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

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Executive Summary

As shown by IPCC (2023), the effects of climate change are likely to accelerate over the coming years, with a growing consensus among experts as surveyed by NGFS (2023).

The scope of the review is to describe the recent empirical literature in economics and finance focusing on how banks are affected by climate change, with a particular emphasis on microeconomic evidence.

Many of the studies which analyze the impacts of climate change on the economy and the financial system rely on modeling assumptions at the macroeconomic level. In order to improve upon these assessments, granular information is required on the effect of climate change on specific portfolios, which will then help calibrate the models used for stress tests.

The particular focus of the paper is to understand the reason why the impact on banks as observed so far is relatively moderate. We consider two alternative hypotheses: whether the risk is effectively small, or negligible, or whether it is mispriced by banks or markets, which would be more a source of concern for supervisors.

We investigate the effects of climate change on three metrics: credit risk, market risk and lending standards. We also discuss the impact of climate change on particular portfolios, namely residential and corporate real estate, as well as more generally the effects of climate change on non-financial corporates as well as central and local governments (states and municipalities). We also broaden the perspective by considering macroeconomic interactions, as well as second round effects, which are not negligible in the analysis.

All in all, the main contribution of the paper is to provide 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.

The main conclusions are that:

1. Apart from a few outliers, according to the overall distribution of impact across academic studies, the microeconomic impact of climate change on particular portfolios is so far relatively small, below 50 bp on loan and bond spreads. Stock markets appear to react more significantly and have started pricing some, but maybe not all, the risks. There is some evidence of discount in real estate prices for high flood risk areas. As a consequence, significant uncertainty remains regarding the magnitude of the effects of climate change.

[1] The work stream was led by Olivier de Bandt. Comments by other members of the Research Group as well as from other Basel Committee groups are gratefully acknowledged, but remaining errors are from the authors.

2. There are various reasons that may explain why at the macro level banks may be able to manage risks from climate change, although the situation might change over time, as climate change accelerates. Several authors conclude that realized returns on assets related to companies vulnerable to climate-related risks are below expected returns, providing evidence of underestimation of risk.

3. New dimensions are uncovered, like the impact of Environmental ESG criteria for lenders and borrowers as well as the effect of reporting on exposures, which also help partly reduce uncertainty. However, the liquidity impact of climate risk is under-researched.

4. The overall impacts of climate change, which are multifaceted and affect various portfolios at the same time and in a correlated fashion, might be more significant.

5. There are still data issues, notably in terms of granularity, as well as methodological issues, which prevent a definite assessment of the situation, both for physical risk (lack of exact location of the exposures in many instances) and transition risk (notably the lack of evaluation for SMEs).

All in all, one may conclude that the overall balance is more in the direction of an underestimation of the risks from climate change from the perspective of banks, rather than a situation where the risks are likely to be fully measured and managed by banks. The main channel is the materialization of unexpected risk insufficiently priced in lending or bond spreads.

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

JEL: Q54, Q52, Q51, G21

Introduction

While experts agree on the urgency of policy action to alleviate the effects of climate change (European Central Bank, 2022), the economic and financial literature often indicates that, so far, climate change has had ambiguous measurable effects on bank risk in advanced countries.

The scope of the review is the empirical literature published in top refereed journals in economics and finance, focusing on how banks are affected by climate change and the transition to a low carbon economy. The review includes 190 papers and covers the effects on both credit risk and credit supply; impacts on market risk are also examined.[2] This may let aside practitioners' results, but it allows us to be more confident and to trust results on the basis of a clear and transparent methodology.

While the IPCC concludes that there is a quasi-linear relationship between accumulated emissions and earth surface temperature (IPCC, 2022, 6th Report), global emissions are accelerating. Therefore, conclusions based on past evidence is likely to underestimate the amount of climate change-related damages, including the effects on banks' portfolios. In addition, there is evidence that some markets might ignore climate related information. There may be good reasons for limited reactions of participants in financial markets in some instances, for example when exposures have a short maturity (Acharya et al. 2023). Nevertheless, Eren et al. (2022) note that concerns are growing that current financial asset prices do not sufficiently reflect climate risks. There is thus a risk that future price corrections can be more pronounced in such areas, creating a risk to financial stability. That said, there are no clear benchmarks that quantify climate risks and fair pricing of such risks. Therefore, it is not feasible to gauge whether current asset prices underestimate or overestimate climate risks and the scope for repricing. It should also be noted that most of the empirical literature is concentrated on advanced economies – Europe, United States, Japan, and Australia. Only a few studies look at effects in emerging markets, despite these countries being potentially more vulnerable to both physical climate risk and the costs of transition.

Before going into detail on the evidence provided by the literature, it is useful to offer a general perspective of the issues at hand. The ultimate impact of climate-related risks, both physical and transition risks, on banks' credit exposures is not easy to quantify. This is true for a number of reasons. One is that conventional risk models do not capture potentially severe facets of climate-related risks, such as tipping points and outcomes such as climate-induced mass migrations and associated warfare. This omission is understandable, as these effects are extremely difficult to model; yet their omission is likely to lead to an underestimation of the impact of climate change on banking systems and economies more broadly (e.g., Stern (2013)). A second reason is the indirect nature of climate-related risks for banks, such as impacts to their customers' supply chains arising from climate physical risks, and the unpredictability of transition risks associated with political measures to mitigate climate change. Third, and perhaps the main reason why it is difficult to quantify the impact of climate change, is the related 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. And, as noted by Pindyck (2020), considerable uncertainty remains about how much average temperatures will rise given any assumed path for greenhouse-gas emissions. For example, the extent of coastal flooding from future sea level rise (SLR) is likely to be substantial but highly uncertain, making it extremely difficult to estimate damages to coastal real estate from future SLR. All in all, the long-term forecasting horizons and data gaps only make the task of estimating the impact of climate-related risks more difficult.

[2] The analysis is based on papers published since 2010 in refereed economics and finance journals, as well as a few energy and environment journals. In order not to miss more recent contributions, we also consider working papers by the NBER, the BIS, 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 CEPR Discussion Papers.

It is important for climate-related risks to differentiate between risk and Knightian uncertainty (Stern (2007, 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. At the same time, probabilities associated with various levels of SLR are required for standard risk analyses. Despite this uncertainty, most research finds a measurable impact of climate risk on banks' credit exposure. Some research tries to capture the effects of this uncertainty, e.g., Ilhan, Sautner and Vilkov (2021) show that climate policy uncertainty seems to be priced in the option market. More precisely, the cost of option protection against downside tail risk is larger for S&P 500 firms with more carbon-intense business models.

Putting these pieces together and keeping in mind the uncertainty of the analyses as well as the lack of comprehensive analysis for banks' credit and market exposure as almost all papers focus on specific borrower types (see Kousky et al. (2020b) and Capasso et al. (2020)), it becomes apparent why climate risk in banks' credit exposures might not yet be well-understood.

Beyond these caveats, it is important to survey the available evidence, with a view to complementing past reviews,[3] given the significant acceleration of published works in the area of climate change-related risks. Moreover, the review concentrates on the transmission channels to banks.

Note that the regulation of banks regarding their exposure to climate change is not addressed in the paper. Although we rationalize the existing quantitative literature, uncertainties on the magnitude of the impact remain.

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 concludes and makes suggestions for future research.

Part 1: Transmission channel 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 (in particular lending volumes). Credit risk includes risk of default on loan and bond exposures, while our review of 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

Credit risk is an important dimension of banks' portfolio management. It is managed by banks through an assessment of the probability of default (PD) and may translate into lending spreads, or more generally bond spreads. As argued by Acharya et al. (2023), a key aspect of the risk sensitiveness of banks' banking books is the maturity of bank loans. To the extent that banks can reshuffle loan portfolios before climate change-related risks materialize, they will not be much affected by climate shocks.[4] There are nevertheless two caveats. First, banks do hold assets displaying long-term maturities, especially for real estate. This

[3] See BCBS (2021a) and BCBS (2021b).

[4] This may distinguish banks from insurance companies (see box below).

issue is discussed more fully in section 2.1. Second, banks' franchise values will be affected if their traditional customers and notably non-financial companies are threatened by climate change, as discussed in section 2.2.

Here we discuss general findings on credit risk, leaving these more specific issues notably the effect on real estate prices (and collateral value) for part 2. First, we cover physical risk (1.1.1), then transition risk (1.1.2).

We gather empirical evidence from around 30 papers with a quantitative estimate, that we summarize in charts on the distribution of the documented estimates. The charts distinguish between loan spreads (Figure 1) and bond spreads (Figure 2), and within each figure, between physical and transition risk.[5] Even if the estimates appear comparable, one should keep in mind a few limitations: climate shocks, notably physical, are of different kinds as explained below (with floods, sea level rise, drought, etc as opposed to public policies limiting GHG emissions) and the empirical results are backward-looking.

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

1.1.1.1 Loans to agriculture

The agricultural sector is directly affected by physical climate risks. In a comprehensive simulation, 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. At the country level, 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).

1.1.1.2 Floods

Physical risks not only destroy property and harvests, but also impact the probability of repayment of retail loans as Kousky et al. (2020b) show. After a flood event, the probability of default (of a non-insured moderately priced property) increases by 2.6 times after two years.

Correa et al. (2023) find that, following climate change-related disasters, 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. These changes in loan spreads are economically sizable, as they represent between 5% and 10% of the unconditional spread charged on loans included in the sample.

Garbarino and Guin (2021) study how lenders react after a flood event using UK data for the mid-2010s. In contrast to other studies, they find that "banks do not mark-to-market against local price declines and lenders do not offset the valuation bias by adjusting interest rates or loan amounts". The absence of effects of floods in their analysis may be explained by public flood subsidizing high income households, and high-income households self-select into high flood areas. Indeed, there is a general concentration of wealthy borrowers along rivers and seashores that are most affected by climate change-related risks.

1.1.1.3 Heat and droughts

The empirical analysis proposed by Do et al. (2021) shows that banks charge higher interest rates to borrowers located in drought-located areas. In addition, this higher premium is more pronounced for food

[5] The figures report the impact arising from a unit climate risk shock, i.e. $\frac{\Delta y}{\Delta x}$, where y is the credit or lending spread, measured in basis points, and Δx is a unit climate shock. The latter depends however on the nature of the risk, with a cross-sectional dimension for transition risk (e. g. difference in carbon emissions) and a time series dimension for physical risk (e. g. probability of flood occurrence or heat wave).

industry borrowers; a one standard deviation increase in their adopted drought measure induces an increase of 11 bp on the interest rate charged to food industry borrowers.

Acharya et al. (2022) show that heat stress is correlated with municipal bond yield spreads and document an increase of 15 bp per annum. The authors conclude that "the effect is larger for longer-term, revenue-only and lower-rated bonds, and arises mainly from the expected increase in energy expenditure and decrease in labor productivity". In particular they find that "among S&P 500 companies, a one standard deviation increase in exposure to heat stress is associated with yield spreads that are higher by around 40 bp for sub-investment grade corporate bonds".

Similarly, Javadi and Masum (2021) find empirical evidence 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. The authors follow Huynh et al. (2020) and use the location of a firm's headquarters to measure its exposure to climate risk. They assume, as observed in previous research, that a firm's headquarter location is usually close to its operations and core business activities. To alleviate the concern regarding the validity of this assumption, they also include information on the location of the customers of the borrowing firms They conclude that the interest rate spread on loans is significantly higher for firms when their customers are more exposed to climate risk. In addition, the authors conclude that "the effects are even more pronounced for long-term loans of poorly rated firms". For example, they assess that "loan spreads are about 5.8% higher for long-term loans of poorly rated firms in the top quartile of climate risk than those in the bottom quartile". The study also adds supporting evidence to the notion that climate risk is not fully anticipated as they find no significant difference between firms in the food industry and others (see 1.2. for similar results for equities).

1.1.1.4 Sea Level Rise (SLR)

As far as SLR risk is concerned, there is evidence on the effects of climate change, for loans and bonds.

For loans, Nguyen et al. (2022) show that lenders charge higher interest rates for mortgages on residential real estate exposed to more SLR. The main conclusion is that the interest rate spread for mortgages in a zip code where all residential real estate are exposed to SLR risk is approximately 7.5 bp higher than the interest rate spread for mortgages in a corresponding area where 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 investor's loss (as holders of the municipal bonds) is around half of the estimated physical damage induced by the relevant natural disaster. This corresponds to a loss of around 31 bp for the investors in the weeks after a disaster.

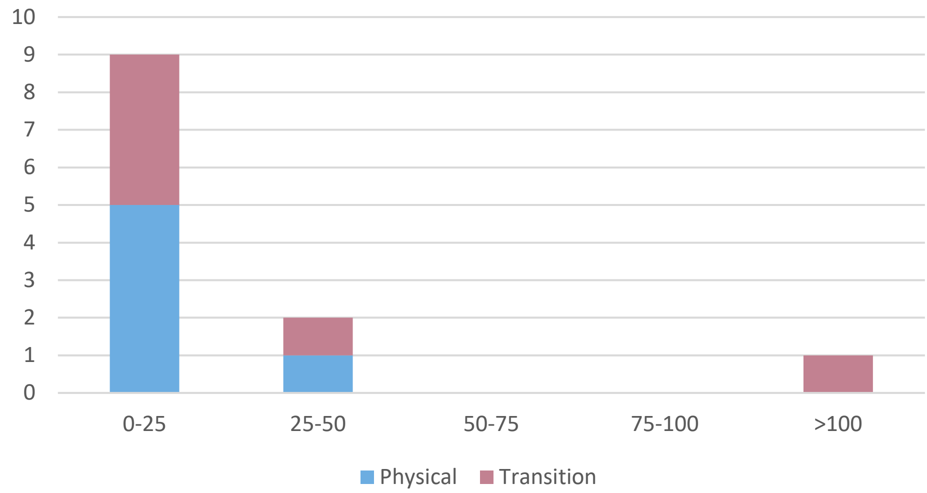
1.1.2 Impact of the transition to a low-carbon economy on lending and bond spreads

a) Bank loans

For higher risks and spreads on bank loans facing transition risk, there is evidence on both the corporate loan and mortgage markets. Some studies only consider default risk. Others offer a more complete analysis and also measure the implications of loan spread adjustment to higher risk.

Impact of climate change on loan spreads

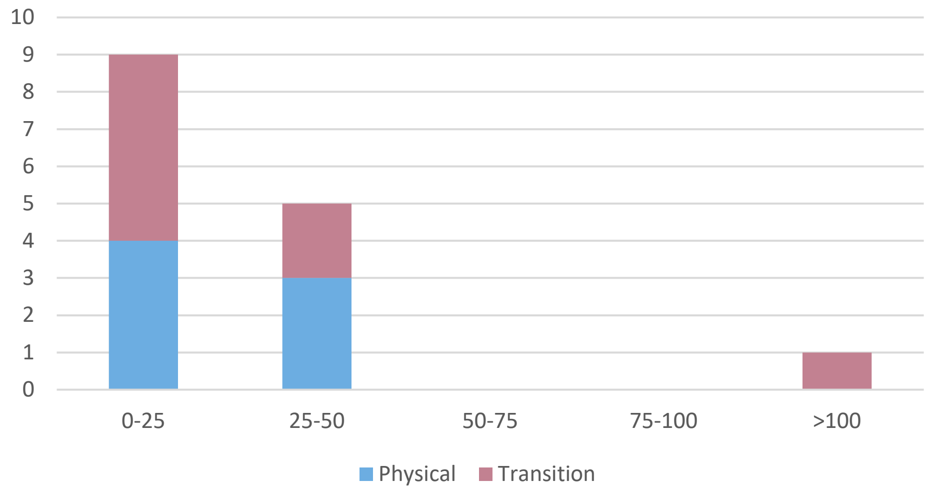
12 entries Figure 1



Source: authors' calculations, based on the review of 12 estimates provided by the academic literature, number of studies (vertical axis) providing an estimate of yield spreads of bank loans, in basis points (horizontal axis). Impact is usually measured as the response to a one standard deviation on climate change exposure. The articles displayed here are: 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); Garbarino and Guin (2021); Huang et al (2021); Javadi and Masum (2021); Kleimeier and Viehs (2018); Nguyen et al. (2022). The studies investigating shocks in terms of physical risk are depicted in blue, transition risk in red. The reference above 100 bp is Huang et al. (2021).

Impact of climate change on bond spreads

15 studies Figure 2



Source: authors' calculations, based on the review of 15 estimates provided in the academic literature, number of studies (vertical axis) providing an estimate of yield spreads on corporate or sovereign bonds, in basis points (horizontal axis). Acharya et al (2022) -2 entries; Auh et al. (2022); Baker et al (2018); Cevik and Tovar Jalles (2020); Goldsmith-Pinkham et al. (2021); Höck et al. (2020); Kim and Pouget (2023) -2 entries; 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).

Delis et al. (2023) analyze in the corporate loan market the extent to which U.S. banks price firms' climate policy risk exposure to (stranded) fossil fuel reserves. In particular, they estimate whether banks charge a higher loan rate to fossil fuel firms. The authors find that (1) the effects of fossil fuel reserves held by the borrowing firms, on the loan rate is more pronounced for firms in countries with stringent policy, or with close costal proximity; (2) fossil fuel firms obtain larger loans compared to non-fossil fuel firms; and (3) higher loan pricing to fossil fuel firms by "green banks". Their results also support the view that the fossil fuel industry has lost some access to equity finance, leading to larger borrowing by these firms. Thus, part of the reason that these firms pay larger spreads could be related to greater loan demand. Consistent with this idea, Degryse et al. (2023), based on international syndicated loans, show that green firms borrow at a significantly lower spread, especially when the lender consortium can also be classified as green, especially after the Paris Agreements. 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.

Ehlers et al. (2022) investigate whether a higher carbon intensity drives the associated risk premium a company has to pay. Although the premium is rather small, the authors conclude that banks charge higher loan spreads only in case of higher emissions narrowly attributable to the firm's activity, and not to the broader carbon footprint of the firm (i.e. indirect emissions related to energy consumption and production inputs). 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.

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 estates 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) on pre-2018 loans, so far 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. 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 measured at 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.

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. Pastor et al. (2022) predict that similarly to the existence of a "greenium" for green bonds (i.e., lower interest rates on green than brown 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 may 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, Box 1 considers research on ESG information and lending. The perspective of risk for equities is discussed in section 1.2.

Box 1

Box 1: Bank lending and environmental sustainability

A growing literature investigates the impact of environmental, social and governance (ESG) performance and objectives on credit risk. As discussed by Bolton and Kacperczyk (2022), the increasing importance of such factors "may reflect the growing frustration with inadequate policies". We first discuss the research on the effect of ESG performance on borrowers. Subsequently, we summarize the literature on lenders' ESG scores and outcomes related to credit risk.

For borrowers, Höck et al. (2020) show that environmental sustainability reduces the credit risk premium measured in CDS spreads but only for companies with a good creditworthiness. Billio et al. (2022), as well as Carbone et al. (2022), find that sustainability also affects borrower ratings positively and leads to a decline in the credit spread for those corporates. In addition, some papers explicitly connect emissions, ESG ratings, and credit spreads. They document that both high emissions and low ESG ratings are connected to a higher probability of default and higher credit spreads (Kleimeier and Viehs (2018), Capasso et al. (2020), Ehlers et al. (2022)). Chava (2014) shows that lenders charge a significantly higher interest rate on the bank loans issued to firms with these environmental concerns Further, the paper documents that banks are also more reluctant to lend to these firms, as witnessed by the lower number of banks participating in their loan syndicate than for the firms without such environmental concerns. In line with this evidence, recent papers document a rise of sustainability-linked lending, in which lenders reward sustainable borrowers with lower lending rates (Kim et al., 2022, Carrizosa and Gosh, 2022).

From the perspective of **lenders**, Birindelli et al. (2022) show that banks' commitment to climate issues – meaning a medium to high attention to this topic – is connected to a lower risk of bank loans. Besides the management of financial and event risk, the studies allude to lowered reputational risk as a driver of banks' attention to non-financial characteristics of their borrowers.

Some studies indicate that the effects are concentrated in groups of lenders and borrowers with high similarity. For instance, Kim, Surroca, and Tribo (2014) study bank lending in 19 countries and find that banks offer better financing conditions to ethical borrowers as measured by sustainability scores. They document a substantial decrease in mean spreads by almost 25% for a one standard deviation increase in a measure of ethical behavior of the borrower. The reduction is even larger with 38% compared to the sample mean when lenders also rank high in ethical behavior. In line with this result, Hauptmann (2017) finds that borrowers with higher sustainability ratings pay lower loan spreads only when the lending bank exhibits strong sustainability performance as well. Chen et al. (2021) find that banks require higher loan spreads from borrowers with higher levels of chemical pollution. Similar to Kim et al. (2014) and Hauptmann (2017), they document that the effect is concentrated in lenders with higher social responsibility performance. Moreover, Degryse et al. (2023) show that green banks, measured by their membership in the UN Environment Program Finance and their reporting to the Carbon Disclosure Project, offer better loan conditions to green firms after the ratification of the Paris Agreement.

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. In this section, we focus on equity markets, as bond markets are 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. The same caveats as for Figures 2 and 3 apply. 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 security prices of corporate bonds and equities reflect the impact of climate change 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 which 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. They also document that this overreaction can be costly to fund investor performance. In contrast, Choi et 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 for 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. 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 which 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. 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).

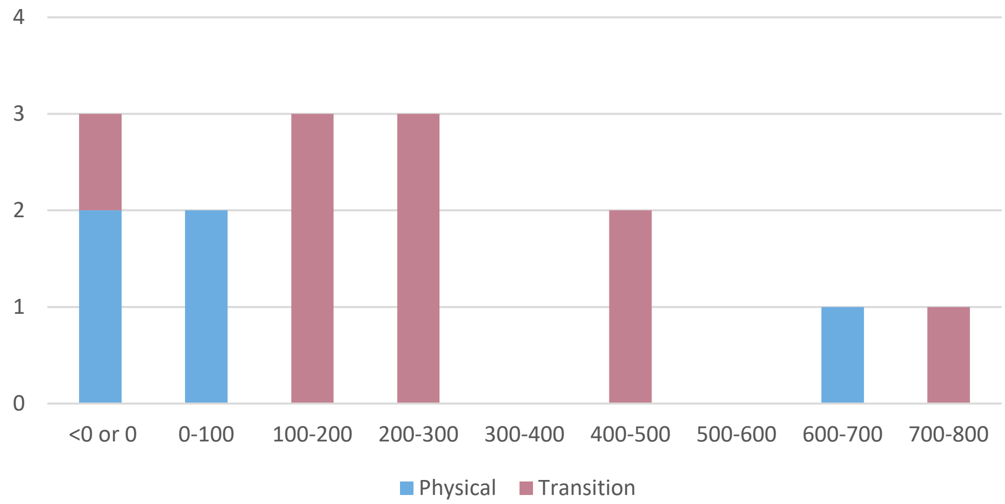
Bua et al. (2022) investigate the climate risk premium on European equity markets. Using a low-minus-high transition (physical) climate beta portfolio, they identify positive excess returns, measuring a climate risk premium 7.05% and 6.14% on average per-year after 2015, for transition and physical risk,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

The quality of information on firms' carbon emissions is a common challenge for studies on transition risk. Aswani et al. (2021) 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 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 studies

Figure 3



Source: authors' calculations, based on the review of 15 papers in the academic literature, number of studies (vertical axis) providing an estimate of risk premium on non-green, or carbon-intensive, or non-ESG stocks, in basis points (horizontal axis). 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 spread.

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. In an international context, Krueger, Sautner, Tang, and Zhong (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, Krueger, Sautner, and Starks (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 both in terms of 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.

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 are in a position to adjust credit supply to changes in risks and expected rewards. Climate change-related factors could affect how banks perceive these risks and rewards.[6] 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,[7] 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 risk

In the area of physical risk, some papers concentrate on the effects of floods and natural disasters. No paper investigates the impact of drought and heat stress.

Meisenzahl (2023) 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.

6 Demand effects by corporates are discussed in section 2.2.

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

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 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, Li, and Sanders (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 and sell government bonds to finance this credit surge driven by natural disasters.

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

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 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.

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), writing on syndicated loans, 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 no effect on brown firms' environmental score.

Mesonnier (2021) 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.

1.3.3.4 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.

1.3.3.5 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: Benincasa, Kabas and Ongena (2021); 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.

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 to green projects or 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.

Box 2

Insurance markets and climate risk

A healthy insurance industry could play an important role in mitigating the impact of climate events on financial systems and economies globally; however, the natural response of insurers to growing physical risks from climate change is to reprice insurance coverage or reduce its availability, leading to larger insurance protection gaps. Financial sector supervisors are aware of this and have taken actions in at least two ways. One way is to help ensure that insurance companies manage climate risks well, to protect policy holders and support financial stability (see, for example, Cleary et al. (2019)). A second way is that insurance companies are sometimes included in the climate stress tests financial sector supervisors run to assess the impact of climate change-related risks on financial systems (see Box 3 on climate stress tests). One potentially important channel operating via insurance would be the increased risk of mortgages held by banks if residential and commercial properties, which serve as collateral, become less insurable against natural hazards. A second potentially important channel is the reduced availability of business continuity insurance. Growing insurance protection gaps in these two areas could threaten financial stability.

Insurance can mitigate the effect of climate related disasters

Climate physical risks can of course have a direct impact on economies and financial systems, and ECB (2023) argues that catastrophe insurance is a key tool to mitigate macroeconomic losses following extreme climate-related events, as it provides prompt funding for reconstruction and should incentivize risk reduction and adaptation. Rousová et al. (2023) suggest that if a large disaster of 1% of GDP hits a country, GDP growth declines by 0.24 percentage points in the quarter of impact. However, if 25% of the losses are insured, the GDP growth rate is estimated to only decline by around 0.15 percentage points. For unusually high shares of insured losses – e.g., a 75% insured share corresponding to the 90th percentile of the distribution – the empirical model even suggests an almost immediate (within quarter) rebound in GDP growth.

Climate change can make it more difficult to price insurance

Insurance only exists if the risks to be insured can be priced correctly and transferred to reinsurance companies and to the capital market. Charpentier (2007) argues that "[i]t is extremely difficult to insure in a changing environment". In his view, climate risk – and more specifically natural disasters – is a challenging issue for the insurance industry, since it involves the possibility of extremely large losses. He concludes that involving reinsurance markets and insurance linked securities seems one solution to avoid insolvency problems. But climate is changing fast, and if this uncertainty cannot be reduced, it might lead to challenges in the availability, pricing and affordability of insurance.

Some markets already see sharp increases in the price of home ownership insurance due to potential climate related hazards. Keys (2023) reports that while the average price of home insurance in the United States is $1,900, the price in New Orleans is $4,000 and the price in Miami $5,000 per year. If a price cannot be set, insurance coverage may be incomplete, possibly triggering non-linearities when the natural disasters go beyond initial basic coverage and governments do not step in. ECB (2023) documents a large insurance protection gap, especially in southern and Eastern Europe. Only about a quarter of climate-related catastrophe losses are currently insured in the European Union.

Oh et al. (2022) provide evidence that price regulation might cause a decoupling of insurance rates from the underlying risks. In the U.S. states where price regulations appear most restrictive, rates are least reflective of risks. In these high friction states, insurers are restricted in their ability to change rates in response to losses. As a result, rates have not adequately adjusted in response to growth in losses. To overcome these frictions, insurers cross-subsidize high friction states by raising rates in low friction states.

If climate change triggers an increase in the frequency of natural disasters, this can have significant impacts on insurance, potentially increasing the risk of insurance companies not being able to cover their liabilities. Gray (2021) argues that extreme weather has begun to diverge from historical records. Firms using models based on historical data have struggled to integrate new information about climate change and climate variability into their forecasts.

Hadzilacos et al. (2021) find that most insurance models assume events to be uncorrelated. If extreme events are correlated, expected maximum pay-outs might increase substantially. They find a positive correlation of 20–40%. Ntelekos et al. (2018) find that U.S. hurricanes tend to cluster. In a year when two or more Group 3 major hurricanes occur, they estimate that there is around a 50% chance that they will occur within two weeks of each other.

Insurance-linked securities provide a protection against natural disasters

Insurance-linked bonds are paid if an event occurs. Polacek (2018) discusses CAT bonds. Catastrophe (CAT) bonds have been provided since 1997. Unlike traditional insurance, CAT bonds are 100% collateralized. CAT bonds are also structured to eliminate counterparty risk. CAT bonds have an appeal to investors as their returns are largely uncorrelated with the returns of other financial market instruments. In the past, CAT bonds have provided strong returns. This has helped attract alternative sources of capital into insurance markets.

Insurance-linked bonds can also be used as protection against negative weather events. Such bonds will normally be index-based. A literature study by Kraehnert et al. (2021) finds that the CAT bond market has become a vital pillar of the risk management of insurers. Weather derivatives, on the other hand, still seem to be a niche product outside the United States. One challenge with insurance-linked securities is that there are economies of scale and therefore easier for larger companies to use these tools than for smaller ones. With risk-based premiums one needs to monitor the potential unaffordability of insurance. This will especially be the case if the less affluent tend to locate in high-risk areas.

Index-based insurance might be a solution for the agricultural sector, but so far uptake is low

Index-based insurance has been used to protect farmers against negative outcomes. With index-based insurance pay-outs depend on an index that strongly correlates with losses in income or assets. Kraehnert et al. (2021) argue that index insurance especially can welfare-enhancing effects in developing countries. However, uptake rates so far remain low despite the use of subsidies through vouchers or premium reductions. One reason for the low uptake might be low levels of trust in the insurance provider. Individuals might also have difficulties assessing the probability that a natural disaster will strike and therefore have problems understanding when the index-based insurance will be triggered.

Citino et al. (2021), looking at agricultural insurance in Italy, also document a low uptake of insurance. They find that adverse selection and choice frictions render price mechanisms like subsidies less effective. Instead, one should consider mandates to assure a greater insurance coverage.

Low uptake of flood insurance

Kraehnert et al. (2021) find that in markets with voluntary flood insurance uptake is low, typically below 50%. Low-probability, high-impact events are often underestimated by economic agents. Large-scale information campaigns on flood risks and insurance possibilities have been ineffective so far. Another issue is moral hazard, as individuals might expect government relief in response to a large amount of uninsured losses. This might help explain the finding of Kousky et al. (2020a) that most households are uninsured or underinsured against floods, despite flooding being the most frequent and costliest natural disaster in the United States. Of course, any expectation on the part of households that government agencies will provide sufficient post-flood assistance could be, in the event, incorrect.

In the Netherlands flood insurance is not even available, as the government is responsible for providing flood relief. Botzen and Van den Bergh (2008) examine existing risk-sharing arrangements and the possible role of private insurance in some detail. They argue that private insurance has a role in spreading risk and raising incentives to reduce economic losses.

Mandatory insurance coverage schemes

Public-private initiatives can be used to increase insurance coverage against natural disasters. European Central Bank (2023) suggests that public-private partnerships (PPPs) and ex ante public backstops can be suitable safeguards and give incentives to promote risk mitigation. This might be necessary to ensure broad insurance coverage. Gray (2021) points out that how to incorporate knowledge about climate impacts into routine economic processes, such as insurance pricing, can trigger broader political disputes about how these risks should be socially distributed.

There is a trade-off between actuarial fairness and social solidarity in public–private mixed insurance schemes. Mandatory schemes reflect the principle that natural disasters are hard to predict and therefore offer wide coverage for moderate premiums to all. Owen and Noy (2019) look at payments after an earthquake in New Zealand and find that payments from the system are highly regressive. They find that the poor are subsidizing the rich. They suggest a simple shift from effectively flat premiums to a set percentage of the total private sum insured. Charpentier et al. (2021) look at the French system for flood insurance. Historically, the system was meant to give protection to the worst off. However, experience accumulated over past decades now makes it possible to assess physical risks that previously were not well understood. Flood losses, long considered uninsurable, is one example. In the current situation well-off properties might be the main beneficiaries of the natural disaster compensation scheme.

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 Box 2).

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 smaller literature on transition risk, especially related to energy efficiency.

2.1.1 Effects of physical risks

Property is directly exposed to acute physical risk associated with climate change. 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.

Acute physical risks are hazards that can become more frequent with rising global temperatures. The most common examples are rising maximum tide levels due to sea level rise (SLR), higher probability of floods due to periods with extreme rainfall and higher exposure to forest fires due to periods with heat waves and drought. In addition, some regions might see a higher frequency of storms.

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.

The countries most exposed to acute physical risks are probably 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 either arise 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.

Many papers find that properties in potential flood areas sell at a discount. Baldauf et al. (2020) and Bernstein et al. (2019) find that "homes exposed to SLR sell for approximately 7% less than observably equivalent unexposed properties equidistant from the beach". Keys and Mulder (2020) find that for exposed properties in Florida transaction volumes declined 16–20% from 2018–2020 while prices declined 5%. Mirone and Poeschel (2021), looking at Demark, find that properties 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.

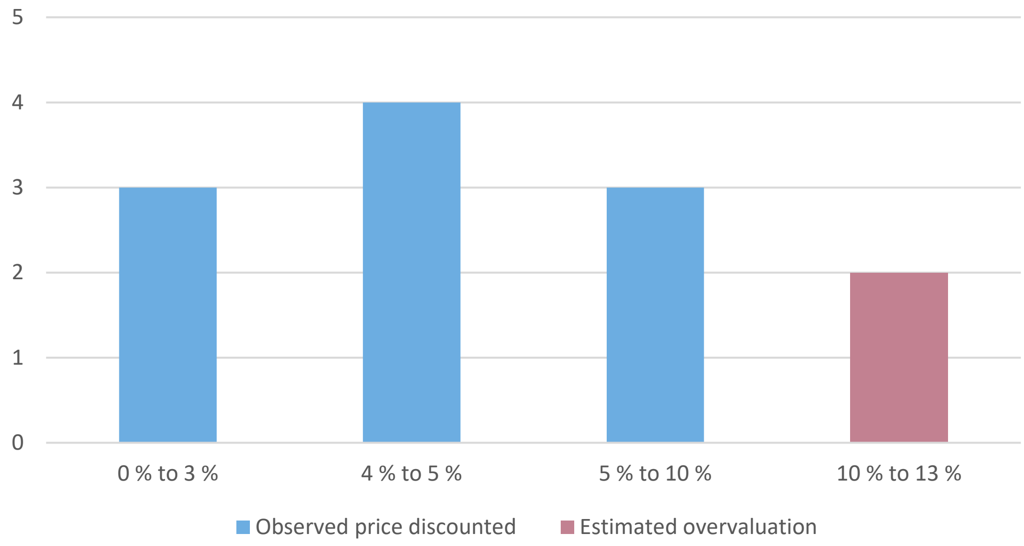
Beltrán et al. (2018), in a meta-analysis, find that "for inland flooding the price discount associated with location in the 100-year floodplain is -4.6% in the United States". Hino and Burke (2020) estimate that full pricing of presence in a floodplain in the United States should reduce property values 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%.

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%.

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

12 studies

Figure 4



Source: authors' calculations, based on the review of 9 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 included: 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), Hino and Burke (2020), Keys and Mulder (2020), Mirone and Poeschel (2021), Murfin and Spiegel (2020), Reeken and Phlippen (2022).

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 important. Baldauf et al. (2020), as well as 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 to improve risk communication could influence market outcomes.

Gourevich et al. (2023) present a broad study of flood risk across the United States. They 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. They 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. On the other side, 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

Building accounts 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).[8] 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 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 suffers only

8 See Eurostat: Energy consumption in households - Statistics Explained (europa.eu).

provides a lower bound of the effect so that it is not possible to know the full extent of the decline in house prices.

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. 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 financially constraints firms shift emissions in other states following implementation of the Californian cap-and-trade system. Li et al. (2020) conduct a textual analysis and find that firms facing high transition risk are valued at a discount. Ramelli, Ossola, and Rancan (2021) 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, Wagner, Zeckhauser, and Ziegler (2021) 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 in 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.[9] 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.[10]

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.

Several studies look into 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, spreads increase 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 Intergovernmental Panel for Climate Change. 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. 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).

9 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.

10 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.

Note that the review does not 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

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 banks and notably on their profitability. From that perspective, 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. 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. This is consistent with Cortés and Strahan (2017) who show that banks reallocate credit from less exposed to more exposed areas.

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.

Bottom-up stress tests provide 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, e.g., moderate scenarios compared to conventional stress scenarios and data and modeling techniques that are at a preliminary stage. (See Box 3 on climate stress tests for a discussion of some of the challenges facing climate stress tests and also some of the limitations of the exercises.)

3.2.2 There is limited 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). But 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) do 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 Research is active to assess 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[11]), 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) analyze 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 framework of the climate stress test of the financial system 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 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 rises 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 on the following steps:
- First, using a GARCH model, they estimate time-varying Value-at-Risk (VaR) from the stock returns of financial institutions of interest. Then, from the estimated correlation matrix of those individual measures of tail risk (relevant for financial stability), they extract the first principal component, namely an indicator of systemic tail risk dependence within the financial sector.
- Second, they construct climate risk factors, distinguishing between transition and physical risks, and they estimate associated VaR measures.
- Third, building upon the previous steps, they propose a two-pass regression procedure to assess whether climate risks can exacerbate tail risk dependence among financial institutions. First, they run a time-series regression to verify if an increase in climate risks is associated with a contemporaneous increase in downside risk within the financial sector. Then, they perform a cross-sectional regression to test if the financial institutions most exposed to climate risks have stronger tail dependence with the rest of the financial sector.
- Fourth, they investigate the characteristics of the financial institutions that correlate with individual climate risk exposure.

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

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

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 3

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 transition 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 fairly 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)). 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 quantitat3ive 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 Box 2) 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 also Box 2). 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.

Conclusion and suggestions for future work

The survey acknowledges the great number of new research papers that have very recently been made available to understand better the various transmission channels by which climate change impacts banks. The richness of these studies helps provide a first assessment of the distribution of risk spreads for loans, bonds and equity, indicating that banks have started pricing these risk, while the issue remains of whether it is adequate. Based on this material, a few provisional conclusions may be drawn, which provide directions for future research, with a particular view to assess the robustness of these findings.

1. Apart from a few outliers, according to the overall distribution of impacts across academic studies, the microeconomic impacts of climate change on particular portfolios are relatively small, below 50 bp on loan and bond spreads. Stock markets appear to react more significantly and appear to have started pricing some, but maybe not all, of the risks. As a consequence, significant uncertainty remains regarding the magnitude of the effects of climate change.
2. There are various possible explanations for why banks may be able to manage risks from climate change at the macro level, although the situation might change over time, as climate change accelerates. Acharya et al. (2023) argue that the pricing of climate change-related credit or market risks only partly offsets the impacts of the realization of climate change-related shocks. Indeed, several authors conclude that realized returns on climate change-related risks are below expected return, providing evidence of an underestimation of risk.
3. New dimensions are uncovered, like the impact of ESG criteria as well as the reporting on exposures, which also help to partly reduce uncertainty.
4. Liquidity issues arising from climate change-related shocks are still insufficiently researched.
5. The overall impact of climate change, which becomes multifaceted and affects various portfolios at the same time and in a correlated fashion, may therefore be more significant. In particular, the difficulty to model possible non-linear effects related to climate change and to capture tipping points might lead to an underestimation of risks.
6. There are still data issues, notably in terms of granularity, as well as methodological issues, which prevent a definite assessment of the situation, both for physical risks (lack of exact location of the exposures in many instances) and transition risks (notably lack of evaluation for SMEs).

All in all, one may conclude that the overall balance is more in the direction of an underestimation of the risks from climate change from the perspective of banks, rather than a situation where risks are likely to be fully manageable by banks. The main channel is the materialization of unexpected risks insufficiently priced in lending or bond spreads.

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 financial risks, they 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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