives to keep their information on establishment locations private. Further, it is difficult to measure indirect impacts on firms through their supplier networks in a world of limited supply-chain transparency. For these reasons, existing studies estimate the effects of climate change-related hazards across a subset of the universe of firm locations.

The literature on firms and physical risk is most developed related to temperatures. Somanathan et al. (2021) study the effect of heat on the productivity of Indian firms. They find a sizeable negative effect of heat on worker productivity as well as an increase in absenteeism. The estimates decrease with climate control availability. In support of the importance of the labor channel in explaining the destructive effects of heat, the authors find that that the estimates are large enough to explain observed cross-country output losses. Related to this study, Li et al. (2016) find that export quantities of firms in China decrease with heat, and Zhang et al. (2018) document that heat reduces the productivity of Chinese establishments. For firms in the Ivory Coast, Traore and Foltz (2017) also find a negative link between heat and measures of firm performance. In an international sample of over 90 firms, but excluding the United States, Pankratz et al. (2019) find that hot days reduce revenues and operating income, with a one-standard-deviation increase in the number of hot days decreasing operating income by 1.8% of the average quarterly value. In contrast, Addoum et al. (2020) find no effects of abnormally high or low temperatures on establishment sales in the United States, apart from a positive impact of low temperature on sales in the energy sector. Hong et al. (2019) study droughts and document decreases in the profitability of firms in the food sector. Apart from heat, Kruttli et al. (2021) study the effects of hurricanes and show that stock options on firms in the landfall region show increases in implied volatility of 5–10%. Floods and storms have been implicitly studied using aggregate data on natural disasters.

Despite the data limitations outlined above, a few papers investigate firms' indirect exposure to climate change-related hazards through supply chains. For example, Barrot and Sauvagnat (2016) find that natural disasters at supplier locations in the United States impose substantial output losses on their customers. The effects are pronounced when suppliers provide specific inputs. Pankratz and Schiller (2019) study how heat and floods affect firms' financial performance and operational risk management in global supply chains. They find that adverse weather at supplier locations reduced both the operating performance of the directly affected suppliers and their remotely located customers. In addition, they document that customers respond to increases in the exposure of their suppliers and are more likely to terminate existing supplier relationships when the realized number of heat or flood days exceeds ex ante expectations.

The documented effects on firms are economically relevant from the perspective of equity holders. Lenders and bondholders, in contrast, may be less concerned about residual changes in firm value due to their short investment horizon and liquidity preference. Potentially, shocks of moderate severity could magnify and affect operations and creditworthiness if increasing frequencies limit companies' access to insurance. However, the evidence on the effect of physical risks on firms' probability of default so far is limited. As one exception, Xie (2017) finds that the exposure to heat may not only affect firm performance but also the survival probability of firms in Indonesia.

Besides default risk, decreases in productivity and increases in uncertainty could affect firms' demand for credit and volume of deposits. Related to the demand for bank credit, Ginglinger and Moreau (2019) find that firms decrease their leverage when they face increased physical risk, which may be a sign of lower loan demand. When it comes to deposits, the existing evidence points in different directions. On the one hand, the repercussions for firm performance documented by the aforementioned studies could thin out firms' cash buffers and bank deposits. On the other hand, firms may respond to actual or perceived uncertainty by increasing cash holdings. For instance, Dessaint and Matray (2017) show that corporate managers increase cash holdings when firms in neighboring countries are hit by hurricanes.

2.2.2 Transition risk

In addition to physical risk, regulatory pressure and transition risk could affect firms' financial health, demand for credit, and deposits. Recent studies examine the effects of climate policy on stock prices and returns. For instance, Meng (2017) studies the failed attempt to pass a cap-and-trade climate policy in the U.S. Senate and finds significant differences in the stock price reactions of affected and exempted firms. Bartram et al. (2022) use a diff-in-diff analysis to document that, following implementation of the Californian cap-and-trade system, financially constrained firms shifted emissions to other states. Li et al. (2020) conduct a textual analysis and find that firms facing high transition risk are valued at a discount. Ramelli et al. (2021a) document decreases in the stock prices of carbon-intensive firms around the first global climate strike of 2015. They argue that the strike marked a turning point in climate activism and find that the unanticipated success is also linked to analyst downgrades of firms' long-term earnings projections. Further, public attention to climate activism appears to be a plausible driving channel of these effects. Ramelli et al. (2021b) show that stock prices move with expectations related to climate policy around the U.S. 2016 and 2020 Presidential elections. Ochoa et al. (2022) study carbon taxes in Germany and find that the value of firms with low carbon emissions increases compared to high carbon counterfactuals. Whereas these studies point to the sensitivity of equity markets to transition risks, the potential consequences for default frequencies and losses given default are studied less frequently.

Related to questions about the demand for credit from corporate borrowers in response to climate policy and uncertainty, recent work suggests that affected borrowers may shift from public to private sources of financing. Beyene et al. (2021) find that bond markets price the risk in fossil fuel firms, whereas syndicated loan markets do not appear to respond. In line with this gap, they find evidence that fossil fuel firms increasingly rely on syndicated loans instead of bonds.

Like the effects of physical risks, the uncertainty created by transition risks could affect the preferences of non-financial firms for holding cash. While international evidence is scarce, two studies point in this direction in China: Wu, Shih, Wang and Zhong (2023) document that carbon-intensive firms increase cash holdings after the adoption of the Paris Agreement. Further, Yuan and Gao (2022) find that firms increase their cash holdings with the enforcement of green credit guidelines.

2.3 Climate impact on government bonds

Understanding the extent to which climate risk is priced into government bonds (including those issued by central governments and local governments) is important to assess banks' exposure to climate risk. This is because government bonds often account for a non-negligible share of banks' holdings of securities.

Climate risks, both physical and transition risks, can affect sovereign risk mainly through the following three channels (Volz et al., 2020; and Zenios, 2021). Fiscal channel: climate risk is likely to increase governments' debt burden. For physical risk, natural disasters may damage government assets and public infrastructures, increasing public expenditure. Also, natural disasters are likely to disrupt economic activity, lowering tax income and other public revenues and increasing social transfer payments. As regards transition risk, adaptation and mitigation policies in response to the challenges that climate change poses require large government investments.[11] In addition governments may lose the tax revenues from oil consumption, if the economy decarbonizes. Macroeconomic channel: climate risk, especially physical risk, is likely to adversely affect both supply and demand sides of the economy. Extreme weather events and global warming may reduce supply by damaging the capital stock and reducing investment and consumption by weakening balance sheets of corporates and households.[12] Financial stability channel: climate risk would decrease financial stability. Both physical and transition risks would manifest as credit risk for banks, reduce insurers' margins due to higher insurance claims and trigger repricing of certain, especially "stranded", assets (see Campiglio et al.,2018).

Several studies investigate the pricing of climate risk in government bond yields. Their findings generally suggest that higher climate risk comes with more expensive borrowing costs for governments. A few papers focus on physical risks. Mallucci (2020) finds that extreme weather restricts a country's access to financial markets. While a clause that allows governments to suspend payments when extreme weather hits can allow governments to borrow more; however, spreads increase by 40% to compensate investors for the risk that governments activate the disaster clause (based on Caribbean countries' data). Bowman et al. (2022) propose an approach to assess climate change's impact on sovereign bonds with outputs from climate models reviewed by the IPCC. Then, they consider their economic impacts from the literature and use those as overlays in a pricing model for sovereign bonds. Their estimates suggest that, under the RCP 4.5 mean scenario, the impact on G20 countries' sovereign spreads ranges from close to 0 to 20 basis points, with a bigger impact on poorer countries. Klusak et al (2023) use machine learning to integrate climate economics to sovereign credit ratings and borrowing costs. They first train a random forest model that relates macroeconomic variables and sovereign rates issued by S&P. Then they examine how climate

[11] That said, a low-carbon transition can also have some positive impacts on fiscal space. For example, the transition could generate significant public savings from phasing out fossil fuel subsidies. For another example, governments could generate substantial revenue from carbon taxes.

[12] In the long run, gradual global warming and transition policies have important implications for growth potential by causing fundamental and enduring structural changes to the economy.

change affect macroeconomic outcomes using existing models. Lastly, they feed macroeconomic variables incorporating climate changes to the prediction model to calculate climate-adjusted sovereign ratings and borrowing costs. They find that only stringent climate policy consistent with the Paris Agreement could eliminate adverse impact of climate change on ratings. Goldsmith-Pinkham (2021) and Acharya et al. (2022) examine how physical risks affect U.S. municipal bonds (see 1.1.1). Cevik and Jalles (2020)'s estimates suggest a 233 bp spread between the top and bottom quantile of countries ranked by climate vulnerability. The economic and statistical significance of these effects are much greater in developing countries with weaker capacity to adapt to, and mitigate the consequences of, climate change. Beirne et al. (2021) find that the premium on sovereign bond yields due to climate risk amounts to around 113 basis points for EMEs overall. In contrast, exposure to climate risk is not statistically significant for advanced economies overall.

Part 3: Aggregate and macro-economic effects

To assess the impact of climate-related shocks on banks, it is also important to consider the overall effects on individual banks, the aggregate effect on the whole banking system, with possible spillovers across banks, as well as the macroeconomic environment, together with feedback effects (see also European Systemic Risk Board, 2021 and 2022).

Note that the review does not fully cover the aggregate effect on banks in the case a climate event comes through the liquidity channel. Acharya et al. (2023), reviewing the literature, find some papers that document that climate events can cause deposit withdrawals as well as increased demand for loans. See in particular Brei et al. (2019). However, compared to other channels, they argue that the liquidity risk channel of climate risk has been relatively understudied. Further, they find no paper that has studied the effect of transition climate risk on banks through the liquidity risk channel.

3.1. Aggregate effect on banks' risk and profitability

Beyond the effect of climate change on individual portfolios and specific risk, it is important to get a comprehensive view of the overall effect of these different channels on the situation of individual banks and notably on their profitability.

Regarding physical risk, Song and Fang (2023) document that higher temperatures significantly increase a new nonlinear tail-event driven network (TENET) conditional value-at-risk (CoVaR) - a measure for bank systemic risk, and the impact of temperature shocks is significantly larger during colder periods. Boungou and Urom (2023) use a textual analysis derived from US climate change legislation, international summits, global warming, and natural disasters to capture climate risks, and highlight that bank stock indices are sensitive to climate change risks.

Concerning more precisely the impact on profitability, Pagliari (2023) focuses on flood risks and exploits the peculiarities of business models for small European banks to proxy for the location of the banks' counterparties. She finds that "ROA has been on average lower at banks located in areas that have been historically subjected to severe flooding events". This is partially due to what she identifies as the "core lending channel of transmission", whereby flood risks can hinder banks' profitability via the decrease in lending to households and non-financial companies. Noth and Schüwer (2023) show that weather-related natural disasters in the United States lead to higher non-performing asset ratios for banks and also raise banks' probabilities of default. Similarly, Schubert (2023) finds that, in the cross-section of stock returns, small banks with high exposure to flood risk underperform other banks, on average, by up to 8.7% per year. Blickle et al. (2022), on the other hand, find that FEMA disasters over the last twenty-five years had insignificant or small effects on U.S. banks' performance. They highlight that disasters increase loan demand, which offsets losses and boosts profits over the medium run at larger (multi-county) banks.

Regarding transition risk, the exposure of banks is likely to vary across countries and across sectors. Semieniuk et al (2022), investigating equity risk ownership from oil and gas production assets by ultimate investors, find that banks are only moderately exposed while funds own a much larger share of risk; most transition risk falls on private investors, overwhelmingly in OECD countries, partly through pension funds. See also above the articles that measure the exposure of banks to transition risk in Europe (D'Orazio et al. (2024) for Germany; Faiella and Lavecchia (2022) for Italy). But regarding international exposures, Janssen et al. (2021) argue that current measures of carbon footprints might be misleading. They propose a measure that corrects for macroeconomic impacts, notably inflation and exchange rates for international exposures, to create a harmonized global framework.

3.2 Effects on the overall banking system, in particular through the lens of stress tests

The second dimension is the effect of climate change on the banking system as a whole, as opposed to individual banks, and how it interacts with macroeconomic developments. A first type of approach is based on sectoral dynamics. Alogoskoufis et al. (2021) suggest that high indirect emissions in the manufacturing sector may point towards concentrated transition risks. Zhang et al. (2022) conclude that the adoption of a policy towards a low-carbon economy has led Chinese banks to be more dependent, as measure by stock market volatility on the new energy sector (nuclear, solar wind) than the traditional energy sector.

Bottom-up stress tests provide additional information on the aggregate effects of climate change-related shocks. There is also limited evidence for non-linearities at the aggregate level. However, research is active to assess second-round effects.

3.2.1 Bottom-up stress tests

The results of climate change-related stress tests run by banks on the basis of scenarios provided by supervisors indicate that the risks are significant, but banks have the capabilities to withstand the shock. For the euro area, the European Central Bank (2022) conducted a constrained bottom-up climate risk stress test in 2022. Based on modified NGFS scenarios, banks assessed the impact of transition and physical risks on corporate exposures and exposures secured by real estate. The results showed that banks are to a varying degree exposed to the materialization of physical risks. Taking the impact of physical and transition risks together, the projections of 41 banks indicate a loss of around 70 bn EUR for the analyzed scenarios. These additional provisions correspond to around one third of the total exposure of participating banks and the amount is highly likely to underestimate the impact of climate risk due to numerous additional reasons (see box on "Issues raised by evidence from stress tests").

3.2.2 Evidence of non-linearities at the aggregate level

There is currently only limited information regarding possible non-linearities (as well as contagion effects discussed in the next section). However, it is very likely that we underestimate the risk.

Danielsson (2020), looking at Swedish data, finds that the number of coastal homes below 2 meters above sea level is small. This can be interpreted as showing that the risk of flooding was considered when the housing was built. The low number of homes on these low levels may thus partly be due to the risk of flooding being high if a house is too close to sea level; it is safer to build houses at a higher point above sea level. The rapid increase in the number of owner-occupied and tenant-owned homes at 2–3 meters above sea level also means that, should the sea level rise much, even more housing will be exposed to the risk of flooding, as significantly more housing is situated 2.5–3 meters above present sea level than at levels of up to 2 meters.

Caloia and Jansen (2021) implement a reverse stress test of how a flooding event in the Netherlands might affect Dutch banks. They find that the Dutch banking system is well capitalized to withstand floods in unprotected areas, with little real estate, as this will have a negligible effect on banks' capital. However, a major flooding event affecting densely populated areas might have a significant effect on bank capital. They estimate that a major flooding event might cause a 10% fall in GDP, and a possible impact of up to 700 basis points on bank capital. It should be noted that these scenarios are very much in the tail of the distribution. However, the study shows that the cost of not mitigating climate change in an effective manner can potentially be very costly.

In addition, the existence of "tipping points" with the breach of biophysical thresholds (like the loss of the Greenland ice sheet), with irreversible effects on climate change, would have considerable effects on the overall banking system. As described by Bolton et al. (2020), "green swan" events may trigger non-linearities and have far reaching consequences on banks, including profitability and charter value. A new emerging literature considers the increasing likelihood of the simultaneous breach of several tipping points.

3.2.3 Second-round effects of climate change-related shocks

There is a substantial literature on the existence of second-round effects of climate change-related shocks, in particular from the stress testing literature, as the financial system may amplify initial climate shocks, notably through uncertainty channels.

Battiston et al. (2017) show in their climate stress test for the 50 largest EU banks that second-round effects can be of comparable magnitude to first-round effects. In their analysis, second-round effects are in particular the consequences of fire sales, triggering a fall in asset prices, which affects the value of the portfolio of banks, leading to an even larger sell-off. De facto, some analyzed banks only experienced second-round losses and only marginal first-round losses.

Even if they do not focus on climate change, Ahnert and Georg (2018) find that, when banks are subject to common exposure, information contagion increases systemic risk. Aldasoro et al. (2017), studying a network model of the interbank market, show that contagion occurs through interbank interlinkages, fire sales and liquidity hoarding. Extending such analysis to climate change-related shocks is a relevant issue for future research.

Indeed, the exposure to common asset classes of different market participants, interdependencies among financial institutions, and potential fire-sale dynamics could amplify the impact of climate risks on banks.

For instance, Roncoroni et al. (2021a) study how the structure of a financial network and market conditions affect financial stability in the European banking system. They detect two channels of financial contagion: i) *direct interconnectedness*, via a network of interbank loans, bank loans to non-financial corporates and retail clients, and security holdings; and ii) *indirect interconnectedness*, via overlapping exposures to common asset classes. They uncover a strongly *nonlinear* relationship between diversification of exposures (distinguishing whether it takes place vis-à-vis the real or the financial sector[13]), shock size, and losses due to interbank contagion. They also demonstrate the potential for contagion effects to amplify first-round stress test results due to interconnectedness.

Roncoroni et al. (2021b) extends the previous analysis to the effects on financial stability of the interplay between climate transition risk and market conditions. To this end, they extend in a novel way the aforementioned framework by including an ex ante network valuation of financial assets (that accounts for asset price volatility as well as for endogenous recovery rate on interbank assets). Moreover, as in the previous paper, they consider the dynamics of indirect contagion of banks and investment funds, which

[13] In their analysis, diversification within the financial sector is less likely to reduce systemic risk.

are key players in the low carbon transition, via exposures to the same asset classes. More precisely, the methodology combines the estimation of losses arising both from interbank distress contagion, as well as from common asset exposures.

In other words, they identify conditions under which total losses of the financial system are large, even if the direct exposure to shocks is small. They also show that the combination of distress contagion and common exposure contagion gives rise to losses that are larger than the sum of individual contributions. This result naturally reminds us of the distinctive features of climate change risks. Indeed, physical and transition risks may trigger complex, non-linear chain-reaction effects with associated tipping points and irreversible impacts (see Bolton et al. (2020) for further details).

Jourde and Moreau (2023) propose a market-based framework to study systemic climate risks in the financial sector. More precisely, they propose a test procedure to assess whether climate risks can exacerbate contagion effects among financial institutions, which is a key element to assess the level of systemic risk in the financial sector (e.g., Billio et al. (2012)). More precisely, the proposed procedure is based the estimation of time-varying Value-at-Risk (VaR) from the stock returns of financial institutions of interest. They apply their framework to large European financial institutions, observed between 2005 and 2022, and show that: i) exposure to transition risk has increased since 2015, mainly for banks and life and non-life insurance companies; and ii) unlike physical risk, transition risk can exacerbate tail dependence among financial institutions and, thus, significantly influence systemic risk.

In other words, there is a clear need to integrate the contributions of second-round effects of the initial climate change-like shock induced by the contagion channels characterizing a banking system. Belloni, Kuik, and Mingarelli (2022) assess the effects of changes in carbon prices on the European banking system by means of four contagion channels (real economy credit risk, interbank credit risk, liquidity risk, and market risk). They find that the European banking system may be facing substantial risks only in cases of high and abrupt changes in carbon prices, if emissions are unchanged. The paper also finds that large increases in carbon prices might still entail tail risks for the banking system if firms reduce emissions only slightly.

Box: Issues raised by evidence from stress tests

Financial sector supervisors are aware that there is the possibility that financial institutions will underestimate risks from climate change and that this poses a threat to financial stability. To date, the main response of financial sector supervisors has been the development of stress tests for climate change for macroprudential and microprudential purposes (see, e.g., Vermeulen et al., 2021, for a top-down stress test for the Netherlands). These exercises are different from traditional stress tests in a number of ways. Baudino and Svoronos (2021) discuss the main features of several early stress tests for climate change, which are also shared by more recent climate stress tests. It is recognized that climate stress tests are in a very early stage of development. Nevertheless, novel approaches to assess climate risk in stress tests are developed continuously. In particular, Jung, Engle and Berner (2023) compute banks' expected shortfall or CRISK, similar to Brownlees and Engle's (2017) SRISK. Such a market-based approach allows one to analyze large global banks' vulnerability, measuring the impact of disorderly stress scenarios, including a stranded asset factor (*). There is thus considerable uncertainty about the outcomes of these exercises, in part because of their early stage of development but also because of the inherent uncertainty of climate change risks and the long time horizons of the exercises. Because of this greater uncertainty, it is common for climate stress tests to involve the running of more scenarios than traditional stress tests (see, for instance, Allen et al. (2020) and Emambakhsh et al. (2023)). As described above, Fuchs et al. (2024) study the French ACPR stress test and conclude that stress tests are an "information revelation mechanism", through which banks gather information on borrowers, leading them eventually to increase lending to emitting firms with a higher spread. The results for individual financial institutions also tend not to be disclosed, given that the exercises are in an early stage of development. Another key difference is that, to date, the quantitative output of stress tests for climate change have not been used to determine capital requirements for climate risks, although qualitative results may sometimes have an impact on (bank-specific) Pillar 2 requirements (P2R in the European Single Supervisory Mechanism).

It is recognized that climate stress tests have general limitations, even if they are nevertheless viewed as useful risk management exercises. Indeed, there are general limitations to any quantification due to the lack of appropriate data. As mentioned in the main text, this creates the potential to underestimate the risks that climate change poses to financial institutions. This is true for a number of reasons. Firstly, climate physical and transition risks are mostly absent from past data, while most risk management techniques rely heavily on risk realizations in past data to measure future risks. Secondly, granular data is needed to properly assess risks from climate change, and financial institutions often do not have this data. Thirdly, it is also generally agreed that in times of economic stress correlations diverge from regular, non-stressed periods, although as observed by Forbes and Rigobon (1999) as well as Loretan and English (2000) care must be taken when measuring correlations during times of high volatility because there is a mechanical effect of rising volatility on measured correlations. Consequently, for climate-related risks with only scarce historic observations, measuring stressed correlations is almost impossible, which makes climate stress testing even more challenging.

Another general limitation is the high level of uncertainty surrounding the results arising from the fact that climate change-related risks play out over a time horizon much longer than for other, more common risks. These stress tests usually assume a static balance sheet; thus, second-round effects are ignored. Second-round effects can amplify the stress of a climate scenario to individual banks and the banking system as a whole through, for example, effects within the interbank credit market, spillover effects to other financial institutions (e.g., insurance companies, see de Bandt et al, 2023) and direct impacts on the real economy (e.g., credit supply reduction). The role of insurance companies is crucial because increased realizations of physical risks could lead to less insurance coverage and larger insurance protection gaps, leading to larger credit risks for banks if the collateral backing mortgages becomes uninsurable against natural hazards (see de Bandt et al, 2023). Given the long time horizon of climate stress tests, it is agreed that the static balance sheet assumption is problematic. It should arguable be relaxed, so that second-round effects can be incorporated into the analysis. Alogoskoufis et al. (2021) also show for the European economy that second-round effects amplify the impact of the stress, and it is crucial to analyze the effects of a climate risk scenario. The same reasoning applies to Acharya et al. (2023) who, in addition to noting the importance of second-round effects and feedback loops, argue that it is essential to account for “compound risk” scenarios, which allows one to analyze the co-occurrence of climate risks and conventional economic stress. This criticism notwithstanding, climate stress tests are viewed as useful risk management exercises mainly because of the potential for financial institutions, typically banks and insurers, and financial sector supervisors, to understand more fully the threats climate change poses to individual banks, the banking system and financial stability.

(*) This factor is developed by Litterman and the WWF and is constructed as an equity-based hedge portfolio that is long in global fossil energy index and short in S&P 500.

Conclusions and suggestions for future research

The paper reviews the recent empirical literature in economics and finance focusing on how climate change affects banks, with a particular emphasis on microeconomic evidence. The particular focus of the paper is to investigate possible reasons behind the fact that the impact on banks’ loan and bond spreads, based on banks and bond markets perceptions and pricing of climate change-related risks, is estimated to be relatively moderate in many applications. First, we provide an overview of empirical estimates to back up the notion that documented risks are effectively small in magnitude. Second, we create an inventory of studies and survey papers and offer a distribution of quantitative impact on banks along several dimensions. Based on the observation that the assessed impact of climate risks on the two previously mentioned spreads could appear limited, we consider whether this could be due to a mispricing by banks or bond markets. In particular, the second aspect would be a source of concern for supervisors and regulators.

The paper investigates the effects of climate change on three metrics: credit risk, market risk, and lending standards. We also discuss the impact of climate change on residential and corporate real estate, non-financial corporations, as well as central and local governments such as states and municipalities. To further broaden the perspective, we consider some macroeconomic interactions and indirect effects, which turn out to be non-negligible.

Overall, the main conclusions are that:

1. In debt markets, the severity of their perceived impact of climate change-related risks on both loan and bond spreads appears to be limited, with estimates of the effects below 50 bp. In comparison, studies on stock markets document responses that are more substantial. In real estate markets, there is some evidence of price effects not limited to but including flood risks associated with sea level rise.
2. The cross-section of studies suggests that market participants anticipate some but not all types of climate hazards. For instance, some studies find that higher expected returns for firms subject to climate risk as well as an association of analysts' forecast corrections related to climate change-related risks. In addition, other studies show that realized returns on assets related to companies vulnerable to climate change-related risks are below expected returns, consistent with the possibility that risks are underestimated. In real estate markets, papers on the anticipation of risk related to sea level rise point to different directions and paint an uncertain picture.
3. As an adjacent area, the review also briefly examines the relationship of environmental, social, and governance (ESG) criteria for lenders and borrowers as well as the effects of sustainability disclosures and reporting on lenders and borrowers risk exposures. In principle, the provision of information through these channels could help to reduce uncertainty. However, some studies document challenges related to information verifications and incentives for greenwashing.
4. A large share of included papers studies a particular aspect or a subset of risks related to climate change in isolation. Due to the multifaceted nature of risks and the effects on various markets and portfolios, the cumulative effects are challenging to estimate. In addition, there is little research on the correlation of damages, as well as the potential risk of compounding effects of economic downturns and climate damages.
5. Despite the rapid growth of the literature, some data and methodological challenges persist. For example, studies on the financial effects of physical risk would benefit from more granular information on the exact exposure locations. For transition risk, data sources focus on large firms and complicate the evaluation of risks for small and medium sized enterprises (SMEs).

Overall, the predominance of studies relying on historical data and events could imply that the potential damages of climate change are not yet well quantified. In addition, studies on the effectiveness of banks' measurement and management of risks paint a mixed picture.

Note that the review did not consider the policy implications in terms of optimal prudential regulation. Although we investigated to what extent the channels may interact with regulation, the review did not investigate how regulation could mitigate these effects from a financial stability point of view. Dafermos and Nikolaidi (2021) argue that capital requirements have the potential to reduce the pace of global warming if green supporting factors and brown penalizing factors are implemented simultaneously and in tandem with fiscal policies. However, alone the effect of regulation is rather small. In contrast, Oehmke and Opp (2022) show that while banking regulation might reduce climate change-related risks, it might not necessarily reduce emissions. Acharya et al. (2023) note that any increase in capital requirements for high-emission firms to account for their more substantial transition risk exposure might raise the cost of capital for those firms and could thus itself constitute a source of transition risk. It is important to consider, among other things, whether green capital requirements will shift the funding of high-emission firms from the regulated banking sector to the unregulated, or less-regulated, shadow banking sector.

In addition, while it is not a central objective of financial regulation, and maybe not an objective at all, we did not cover an assessment of schemes with a preferential treatment for banks involved in green lending.

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Débats Économiques et Financiers

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