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The public costs of climate-induced financial instability

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Recent evidence suggests that climate change will significantly affect economic growth and several productive elements of modern economies, such as workers and land[1–4]. Although historical records indicate that economic shocks might lead to financial instability, few studies have focused on the impact of climate change on the financial actors[5,6]. This paper examines how climate-related damages impact the stability of the global banking system. We use an agent-based climate–macroeconomic model calibrated on stylized facts, future scenarios and climate impact functions[7] affecting labour and capital. Our results indicate that climate change will increase the frequency of banking crises (26–248%). Rescuing insolvent banks will cause an additional fiscal burden of approximately 5–15% of gross domestic product per year and increase the ratio of public debt to gross domestic product by a factor of 2. We estimate that around 20% of such effects are caused by the deterioration of banks' balance sheets induced by climate change. Macroprudential regulation attenuates bailout costs, but only moderately. Our results show that leaving the financial system out of climate–economy integrated assessment may lead to an underestimation of climate impacts and that financial regulation can play a role in mitigating them.

Historical records suggest that financial crises are not rare events (Supplementary Fig. 1). On a global scale, the past 50 yr have witnessed a myriad of crises, entailing an average cost of around 35% of the gross domestic product (GDP) of the country facing the event in terms of output lost and a fiscal burden for the government of 13% of the country's GDP[8]. Such crises reflect imperfections in the functioning of modern economies, financial systems and, in particular, capital allocation mechanisms[9–11].

Recent research on climate damages emphasize that increased temperatures will have significant, nonlinear effects on the global economy[2,3,12–16]. Physical impacts from unmitigated climate change could also threaten the financial system. For example, increasing stocks of capital at risk (due to floods, landslides or storm surges) would adversely affect insurance companies, thus raising premiums. The deterioration of the balance sheets of affected firms and consumers might induce losses in the lender banks. Specifically, the inability to repay obligations—because of insolvency—generates what are usually referred to as non-performing loans (or bad debt) in the balance sheets of banks and other financial institutions, with possible systemic implications such as those experienced on a global scale during the 2008 financial crisis. Taxpayers are the final groups bearing the risks of instability. Thus, financial crises entail costs both to the economy, because of contractions in demand and production, and to public finances (fiscal costs), due to the rescuing interventions of the governments.

The literature on climate change impacts and finance is scant but rapidly developing. In a 2015 speech, the governor of the Bank of England distinguished between climate-related physical, liability and transition risks[17]. Some recent studies highlight the exposure of the global financial system to such risks[5,6,18–22], though none examines the public costs of the ensuing instability and the role of the latter in amplifying the impact of climate on growth. These preliminary studies have prompted increased attention to how central banks and financial regulation authorities can manage climate-related risks to financial stability[23,24].

This paper contributes to the debate by analysing the impact of climate change on the global banking system, quantifying banking crises and the public costs of bailing out insolvent banks. We single out the potential underestimation of climate change damage estimates that neglect this element. We use a recently developed global agent-based integrated assessment model[25,26] to simulate the behaviour of an economic system comprising heterogeneous households, firms, energy plants, banks and policymakers (a government and central bank) exposed to climate damages affecting the productivity of labour and the stock of capital owned by firms. The model, which we calibrate on stylized facts, reproduces economic growth and emissions consistent with the shared socioeconomic pathways (SSP5 as central case[27]; see Supplementary Methods D and Supplementary Results A for SSP1). We consider four scenarios of climate damages: a baseline with no climate change and three scenarios in which global warming affects the productivity of labour, capital or both, respectively. Empirical studies have found that warming significantly reduces both operational and cognitive tasks of workers, thus lowering labour productivity[28–32]. Likewise, evidence shows that climate change can affect the stock and quality of capital directly through crowding out and indirectly through extreme events[33]. As the magnitude of climate change impacts is extremely uncertain[34], we perform an extensive sensitivity analysis around our central values based on estimates from an earlier study[7]. Damages affect the profitability of firms, which might go bankrupt, creating non-performing loans (loans that will not be repaid) in the balance sheets of banks. To prevent instability of the financial system, when a bank's equity turns negative, we test a bailing-out policy such that the government immediately intervenes by providing fresh capital, saving the insolvent bank. The employed model (Methods) does not allow for analytical, closed-form solutions. This general feature of agent-based models has forced us to perform Monte Carlo analyses to remove the cross-simulation variability and to present results as averages over 500 model runs, as standard in the literature[35,36].

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Table 1 | Main macroeconomic and climate indicators in the baseline and impact scenarios

	No climate change	Labour productivity damages	Capital stock damages	Labour and capital damages
GDP growth (%)	3.4 (0.002)	2.2 (0.004)	2.9 (0.004)	2.0 (0.003)
Firms' 10 yr insolvency likelihood (%)	15.2 (0.031)	32.4 (0.047)	38.8 (0.050)	47.1 (0.052)
Banks' equity-to-total asset ratio (%)	12.0 (0.025)	7.5 (0.034)	9.6 (0.029)	5.3 (0.041)
Public bailouts per 10 years	9.1 (1.28)	14.2 (2.15)	11.5 (3.02)	22.6 (3.96)
Cost of bailouts per year (% GDP)	10.3 (0.013)	15.7 (0.027)	14.6 (0.029)	25.0 (0.031)
Average debt-to-GDP ratio	0.83 (0.04)	1.55 (0.09)	1.38 (0.07)	1.77 (0.011)
Temperature anomaly	5.4[a] (0.312)	5.0 (0.461)	5.2 (0.411)	4.8 (0.470)
Cumulative emissions at 2100 ($GtCO_2e$)	3,061.4 (98.51)	2,810.7 (97.37)	2,961.2 (99.23)	2,720.9 (109.1)

All values refer to averages from a Monte Carlo exercise of size 500; standard deviations are in parentheses. [a]The temperature anomaly that would have been realized in the presence of climate change for the stock of emissions summarized in the line below.

Table 1 summarizes the behaviour of main macroeconomic, financial and climate indicators across the three impact scenarios and the baseline. Climate change has significant negative effects on economic growth, reducing the annual pace from 3.5% in the baseline to 2.0–2.9%, depending on the climate impact scenario. Qualitatively, we confirm these figures when we target an SSP1 scenario (Supplementary Results A). Impacts on the macroeconomy are stronger when climate damages hit labour productivity, reflecting the prevalence of the labour share in most modern economies[37]. Beyond this effect, the accumulation of losses in the banking sector sharpens the impacts, as detailed subsequently. Financial crises and bank bailouts occur even in the absence of climate change: average fiscal costs in the baseline (10.3% of GDP) are comparable to historical values (Supplementary Fig. 1). However, the three impact scenarios significantly raise the number of bank rescues the government must engage in to preserve financial stability, with fiscal costs increasing by a factor ranging from 1.52 (95% confidence interval (CI): 1.04 to 2.00) to 2.43 (95% CI: 1.86 to 3.00) depending on the scenario. Such effects are driven by the stock of bad debt accumulating in the financial system as a consequence of cascades of firm bankruptcies induced by climate damages.

The number of bailouts induced by climate impacts increases over time (Fig. 1a), with the largest hike taking place between 2030 and 2060, when the temperature anomaly reaches approximately 3 °C—consistent with an SSP5 scenario—and the corresponding average damage to firms exceeds 2%. Under labour and capital damages, bank bailouts increase faster than in all other scenarios, and at the end of the century, they become more than twice as frequent as in the baseline (average of 25.0 versus 9.8 in the last decade of simulation), imposing costs to the government reaching 40% of GDP per episode (Fig. 1b). Such costs negatively affect the public budget and, over time, translate into an increasing stock of government debt (Fig. 1c). By the end of the century, the expected debt-to-GDP ratio is slightly above 400%, which should be compared with the 85% of the scenario with no climate change. Note also that bailouts are less frequent in two climate impact scenarios than in the baseline during the first couple of simulation decades (Fig. 1a). This suggests beneficial effects of mild climate change[2,3] (see Supplementary Results A for evidence of a nonlinear relationship between bailouts and GDP losses across scenarios). In an SSP1 future, the impacts are less severe but sizeable: firm insolvency and bailout frequency increase by 33% and 9%, respectively (versus a baseline without warming), and the ratio of public debt to GDP averages 250% in the year 2100 (Supplementary Results A).

Crises in the banking system exacerbate the downturns in the real sector through credit crunches, that is, periods of substantially reduced credit inflow blocking the investments of firms[38,39]. The combination of such events and the direct damages that climate change causes to economic agents in our impact scenarios (Methods) produces large detrimental effects on the long-term performance of the economy (Fig. 2a,b). In the absence of climate change, the yearly growth rates of output are almost identical over the century. When firms suffer labour and capital damages in an SSP5 world, the economy gradually shifts towards regimes of progressively weaker paces of development and greater volatility, with average growth rates corresponding to 91% (95% CI: 67% to 119%), 84% (95% CI: 65% to 108%), 68% (95% CI: 34% to 103%) and 48% (95% CI: 33% to 91%) of those in the baseline for the first-, second-, third- and fourth-century quarters, respectively. In an SSP1 future, we show that output growth rate contracts by 9% (with respect to a scenario without warming; Supplementary Results A). Damages to labour productivity cut firms' operative margins and depress wages and the aggregate demand, with dynamically adverse effects on technical change and the Schumpeterian engine of growth. Moreover, capital stock losses amplify fluctuations in the business cycle, exacerbating the reliance of firms on external financing[25]. Finally, the ability of the banking sector to alleviate the direct implications of climate impacts on firms weakens from the cumulated effects of non-performing loans. See Supplementary Results A for a comparison of the economic damages shown in the current study with previous findings.

To establish the contribution of climate-induced financial distress to such a shrinkage of economic performance, we run an additional simulation experiment comparing the actual bailout mechanism with an alternative regime. In the latter, the government absorbs any non-performing loan, thus fully preserving banks' equity and lending capacity. Such an experiment is run on our preferred impact scenario (labour and capital damages), with results reported in Fig. 2c. We estimate that around 20% (95% CI: 5% to 43%) of growth rate reduction observed in Fig. 2b is attributable to financial distress (an effect of 14% is found for SSP1; Supplementary Results A).

We find that public costs of climate-induced bailouts increase approximately linearly with temperature anomaly (Fig. 3). In the scenario with both labour and capital damages (Fig. 3b), such burden for the public budget moves from a yearly estimate of 17.5% (95% CI: 8% to 24%) of GDP for a temperature anomaly under 2.5 °C in the year 2100 to 31.0% (95% CI: 19% to 48%) for a temperature anomaly of approximately 5 °C in the same year. These values correspond to increments of 7.14 and 20.64 percentage points, respectively, with respect to the bailout costs in the baseline scenario without climate change.

Finally, we test whether macroprudential regulation relying on Basel-type capital requirements can help mitigate the costs of banking bailout. A U-shaped relationship emerges between banks' allowance to loan and the costs from financial distress. Tight capital requirements reduce the availability of loans, forcing firms to rely more on their highly volatile net profits. In addition, a large credit supply allows firms to overfinance unsuccessful investments[40], eventually leading to losses and bankruptcies. Climate change exacerbates this relationship, with the U becoming steeper as the temperature rises. These results underscore a pivotal role of macroprudential regulation in climate risk management. As Fig. 3b shows, climate-dependent

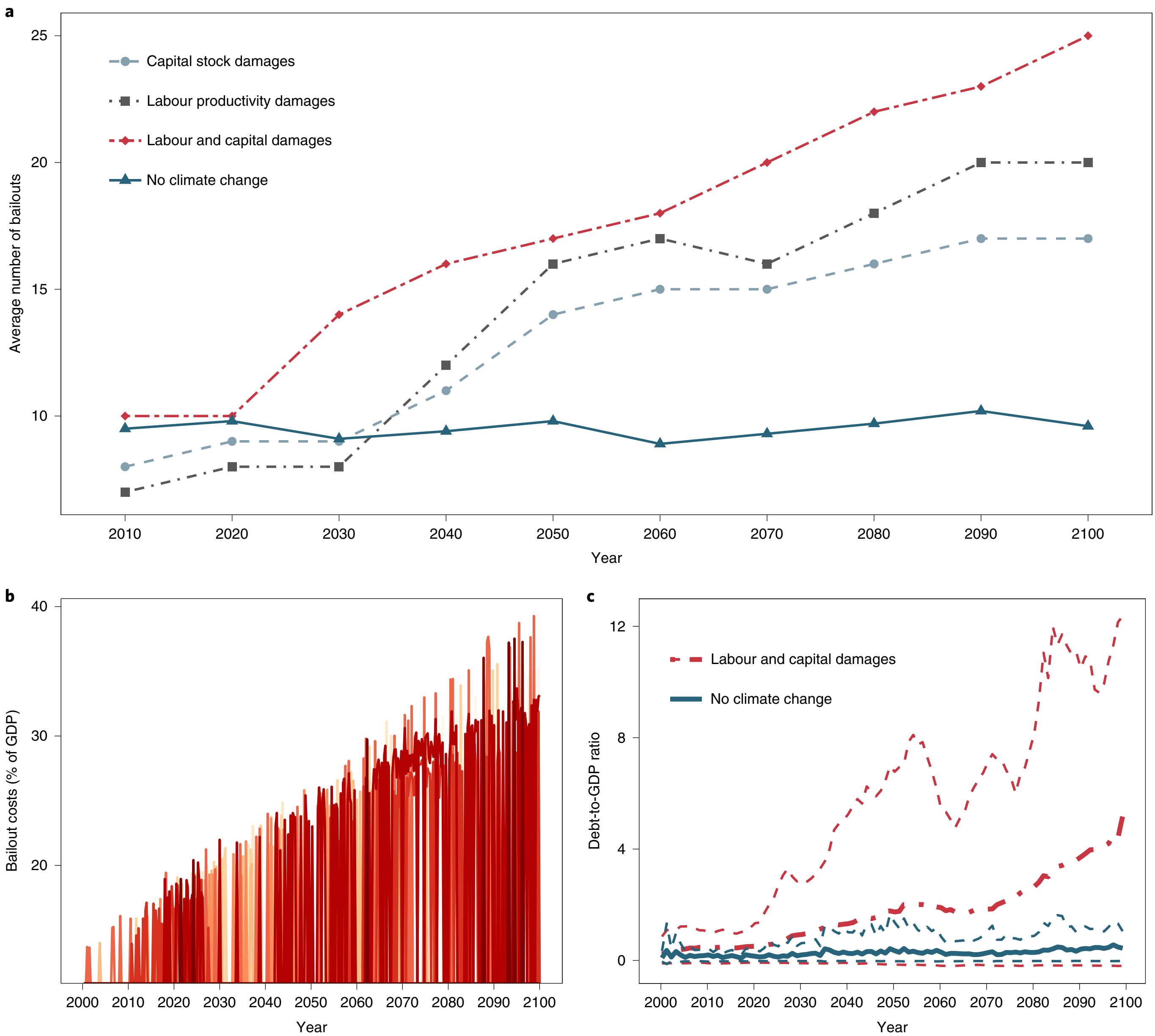

Fig. 1 | Climate-induced effects on the banking sector and public finances across scenarios. a, Average number of bailouts (10 yr averages; out of 500 simulations) in the three scenarios and in the baseline. **b**, Bailout costs as share of GDP in the labour and capital damages scenario; each line represents a model run. **c**, Public debt behaviour in the labour and capital damages scenario and in the no climate change scenario; values are yearly averages (out of 500 simulations); dashed lines are 90% CIs.

capital requirements can counterbalance eventual excessive or reluctant credit provision, accounting for the impacts of climate damages on firms' solvency[23,41]. A counter-cyclical capital buffer (as proposed in the Basel III framework[42]) could help address climate physical risks, even though it proves ineffective when damages surge (Supplementary Results A). Nonetheless, even if such macroprudential regulation is in place, the impact of climate change on financial crises remains dominant. This calls for a broader climate–finance policy mix fostering investments towards low-carbon projects.

The Supplementary Results provide a series of robustness tests. This battery of exercises confirms (1) the role of the banking system in amplifying damages, (2) the relevance of setting adequate capital requirements following both phases of the business cycle and (3) the inadequacy of contractionary fiscal policy in restoring financial stability.

The public costs of climate-induced banking instability are significant, corresponding to a yearly average of 30% of GDP in an SSP5 future (against 10.3% in the scenario with no climate change). Such a result should be tentatively compared with a historical average, which was doubtfully affected by climate change, of 3.5 financial crises per year at the global level, producing fiscal costs averaging 12% of the GDP of the affected country[8]. Although it is admittedly difficult to match model results with reality, the systematic comparison of our impact scenarios with the baseline configuration robustly shows that climate damages affecting the microeconomic behaviour of firms and workers cause a significant amount of additional non-performing loans, threatening solvency of financial institutions. This situation requires extraordinary support from the government to absorb losses.

While our results might overestimate bailout costs because of a baseline with relatively many crises, they also completely neglect

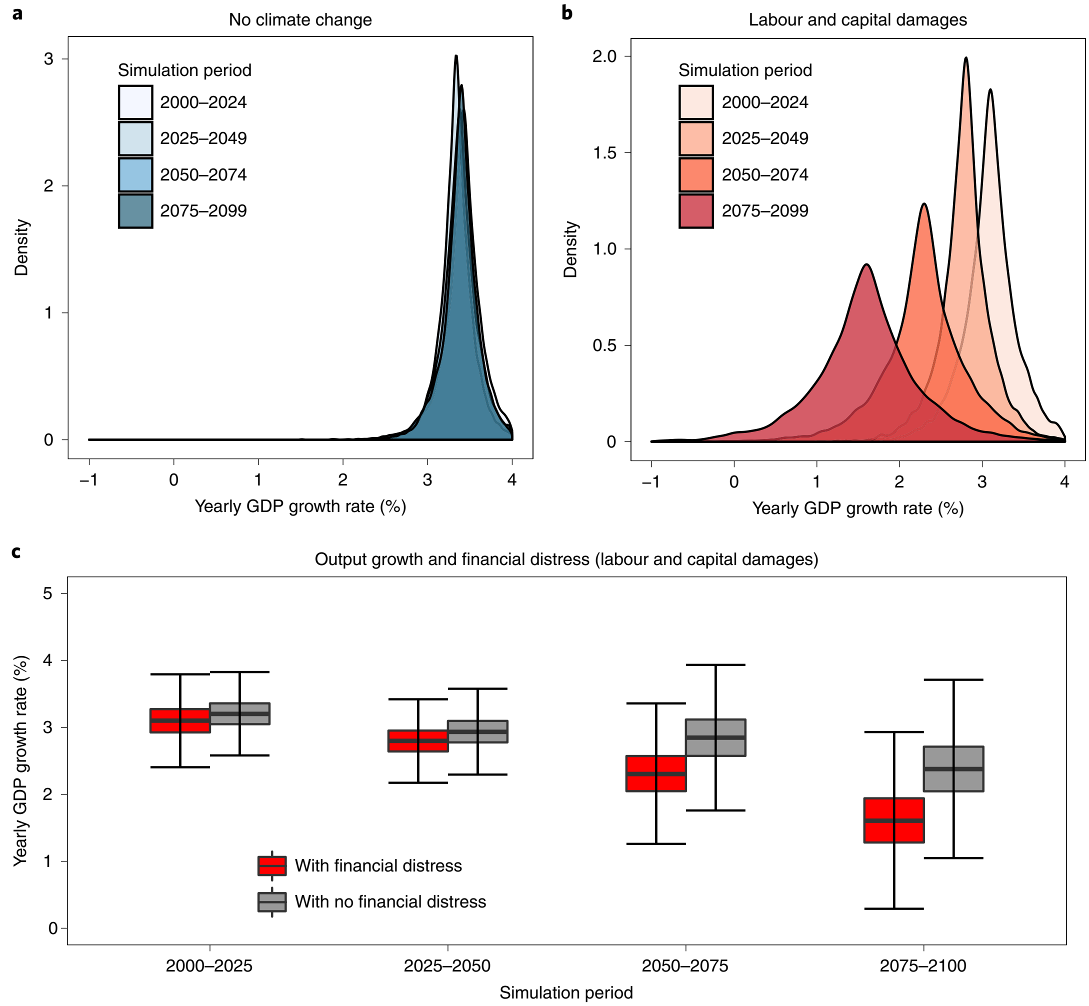

Fig. 2 | Global GDP growth and climate-induced instability. a,**b**, Kernel densities of yearly growth rates of global GDP pooled per 25 yr period in the baseline scenario with no climate change (**a**) and in the scenario with labour and capital damages (**b**). **c**, Box plots of yearly growth rates in the labour and capital damages scenario in the presence and absence of financial distress. Yearly growth rates are computed for each model run, clustered according to each 25-yr period; a Gaussian kernel density plot is than provided for each cluster. The box plots' whiskers contain 95% of the observations, boxes represent the Q1–Q3 interquartile range and solid lines indicate the medians. Each 25-yr period collects projections until the last quarter of its final year.

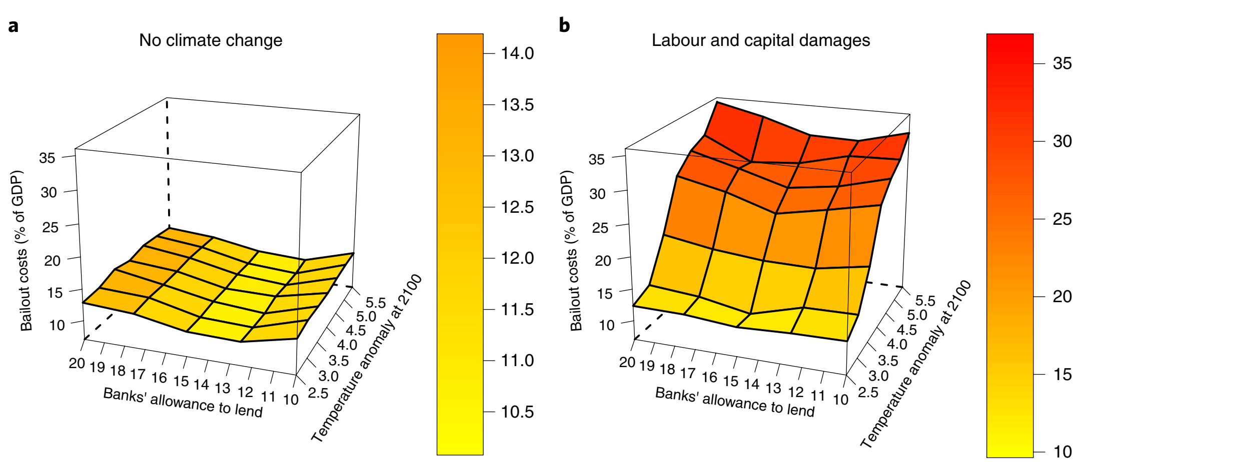

Fig. 3 | Public costs of climate-induced bank bailouts. a,**b**, Public costs of bank bailouts in the baseline scenario in the absence of climate change damages (**a**) and in the scenario with both labour and capital damages (**b**). To produce these figures, we let the parameter τ_{CAR} vary (Methods) to obtain a multiplier $1/\tau_{CAR}$ (banks' allowance to lend) as indicated in the figure. Then, we focused on parameters controlling for the growth rate of the economy (Supplementary Methods B). We constructed a parameter space using ±10% ranges around baseline values (Supplementary Methods D) and randomly sample such space 100 times. For each combination of parameter values, we performed a Monte Carlo exercise of 100 runs. Points in the graphs show the average yearly cost of bailout in the cluster of runs whose 2100 temperature anomaly falls in the represented interval.

(1) any secondary systemic effects of banks' equity deterioration, such that financial institutions exposed to troubled banks may suffer losses in the market value of their assets, potentially triggering contagion phenomena[43–45], and (2) firms' equity holding by banks. Another reason for the potential underestimation comes from the missing link between the energy industry and the banking system.

Our results suggest a central role for macroprudential policies in managing climate-induced financial risks, which might be integrated in a more comprehensive set of adaptation and mitigation interventions. The emerging evidence of a U-shaped relationship between costs of restructuring in the banking sector and its lending propensity suggests the existence of an optimal level of capital adequacy requirements, balancing the needs of fuelling investments and increasing resilience. The findings indicate that deviations from such policy exacerbate bailout costs as temperatures rise. In addition, we report evidence that climate damages reverberate to the financial system, inducing feedback loops that sharpen macroeconomic damages vis-à-vis a system in which allocation of capital is assumed to be frictionless. Thus, we suggest that integrated assessment models of climate change[46] should begin including a financial system and financial regulation authorities. Both direct and indirect effects (linked to contagion phenomena) on the financial system need to be considered, as well as regulations mitigating this potential vicious cycle.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information, details of author contributions and competing interests, and statements of data and code availability are available at https://doi.org/10.1038/s41558-019-0607-5.

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Methods

This paper makes use of a novel development of the Dystopian Schumpeter meeting Keynes (DSK) model[25] to evaluate the impacts of climate change on the financial system, intended as a stylized but realistic banking sector. The DSK model is an agent-based simulation laboratory representing a global economy and its relationship to changes in mean surface temperature. In particular, the model comprises heterogeneous and interacting firms devoted to the production of either capital or consumption goods and receiving inputs from an energy sector, a financial system and a variety of households. Firms compete to serve the demands of both capital and consumption goods; in the case of failure, a novel firm with average characteristics of the firm pool enters the relevant market. Anthropogenic emissions arise from production of goods and, especially, energy, while there is no formal representation of land use and transportation. Cumulative emissions are linked to temperature increases through a single equation model calibrated on recent estimates of the carbon–climate response[47]. Economic growth is driven by endogenous technical change, which ameliorates the set of technologies available to both firms and energy plants. The major modelling innovation this paper brings about is the inclusion of a financial system of multiple heterogeneous banks. The role of the banking sector has historically proved to be pivotal in modern economies, with both positive and negative effects. Primarily, banks collect deposits from households and provide credit to firms to fuel their investments, thus spurring economic growth. By contrast, when banks experience financial troubles incurring equity losses, they freeze funding opportunities for the real economy and slow productivity growth. In our model, we account for both these features through imperfect capital markets. The banking sector, based on ref. [48], encompasses B commercial banks that gather deposits from households/workers and provide credit to firms plus a single central bank running monetary policy and buying government bonds when necessary. Banks are heterogeneous in their number of clients, balance-sheet structure and lending conditions. Imperfect information prevents firms from screening all existing banks in search of optimal lending rates; the bank–firm network is assumed to be fixed, and it reflects the empirical distribution of bank size. The crucial decision for a financial institution concerns the amount of credit to provide to clients. We assume that the supply of credit is a multiple of a bank's net worth (equity):

$$\mathrm{TC}_b(t) = \frac{\mathrm{NW}_b(t-1)}{\tau_{\mathrm{CAR}}\left(1+\frac{\beta \mathrm{BD}_b(t-1)}{\mathrm{TA}_b(t-1)}\right)} \quad (1)$$

where TC is the total credit supplied by bank b at time t, NW denotes the value of the bank's equity and TA is the value of total assets. Credit supply is thus affected by changes in the banks' balance sheet, which is itself affected by bank profits net of loan losses. Furthermore, the policy parameter τ_{CAR} indicates capital adequacy requirements, while β is a behavioural parameter measuring banks' sensitivity to financial fragility of their balance sheet. These two parameters contribute to determining the lending ability of a bank to the real economy: on one side, capital adequacy requirements inspired by Basel-framework rules constrain banks' credit supply; on the other side, evidence indicates that banks maintain a buffer over the mandatory level of capital, whose magnitude is strategically altered over the business cycle according to their financial fragility[49,50], which is proxied by the ratio of bad debt (BD) to total assets of bank b. Indeed, the larger the stock of bad debt created by insolvent firms in a given period, the higher the financial fragility and the lower the amount of credit a bank will supply to the economy. This is the major link among climate change impacts, banking crises and macroeconomic dynamics: if climate damages lead firms to bankruptcy, the loss transmits to the financial system, in which banks exposed to defaulted firms suffer reductions in their equity value. Such an effect provides feedback to the real economy in terms of lower credit supply. If large enough, this effect might also threaten the solvency of banks. The fact that the amount of capital lent to firms shrinks during downturns and financial crises, eventually leading to credit crunches, is a well-established empirical regularity, and the recent financial crisis was not an exception[51–53]. However, other channels leading to financial instability might exist[23]. In our set-up, banks do not exchange assets (for example, overnight loans), and therefore, contagion effects due to interbank exposure are absent, potentially leading to an underestimation of the true societal costs of climate impacts to the financial sector. Crucially, to estimate the public cost of banks' instability, we assume that the government bails out insolvent banks, recapitalizing their equity in the period ahead and preventing the default. In particular, the government is providing fresh capital amounting to a fraction of the smallest incumbent equity, provided that it satisfies the Basel-type capital adequacy requirements (ratio of banks' equity to total loans larger than a given threshold, which equals 8% in our simulations). In such a context, heterogeneity is crucial, as banks with diverse capital structures are differentially vulnerable to (climate-induced) shocks and differentially affect the macroeconomy in case of failure[52], while also possibly triggering bankruptcy cascades. In this respect, our modelling choice allows for a genuine and realistic representation of heterogeneity and interactions among ecologies of individuals. Agent-based models have been increasingly advocated as adequate tools to study complex and intricate sets of relationships, especially in climate change economics[35,54,55], macroeconomics[36] and finance[56,57], where top-down aggregate modelling might hide effects that bottom-up approaches allow disentangling. The model is validated through stylized fact replication at both the microeconomic level (for example, firm size distribution, heterogeneity in productivity, lumpy investment behaviour) and the macroeconomic level (for example, persistent fluctuations in output, identification of cyclical, leading and lagging indicators, distribution of banking crises). A detailed description of the stylized facts replicated by the model is contained in Supplementary Methods C; the description of the model itself is available in Supplementary Methods B.

The model does not allow for analytical, closed-form solutions. This stems from the nonlinearities that characterize agents' decision rules and their interaction patterns and forces us to run computer simulations to analyse the properties of the stochastic processes governing the co-evolution of micro- and macrovariables[36]. Fagiolo and Roventini[36] provide an overview of agent-based macroeconomic models and their technical details. In what follows, we therefore perform Monte Carlo analyses to remove across-simulation variability and present results as averages over 500 model runs, as standard in the literature.

The DSK model is calibrated on a coupled SSP5–Representative Concentration Pathway (RCP) 8.5 scenario[58] characterized by high growth[59], sustained energy demand[27] and soaring emissions concentrations until the end of the century[60]. The choice of such a scenario is justified for two reasons. First, we wanted to isolate the effects of climate-induced financial instability in a context of strong climate change and substantial damages, in a way to evaluate the aggregate effects of mechanisms (default chains) that might be opaque under milder conditions. Second, we deliberately target a worst-case scenario with the aim to characterize the financial costs of inaction, thus providing a first estimate of the public costs of banking fragility associated with climate change under business as usual. The economy–climate linkage is voluntarily simple and makes use of the well-documented approximately linear relationship translating cumulative emissions in temperature increases[61,62], with the preferred specification assuming global mean surface temperature to rise 1.8 °C for each emitted 1,000 GtC (ref. [47]). We model economic losses due to changes in the temperature at the level of firms, which might suffer damages to either their labour or capital production factors.[6] In particular, the across-firms average shock due to climate change follows the quadratic damage function employed in the Dynamic Integrated Climate–Economy (DICE) 2016R model[7]:

$$\Omega(t) = 1 - \frac{1}{1 + c_1 T(t) + c_2 T(t)^2} \quad (2)$$

where Ω indicates damages, T indicates the mean surface temperature anomaly, $c_1 = 0$ and $c_2 = 0.0022$. Such a configuration implies a loss of 0.236% °C^{-2} and leads to damages of 2.1% at +3 °C and 8.5% at +6 °C. To put these numbers into perspective, during the Great Recession (2007–2013), most developed countries experienced average losses in output of 2.66% yr^{-1}, a loss of capital intensity of 0.40% yr^{-1} and a loss in productivity of 1.30% yr^{-1} (ref. [63]). Using an oversimplification, for the average firm, imposing a 2% damage in a given period is vaguely similar to experiencing 1 yr of the recent crisis. The relevant difference with respect to the standard use of such functions[64,65], is that we do not assume that $\Omega(t)$ affects the global level of output (GDP). Instead, employing a model with multiple agents rather than an aggregate economic sector, we consider microeconomic damages ($D_i(t) = \Omega(t) + \varepsilon_i$ where ε_i are independent and identically distributed Gaussian random variables with zero mean and 0.01 standard deviation) hitting each firm. For example, in a scenario where climate change just affects capital stocks[6], each firm suffers an average reduction of its capital endowments amounting to 0.22% for a 1 °C increase in the temperature with respect to pre-industrial levels. The term ε_i captures the fact that different firms (for example, at different locations) tend to suffer a different damage[13,34].

Then we design three impact scenarios: (1) climate damages target the productivity of labour, (2) climate damages target the availability of physical capital and (3) climate damages target both labour productivity and capital stock, with the relative impact weighted according to global labour and capital shares of GDP[6]. By contrast, the baseline configuration of the model runs in absence of climate change and, thus, climate damages. The only difference between the baseline and the three impact scenarios is the presence of climate change (Supplementary Methods C). In addition, to isolate the effect of climate-induced financial distress on the real economy, we run a counter-factual numerical experiment (Fig. 2c) in which we assume that the government exchanges the non-performing loans due to firms' bankruptcies with liquidity to impede deterioration of banks' net worth (equities). In particular, in the experiment without financial distress, the government provides liquidity for an amount equivalent to the non-performing loan.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The simulation data that support the findings of this study are available from the corresponding author on request.

Code availability

The code that supports the findings of this study is available from the corresponding author on request.

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Author contributions

All authors contributed equally to the project planning, design of the simulation experiments, analysis of the results and writing of the paper. F.L. also developed the code and ran the simulations.

Competing interests

The authors declare no competing interests.

Additional information

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Data collection	No software was used to collect data. Model simulations are used to produce simulation data. Model is described in details in Lamperti et al (2018a) and in the Supplementary Information of the present study. Model does not need any proprietary software to run.
Data analysis	We used the R software environment version 3.5.0 (2018-04-23) to analyse model simulation data.

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