Climate change, financial stability and monetary policy

1. Introduction

Climate change is likely to have severe effects on the stability of the financial system (see, for instance, Aglietta and Espagne, 2016; Batten et al., 2016; Scott et al., 2017). Two broad climate-related financial risks have been identified: (a) the *transition risks* that have to do with the re-pricing of carbon-intensive assets as a result of the transition to a low-carbon economy; and (b) the *physical risks* that are linked to the economic damages of climate-related events. So far, most studies have concentrated on the implications of transition risks (see e.g. Carbon Tracker Initiative, 2011; Johnson, 2012; Plantinga and Scholtens, 2016; Battiston et al., 2017). Less attention has been paid to the detailed analysis of physical risks, which have only partially been analysed in macro models by Dietz et al. (2016), Dafermos et al. (2017) and Bovari et al. (2018). The investigation of the physical risks is particularly important: it would help us understand how the financial system could be impaired if the transition to a low-carbon economy is very slow in the next decades and, consequently, severe global warming is not ultimately avoided.

In this paper, we develop an ecological macroeconomic model that sheds light on the physical effects of climate change on financial stability. This is called the DEFINE (Dynamic Ecosystem-FINance-Economy) model, which builds on the stock-flow-fund model of Dafermos et al. (2017). The latter relies on a novel synthesis of the stock-flow consistent (SFC) approach of Godley and Lavoie (2007) with the flow-fund model of Georgescu-Roegen (1971, ch. 9; 1979; 1984).[1] The model is calibrated and estimated using global data and simulations are presented, which illustrate the effects of climate change on the financial system. We pay attention to the following key channels. First, the increase in temperature and the economic catastrophes caused by climate change could reduce the profitability of firms and could deteriorate their financial position. Accordingly, debt defaults could arise, which would lead to systemic bank losses. Second, lower firm profitability combined with global warming-related damages can affect the confidence of investors, inducing a rise in liquidity preference and a fire sale of the financial assets issued by the corporate sector.

[1] See the model's website: www.define-model.org.

Dietz et al. (2016) have recently investigated quantitatively the physical impact of climate change on the financial system. They use a standard integrated assessment model (IAM) and the climate value at risk (VAR) framework. Assuming that climate change can reduce the dividend payments of firms and, hence, the price of financial assets, they provide various estimates about the climate-induced loss in the value of financial assets. Our study moves beyond their analysis in three different ways. First, by relying on the stock-flow consistent approach, we portray explicitly the balance sheets and the financial flows in the financial sector. This allows us to model the climate-induced fragility that can be caused in the financial structures of firms and banks, a feature which is absent in Dietz et al. (2016). Second, we utilise a multiple financial asset portfolio choice framework, which permits an explicit analysis of the climate-induced effects on the demand of financial assets in a world of fundamental uncertainty. This allows us to capture the implications of a fire sale of certain financial assets. These implications are not explicitly considered in the model of Dietz et al. (2016) where climate damages do not have diversified effects on different financial assets. Third, the financial system in our model has a non-neutral impact on economic activity: credit availability and the price of financial assets affect economic growth and employment. Accordingly, the interactions between economic performance and financial (in)stability are explicitly taken into account. This is crucial since the feedback economic effects of bank losses and asset price deflation can exacerbate climate-induced financial instability (see Batten et al., 2016). On the contrary, Dietz et al. (2016) utilise a neoclassical growth framework where long-run growth is independent of the financial structure of firms and banks. This leaves little room for the analysis of the macroeconomic implications of climate-induced financial problems.

Our methodological approach shares more similarities with Bovari et al. (2018) who have investigated how climate change can affect the indebtedness of firms, using an SFC model. However, their model abstracts from asset prices and assumes a passive banking system without explicit credit rationing. The latter implies that the feedback effects of climate-inducing banking instability on the macroeconomy cannot be explicitly explored, as is the case in the current model.

Our simulation results illustrate that in a business as usual scenario climate change is likely to have important adverse effects on the default of firms, the leverage of banks and the price of financial assets. These effects become more severe after global warming passes the 2^{o}C threshold.

Importantly, climate-induced financial instability reinforces the adverse effects of climate change on economic activity.

An additional contribution of this paper is that it examines how monetary policy could reduce the risks imposed on the financial system by climate change. Drawing on the recent discussions about the potential use of monetary policy in tackling climate change (see e.g. Murphy and Hines, 2010; Werner, 2012; Rozenberg et al., 2013; Anderson, 2015; Barkawi and Monnin, 2015; Campiglio, 2016; Matikainen et al., 2017; UN Environment Inquiry, 2017; Monasterolo and Raberto, 2018), we examine the extent to which a global green quantitative easing (QE) programme could ameliorate the financial distress caused by climate change. This programme involves the purchase of green corporate bonds. Our simulations about the effects of a green QE programme are of growing relevance since in a world of climate change central banks might not be able to safeguard financial stability without using new unconventional tools in a prudential manner.

The paper's outline is as follows. Section 2 presents the structure of the model and the key equations that capture the links between climate change, financial stability and monetary policy. Section 3 describes the calibration, estimation and validation of the model. Section 4 analyses our simulations about the effects of climate change on the financial system. Section 5 focuses on the impact of a green QE programme. Section 6 concludes.

2. The model

The DEFINE model (version 1.0) consists of two big blocks: (i) the 'ecosystem' block that encapsulates the carbon cycle, the interaction between temperature and carbon, the flows/stocks of energy and matter and the evolution of ecological efficiency indicators; (ii) the 'macroeconomy and financial system' block that includes the financial transactions, the balance sheet structure and the behaviour of households, firms, banks, central banks and the government sector. The technical description of the model and the data that has been used for its calibration and estimation can be found in the Online Appendix.

It is assumed that there is one type of material good that can be used for durable consumption and (conventional and green) investment purposes. Four matter/energy transformation processes are necessary for the production of this good and all of them require capital and labour. First, matter (non-metallic minerals and metal ores) has to be extracted from the ground and has to be transformed into a form that can be used as an input in the production. Second, useful energy has to be generated based on non-renewable sources (e.g. oil, gas and coal) or renewable sources (e.g. sun, wind). Third, recycling has to take place. Every year a part of the capital stock and the durable consumption goods that have been accumulated in the socio-economic system are demolished/discarded; the material content of these accumulated capital goods and durable consumption goods is called socio-economic stock.[2] A proportion of this demolished/discarded socio-economic stock is recycled and is used as an inflow in the production of the final good. This means that not all of the matter that is necessary for the production of the good has to be extracted from the ground. Fourth, the final good needs to be produced using material and energy inflows from the other processes.

Crucially, all these four processes, in combination with the functioning of the whole socio-economic system, generate by-products. In particular, industrial CO_2 emissions are produced as a result of the combustion of fossil fuels. Energy is dissipated in all transformation processes; this energy cannot be used again. In addition, the demolished/discarded socio-economic stock that is not recycled becomes waste. Part of this waste is hazardous and can have adverse effects on the health of the population.

Since the model focuses on the aggregate effects of production, all the above-mentioned processes have been consolidated and are presented as part of the total production process. An unconsolidated formulation of the production process would make the model and its calibration much more complicated without changing the substance of the analysis that we pursue here. However, such an unconsolidated version would be useful for the analysis of intra-firm dynamics and could be the subject of future extensions of the model.

[2] This is a term used in material flow analysis (see e.g. Krausmann et al., 2015). In general, socio-economic stock also includes animal livestock and humans. However, these stocks (whose mass remains relatively stable over time) are not included in our analysis. As will be explained below, socio-economic stock is measured in Gigatonnes.

Although capital, labour, energy and matter are all necessary in the transformation processes, these resources do not directly determine the level of production as long as they are not scarce: in the absence of scarcity, the level of production is demand-determined, in line with the post-Keynesian tradition. However, if any of these resources is not sufficient to satisfy the demand, production is directly affected by resource scarcity. In particular, we assume that, under supply-side constraints, consumption and investment demand might decline. Moreover, although all these resources are necessary for the production of goods based on our Leontief-type production function (i.e. there is imperfect substitutability), their relative use changes because of technological progress.

The way that carbon emissions affect climate change follows closely Nordhaus (2016). In particular, CO_2 emissions lead to an increase in atmospheric CO_2 concentration. The evolution of CO_2 concentration is affected by the carbon cycle that captures the exchange of carbon between the atmosphere and the upper ocean/biosphere and between the upper ocean/biosphere and the lower ocean. The accumulation of atmospheric CO_2 and other greenhouse gases increases radiative forcing. This increase places upward pressures on atmospheric temperature.

A crucial distinction is made between green capital and conventional capital. Compared to conventional capital, green capital is characterised by lower energy intensity, lower material intensity and higher recycling rate. Moreover, green capital produces energy using renewable sources, while conventional capital produces energy using the non-renewable sources. Hence, the use of green capital is conducive to a low-carbon economy.[3] As the proportion of green capital to conventional capital increases, the goods consumed by households are produced in a more environmentally friendly way. However, we do not make a distinction between conventional and green consumption goods. This means that households' environmental preferences do not have a direct impact on the decisions of firms about green and conventional investment.

[3] A more realistic formulation would be to assume different 'shades of green' depending on the number of 'green' properties that each capital has. In that case, the 'greenest' capital would be that capital that can generate renewable energy and is endowed by lower energy intensity, lower material intensity and higher recycling rate compared to conventional capital. On the other hand, the least 'green' capital would be the capital that has only one of these properties. However, such a formulation would complicate the model significantly since it would require the distinction between many types of green investment and would make the calibration of the model a much more challenging exercise.

Firms invest in conventional and green capital by using retained profits, loans and bonds. Commercial banks accumulate capital and distribute part of their profits to households. They impose credit rationing on firm loans. This means that they play an active role in the determination of output and the accumulation of green capital. Households receive labour income, buy durable consumption goods and accumulate wealth in the form of deposits, corporate bonds and government securities (there are no household loans). Corporate bonds can be either green or conventional. When the demand for green bonds increases, the price of these bonds tends to go up, leading to a lower cost of borrowing for green projects.

Therefore, we overall have that a higher willingness of banks to provide credit for green projects and a higher demand for green bonds by households boosts innovative green investment. At the same time, higher green investment can reduce the physical risks for the financial system, as will be explained in detail below. This implies that our model allows us to investigate the finance-green innovation nexus. However, there are various aspects of the finance-green innovation nexus that are not analysed in this paper. In particular, the financing of green investment can lead to fundamental changes in the way that the production system uses energy and matter, causing a shift to a new techno-economic paradigm. As has been emphasised in the neo-Schumpeterian/evolutionary literature (see e.g. Perez, 2009, 2010), a shift to a new techno-economic paradigm might entail transition risks, can cause financial booms and busts and can lead to fundamental socio-economic changes. The detailed investigation of these aspects of the transition to a more ecologically efficient economy can be the subject of future applications and extensions of the model.[4]

Central banks play a key role in our model. They determine the base interest rate, provide liquidity to the commercial banks and purchase government securities and corporate bonds. When they buy green corporate bonds as part of a green QE programme, they place downward pressures on the green bond yields, and this has positive effects on the cost of borrowing for green projects. Governments collect taxes, decide about the level of government expenditures and can implement bailout programmes if there are financial problems in the banking sector.

[4] For a stock-flow consistent model that has analysed the interlinkages between technological change, finance and the real economy, drawing on the literature on techno-economic paradigms, see Caiani et al. (2014).

Inflation has been assumed away and, for simplicity, the price of goods is equal to unity. We use US dollar ($) as a reference currency. The model has an annual time step.

The skeleton of the model is captured by four matrices. The first matrix is the physical flow matrix (Table 1), which portrays the inflows and the outflows of matter and energy that take place as a result of the production process. The First Law of Thermodynamics implies that energy and matter cannot be created or destroyed. This is reflected in the material and energy balance. The second matrix is the physical stock-flow matrix (Table 2), which presents the dynamic change in material and non-renewable energy reserves, the atmospheric CO_2 concentration, the socio-economic stock and the stock of hazardous waste. The first row of the matrix shows the stocks of the previous year. The last row presents the stocks at the end of the current year. Additions to stocks are denoted by a plus sign. Reductions of stocks are denoted by a minus sign. The third matrix is the transactions flow matrix (Table 3), which shows the transactions that take place between the various sectors of the economy. Inflows are denoted by a plus sign and outflows are denoted by a minus sign. The last matrix is the balance sheet matrix (Table 4) which includes the assets and the liabilities of the sectors. We use a plus sign for assets and a minus sign for liabilities.

Table 1: Physical flow matrix

	Material balance	Energy balance
Inputs		
Extracted matter	$+M$	
Renewable energy		$+ER$
Non-renewable energy	$+CEN$	$+EN$
Oxygen used for fossil fuel combustion	$+O2$	
Outputs		
Industrial CO_2 emissions	$-EMIS_{IN}$	
Waste	$-W$	
Dissipated energy		$-ED$
Change in socio-economic stock	$-\Delta SES$	
Total	0	0

Note: The table refers to annual global flows. Matter is measured in Gt and energy is measured in EJ. A detailed description of the symbols can be found in the Online Appendix.

Table 2: Physical stock-flow matrix

	Material reserves	Non-renewable energy reserves	Atmospheric CO_2 concentration	Socio-economic stock	Hazardous waste
Opening stock	REV_{M-1}	REV_{E-1}	$CO2_{AT-1}$	SES_{-1}	HWS_{-1}
Additions to stock					
Resources converted into reserves	$+CON_M$	$+CON_E$			
CO_2 emissions			$+EMIS$		
Production of material goods				$+MY$	
Non-recycled hazardous waste					$+hazW$
Reductions of stock					
Extraction/use of matter or energy	$-M$	$-EN$			
Net transfer of CO_2 to oceans/biosphere			$+(\phi_{11}-1)CO2_{AT-1}+\phi_{21}CO2_{UP-1}$		
Demolished/disposed socio-economic stock				$-DEM$	
Closing stock	REV_M	REV_E	$CO2_{AT}$	SES	HWS

Note: The table refers to annual global stocks and flows. Matter is measured in Gt and energy is measured in EJ. A detailed description of the symbols can be found in the Online Appendix.

Table 3: Transactions flow matrix

	Households		Firms		Commercial banks		Government sector	Central banks		Total
	Current	Capital	Current	Capital	Current	Capital		Current	Capital	
Consumption		$-C$	$+C$							0
Government expenditures			$+G$				$-G$			0
Conventional investment			$+I_C$	$-I_C$						0
Green investment			$+I_G$	$-I_G$						0
Household disposable income net of depreciation	$-Y_{HD}$	$+Y_{HD}$								0
Wages	$+wN$		$-wN$							0
Taxes	$-T_H$		$-T_F$				$+T$			0
Firms' profits	$+DP$		$-TP$	$+RP$						0
Commercial banks' profits	$+BP_D$				$-BP$	$+BP_U$				0
Interest on deposits	$+int_D D_{-1}$				$-int_D D_{-1}$					0
Depreciation of green capital			$-\delta K_{G-1}$	$+\delta K_{G-1}$						0
Depreciation of conventional capital			$-\delta K_{C-1}$	$+\delta K_{C-1}$						0
Interest on conventional loans			$-int_C L_{C-1}$		$+int_C L_{C-1}$					0
Interest on green loans			$-int_G L_{G-1}$		$+int_G L_{G-1}$					0
Interest on conventional bonds	$+coupon_C b_{CH-1}$		$-coupon_C b_{C-1}$					$+coupon_C b_{CCB-1}$		0
Interest on green bonds	$+coupon_G b_{GH-1}$		$-coupon_G b_{G-1}$					$+coupon_G b_{GCB-1}$		0
Interest on government securities	$+int_S SEC_{H-1}$				$+int_S SEC_{B-1}$		$-int_S SEC_{-1}$	$+int_S SEC_{CB-1}$		0
Interest on advances					$-int_A A_{-1}$			$+int_A A_{-1}$		0
Depreciation of durable consumption goods	$-\xi DC_{-1}$	$+\xi DC_{-1}$								0
Central bank's profits							$+CBP$	$-CBP$		0
Bailout of banks						$+BAILOUT$	$-BAILOUT$			0
Δdeposits		$-\Delta D$				$+\Delta D$				0
Δconventional loans				$+\Delta L_C$		$-\Delta L_C$				0
Δgreen loans				$+\Delta L_G$		$-\Delta L_G$				0
Δconventional bonds		$-\bar{p}_C \Delta b_{CH}$		$+\bar{p}_C \Delta b_C$					$-\bar{p}_C \Delta b_{CCB}$	0
Δgreen bonds		$-\bar{p}_G \Delta b_{GH}$		$+\bar{p}_G \Delta b_G$					$-\bar{p}_G \Delta b_{GCB}$	0
Δgovernment securities		$-\Delta SEC_H$				$-\Delta SEC_B$	$+\Delta SEC$		$-\Delta SEC_{CB}$	0
Δadvances						$+\Delta A$			$-\Delta A$	0
Δhigh-powered money						$-\Delta HPM$			$+\Delta HPM$	0
Defaulted loans				$+DL$		$-DL$				0
Total	0	0	0	0	0	0	0	0	0	0

Note: The table refers to annual global flows in trillion US$. A detailed description of the symbols can be found in the Online Appendix.

Table 4: Balance sheet matrix

	Households	Firms	Commercial banks	Government sector	Central banks	Total
Conventional capital		$+K_C$				$+K_C$
Green capital		$+K_G$				$+K_G$
Durable consumption goods	$+DC$					$+DC$
Deposits	$+D$		$-D$			0
Conventional loans		$-L_C$	$+L_C$			0
Green loans		$-L_G$	$+L_G$			0
Conventional bonds	$+\bar{p}_C b_{CH}$	$+\bar{p}_C b_C$			$+\bar{p}_C b_{CCB}$	0
Green bonds	$+\bar{p}_G b_{GH}$	$+\bar{p}_G b_G$			$+\bar{p}_G b_{GCB}$	0
Government securities	$+SEC_H$		$+SEC_B$	$-SEC$	$+SEC_{CB}$	0
High-powered money			$+HPM$		$-HPM$	0
Advances			$-A$		$+A$	0
Total (net worth)	$+V_H$	$+V_F$	$+K_B$	$-SEC$	$+V_{CB}$	$+K_C+K_G+DC$

Note: The table refers to annual global stocks in trillion US$. A detailed description of the symbols can be found in the Online Appendix.

The model extends the model developed by Dafermos et al. (2017) by including a bond market, central banking, the government sector, household portfolio choice and an endogenous rate of default for firms. In what follows we present the equations of the model that are more relevant for the interactions between climate change, financial stability and monetary policy. A detailed description of the equations of the model can be found in the Online Appendix.

2.1. Green capital, energy intensity and renewable energy

Green capital allows firms to produce the same output with less energy. This is captured by the following logistic function:

$$\varepsilon = \varepsilon^{max} - \frac{\varepsilon^{max} - \varepsilon^{min}}{1 + \pi_5 e^{-\pi_6 (K_{G-1}/K_{C-1})}} \tag{1}$$

where ε is energy intensity, π_5 and π_6 are positive parameters and ε^{max} and ε^{min} are, respectively, the maximum and the minimum potential values of energy intensity. As the ratio of green capital (K_G) to conventional capital (K_C) increases, energy intensity goes down. The use of the logistic function implies that the installation of green capital (relative to conventional capital) initially generates a slow improvement in energy intensity. However, as installation expands further, the improvement reaches a take-off point after which energy intensity improves much more rapidly, due to the learning obtained from installation experience and the overall expansion of green capital infrastructure that has positive network effects. Finally, as energy intensity approaches its potential minimum, improvement starts to slow.

A similar logistic function is used for the effects of green capital accumulation on the share of renewable energy in total energy produced (θ):

$$\theta = \frac{1}{1+\pi_7 e^{-\pi_8 (K_{G-1}/K_{C-1})}} \tag{2}$$

where π_7 and π_8 are positive parameters. By definition, the maximum potential value of θ is 1. Note that in Dafermos et al. (2017) the formulation of the links between green capital and ecological efficiency indicators is quite different since it does not rely on logistic functions. The use of logistic functions in the present model allows for a more realistic representation that takes into account the processes of learning-by-doing and learning-by-installing, which play a key role in the diffusion of new technologies.[5] It also allows us to derive patterns about the future trajectories of energy intensity and renewable energy that are similar with those of other related studies (see, for instance, Jones and Warner, 2016; Peters et al., 2017).

2.2. Output determination and damages

Eq. (13) shows our Leontief-type production function:

$$Y^* = min(Y_M^*, Y_E^*, Y_K^*, Y_N^*) \tag{3}$$

where Y^* is the potential output. The potential output is the minimum of (i) the matter-determined potential output (Y_M^*) which depends on material reserves, (ii) the energy-determined potential output (Y_E^*) which is a function of non-renewable energy reserves, (iii) the capital-determined potential output (Y_K^*) that relies on capital stock and capital productivity, and (iv) the labour-determined potential output (Y_N^*) which depends on labour force and labour productivity.

The actual output (Y) is demand-determined. Aggregate demand is equal to consumption expenditures (C) plus investment expenditures (I) plus government expenditures (G):

[5] For the importance of these processes in energy systems and renewable energy technologies, see e.g. Kahouli-Brahmi (2009) and Tang and Popp (2016).

$$Y = C + I + G \tag{4}$$

However, demand is not independent of supply. When Y approaches Y^*, demand tends to decline due to supply-side constraints (this is achieved via our investment and consumption functions described below).

Output determination is affected by climate change as follows: global warming causes damages to capital stock and capital productivity, decreasing Y_K^*; it also causes damages to labour force and labour productivity, reducing Y_N^*.[6] These damages affect output in two ways. First, by experiencing or observing these damages, households and firms become more pessimistic about their future economic position. In particular, climate damages might increase the fears of entrepreneurs that their capital will be destroyed and that their profitability will be reduced. Moreover, natural disasters and health problems might induce households to save more for precautionary reasons.[7] Therefore, consumption and investment demand are lower compared to what would be the case without damages. As a result, aggregate demand goes down when damages increase.[8] Second, the climate-induced reduction in Y_K^* and Y_N^* leads to a lower Y^*. If aggregate demand is far below Y^*, this second channel does not have a direct impact on output produced. However, when Y becomes sufficiently close to Y^*, investment and consumption decrease even more due to the climate damages, so as to be in line with the supply constraints.

Eq. (5) is the damage function, which shows how atmospheric temperature (T_{AT}) and damages are linked:

$$D_T = 1 - \frac{1}{1 + \eta_1 T_{AT} + \eta_2 T_{AT}{}^2 + \eta_3 T_{AT}{}^{6.754}} \tag{5}$$

[6] For a discussion of these damages, see the Online Appendix and the references therein.
[7] For some empirical evidence about the impact of natural disasters on the saving behaviour of households, see Skidmore (2001).
[8] We assume that the expectations of households and firms about climate change damages are adaptive. Hence, their consumption and investment decisions are determined based on the damages of the previous year.

D_T is the proportional damage which lies between 0 (no damage) and 1 (complete catastrophe). Eq. (5) has been proposed by Weitzman (2012); $\eta_1, \eta_2, \eta_3 \geq 0$.[9] The variable D_T enters into the equations that determine capital stock, labour force, capital productivity and labour productivity, affecting thereby potential output. It also enters into the consumption and investment demand functions. Drawing on de Bruin et al. (2009), a distinction is made between gross damages and net damages. Gross damages are the initial climate changes without adaptation measures, while net damages are the damages after the implementation of adaptation measures.[10] We assume that capital, labour and their productivities are affected by net damages. However, households and firms form expectations based on gross damages. We interpret Eq. (5) as a gross damage function.

2.3. The financing of investment

Firms' investment is formalised as a two-stage process. At a first stage, firms decide their overall desired investment in both green and conventional capital (I^D). At a second stage, they allocate their desired investment between the two types of capital. Eq. (6) captures the first stage:

$$I^D = \left(\alpha \left(\overset{+}{u}_{-1}, \overset{+}{r}_{-1}, \overset{-}{ur}_{-1}, \overset{-}{ue}_{-1}, \overset{-}{um}_{-1} \right) K_{-1} + \varepsilon_I K_{-1} + \delta K_{-1} \right) \left(1 - D_{T-1}\right) \tag{6}$$

where K is the capital stock and δ is the depreciation rate. Net investment is affected by a number of factors. First, following the Kaleckian approach (see e.g. Blecker, 2002), it depends positively on the rate of (retained) profits (r) and the rate of capacity utilisation (u). The impact of these factors is assumed to be non-linear in general line with the tradition that draws on Kaldor (1940). This means that when the profit rate and capacity utilisation are very low or very high, their effects on investment become rather small.

Second, following Skott and Zipperer (2012), we assume a non-linear impact of the unemployment rate (ur) on investment: when unemployment approaches zero, there is a scarcity of labour that discourages entrepreneurs to invest. This employment effect captures Marx's and Kalecki's insights, according to which a high employment rate environment strengthens the power of workers, having an adverse impact on the business climate. Theoretically, this negative effect of employment could be put into question in the presence of immigration and labour-

[9] Our damage function captures the aggregate effects of climate change. For a damage function that considers explicitly the heterogeneity of climate shocks across agents, see Lamperti et al. (2017).

[10] In our definition net damages do not include the financial cost of adaptation.

augmenting investment. In the presence of immigration, entrepreneurs can expect that the flow of immigrants will relax the labour shortage constraint. Thus, investment might not decline when employment approaches the full employment level. However, this does not apply in our model, since we analyse the global economy and, thus, there is no immigration effect. Regarding labour-augmenting investment, it could be argued that when entrepreneurs observe an unemployment rate close to zero, they could relax the labour shortage constraint by increasing investment that enhances labour productivity. However, the adverse impact of climate change on labour productivity, that takes place in our model, makes it more difficult for the entrepreneurs to expect that more investment in labour-augmenting technologies would relax the labour shortage constraint. Therefore, in the presence of climate change, it is less likely that firms will try to invest more in order to increase productivity and reduce the employment rate.[11]

Third, the scarcity of energy and material resources can dampen investment, for example because of a rise in resource prices; ue and um capture the utilisation of energy and material resources respectively. This impact, however, is highly non-linear: energy and material scarcity affects investment only once the depletion of the resources has become very severe.

Forth, in order to capture exogenous random factors that might affect desired investment, we have assumed that I^D also depends on a random component, ε_I, that follows a stochastic AR(1) process. Overall, our investment function implies that demand declines (or stops increasing) when it approaches potential output. This allows us to take explicit into account the environmental supply-side effects on aggregate demand mentioned above.

Eqs. (7) and (8) refer to the second stage of firms' investment process:

$$I_G^D = \beta I^D \tag{7}$$

$$I_C^D = I^D - I_G^D \tag{8}$$

where β is the share of green investment (I_G^D) in overall desired investment (Eq. 7). Desired conventional investment (I_C^D) is determined as a residual (Eq. 8).

The share of green investment is determined as follows:

[11] Note, though, that our model takes into account the general role of labour-augmenting technologies by using the Kaldor-Verdoorn law in the determination of labour productivity.

$$\beta = \beta_0 + \beta_1 - \beta_2 \left[sh_{L-1} \left(int_G - int_C \right) + \left(1 - sh_{L-1} \right) \left(yield_{G-1} - yield_{C-1} \right) \right] \quad (9)$$

where int_C is the interest rate on conventional loans, int_G is the interest rate on green loans, $yield_C$ is the yield on conventional bonds, $yield_G$ is the yield on green bonds and sh_L is the share of loans in the total liabilities of firms (loans plus bonds).

Eq. (9) suggests that the share of green investment is affected by two factors. The first factor, captured by the term $\beta_0 + \beta_1$, exogenous developments, such as the cost of installing and using green capital relative to conventional capital or institutional/policy changes that promote green investment (such as carbon pricing).[12] The second factor, captured by the term $\beta_2 \left[sh_{L-1} \left(int_G - int_C \right) + \left(1 - sh_{L-1} \right) \left(yield_{G-1} - yield_{C-1} \right) \right]$, reflects the borrowing cost of investing in green capital relative to conventional capital. As the cost of borrowing of green capital (via bank lending or bonds) declines compared to conventional capital, firms tend to increase green investment.

As mentioned above, retained profits are not in general sufficient to cover the desired investment expenditures. This means that firms need external finance, which is obtained via bonds and bank loans. It is assumed that firms first issue bonds and then demand new loans from banks in order to cover the rest amount of their desired expenditures. Only a proportion of the demanded new loans is provided. In other words, the model assumes that there is a quantity rationing of credit. This is in line with recent empirical evidence that shows that the quantity rationing of credit is a more important driver of macroeconomic activity than the price rationing of credit (see Jakab and Kumhof, 2015).

For simplicity, the bonds issued by firms are assumed to be one-year coupon bonds.[13] Once they have been issued at their par value, their market price and yield is determined according to their demand. Firms set the coupon rate of bonds based on their yield in the previous year. This means that an increase in the market price of bonds compared to their par value causes an increase in their yield, allowing firms to issue new bonds with a lower coupon rate.

The proportion of firms' desired investment, which is funded via bonds, is given by:

[12] Future extensions of the model could include an explicit effect of carbon pricing on the share of green investment. The model can also incorporate the direct effect of carbon taxes on the profits of firms and the taxes collected by the government.

[13] This assumption, which does not change the essence of the analysis, allows us to abstract from complications that would arise from having firms that accumulate bonds with different maturities.

$$b_C = b_{C-1} + \frac{x_1 I_C^D}{\overline{p}_C} \quad (10)$$

$$b_G = b_{G-1} + \frac{x_2 I_G^D}{\overline{p}_G} \quad (11)$$

where b_C is the number of conventional bonds, b_G is the number of green bonds, x_1 is the proportion of firms' conventional desired investment financed via bonds, x_2 is the proportion of firms' green desired investment funded via bonds, $\overline{p}_C$ is the par value of conventional bonds and $\overline{p}_G$ is the par value of green bonds.

The proportion of desired investment covered by green or conventional bonds is a negative function of the bond yield. Formally:

$$x_1 = x_{10} - x_{11} yield_{C-1} \quad (12)$$

$$x_2 = x_{20} - x_{21} yield_{G-1} \quad (13)$$

where $x_{10}, x_{11}, x_{20}, x_{21} > 0$.

We postulate a price-clearing mechanism in the bond market:

$$p_C = \frac{B_C}{b_C} \quad (14)$$

$$p_G = \frac{B_G}{b_G} \quad (15)$$

where B_C and B_G denote the value of conventional and green bonds held by households and central banks and p_C and p_G is the market price of conventional and green bonds, respectively. Prices tend to increase whenever households and central banks hold a higher amount of corporate bonds in their portfolio. A rise in the price of bonds produces a decline in the bond yield, which has two effects on firms' investment. First, since firms pay a lower interest rate on bonds, their profitability improves increasing their desired investment. Second, a lower bond yield (which can result from a rise in bond prices) induces firms to increase the proportion of desired investment covered via bonds. This is crucial because firms need to rely less on bank lending in order to finance their investment. The disadvantage of bank lending is that, due to credit rationing, banks provide only a proportion of the loans demanded by firms. Accordingly, the less firms rely on bank loans in order to finance their desired investment the higher their ability to undertake their desired investment.

Based on firms' budget constraint, the new loans demanded by firms are determined as follows:

$$NL_G^D = I_G^D - \beta RP + repL_{G-1} - \delta K_{G-1} - \bar{p}_G \Delta b_G \quad (16)$$

$$NL_C^D = I_C^D - (1-\beta) RP + repL_{C-1} - \delta K_{C-1} - \bar{p}_C \Delta b_C \quad (17)$$

where NL_G^D denotes the desired new green loans, NL_C^D denotes the desired new conventional loans, L_G is the outstanding amount of green loans, L_C is the outstanding amount of conventional loans, RP denotes the retained profits of firms and rep is the loan repayment ratio.

Firms might default on their loans. When this happens, a part of their accumulated loans is not repaid, deteriorating the financial position of banks. The amount of defaulted loans (DL) is equal to:

$$DL = defL_{-1} \quad (18)$$

where L denotes the total loans of firms.

The rate of default (def) is assumed to increase when firms become less liquid. The illiquidity of firms is captured by an illiquidity ratio, $illiq$, which expresses the cash outflows of firms relative to their cash inflows. Cash outflows include wages, interest, taxes, loan repayments and maintenance capital expenditures (which are equal to depreciation). Cash inflows comprise the revenues from sales and the funds obtained from bank loans and the issuance of bonds. The default rate is a non-linear positive function of $illiq$:

$$def = f\left(\overset{+}{illiq}_{-1}\right) \quad (19)$$

Eq. (19) suggests that, as cash outflows increase compared to cash inflows, the ability of firms to repay their debt declines.

2.4. The portfolio choice and consumption of households

Households invest their lagged financial wealth (V_{HF-1}), which is a proxy for their expected one, in four different assets: government securities (SEC_H), conventional corporate bonds (B_{CH}), green corporate bonds (B_{GH}) and deposits (D); int_S is the interest rate on government securities and int_D is the interest rate on deposits. In the portfolio choice, captured by Eqs. (20)-(23n), Godley's (1999) imperfect asset substitutability framework is adopted.[14]

$$\frac{SEC_H}{V_{HF-1}} = \lambda_{10} + \lambda'_{10} D_{T-1} + \lambda_{11} int_S + \lambda_{12} yield_{C-1} + \lambda_{13} yield_{G-1} + \lambda_{14} int_D + \lambda_{15} \frac{Y_{H-1}}{V_{HF-1}} \tag{20}$$

$$\frac{B_{CH}}{V_{HF-1}} = \lambda_{20} + \lambda'_{20} D_{T-1} + \lambda_{21} int_S + \lambda_{22} yield_{C-1} + \lambda_{23} yield_{G-1} + \lambda_{24} int_D + \lambda_{25} \frac{Y_{H-1}}{V_{HF-1}} \tag{21}$$

$$\frac{B_{GH}}{V_{HF-1}} = \lambda_{30} + \lambda'_{30} D_{T-1} + \lambda_{31} int_S + \lambda_{32} yield_{C-1} + \lambda_{33} yield_{G-1} + \lambda_{34} int_D + \lambda_{35} \frac{Y_{H-1}}{V_{HF-1}} \tag{22}$$

$$\frac{D}{V_{HF-1}} = \lambda_{40} + \lambda'_{40} D_{T-1} + \lambda_{41} int_S + \lambda_{42} yield_{C-1} + \lambda_{43} yield_{G-1} + \lambda_{44} int_D + \lambda_{45} \frac{Y_{H-1}}{V_{HF-1}} \tag{23n}$$

$$D = D_{-1} + Y_H - C - \Delta SEC_H - p_C \Delta b_{CH} - p_G \Delta b_{GH} \tag{23}$$

Households' asset allocation is driven by three factors. The first factor is the global warming damages. We posit that damages affect households' confidence and increase the precautionary demand for more liquid and less risky assets (see also Batten et al., 2016). Since damages destroy capital and the profitability opportunities of firms, we assume that as D_T increases, households reduce their holding of corporate conventional bonds and increase the proportion of their wealth held in deposits and government securities, which are considered safer.[15] Second, asset allocation responds to alterations in the relative rates on return. The holding of each asset relies positively on its own rate of return and negatively on the other asset's rate of return. Third, a rise in the transactions demand for money, as a result of higher expected income (Y_{H-1}), induces households to substitute deposits for other assets.[16]

[14] The parameters in the portfolio choice equations satisfy the horizontal, vertical and symmetry constraints.
[15] It could be argued that the demand for green corporate bonds is also affected negatively by the climate change damages that harm firms' financial position. However, climate change damages might at the same time induce households to hold more green bonds in order to contribute to the restriction of global warming. Hence, the overall impact of damages on the demand of green bonds is ambiguous. For this reason, we assume that $\lambda'_{30} = 0$ in our simulations. Overall, it should be noted that the modelling of the effects of climate change on portfolio decisions is a very challenging task given the lack of suitable data. Our formulation should therefore be viewed only as a first attempt to model these damages. Further research on this topic is essential.
[16] Note that balance sheet restrictions require that Eq. (23n) must be replaced by Eq. (23) in the computer simulations.

Households' consumption (C_N), adjusted for global warming damages, depends on lagged income (which is a proxy for the expected one) and lagged financial wealth (Eq. 24). However, Eq. (24) holds only when there are no supply-side constraints; in that case, $C = C_N$). If the overall demand in the economy is higher than the supply-determined output, Y^*, consumption adjusts such that the overall demand in the economy is below Y^*; note that pr is slightly lower than 1. This is shown in Eq. (25).

$$C_N = \left(c_1 Y_{H-1} + c_2 V_{HF-1}\right)\left(1 - D_{T-1}\right) \tag{24}$$

$$C = C_N \text{ if } C_N + I + G < Y^*\text{; otherwise } C = pr\left(Y^* - G - I\right) \tag{25}$$

2.5. Credit rationing and bank leverage

As mentioned above, banks impose credit rationing on the loans demanded by firms: they supply only a proportion of demanded loans. Following the empirical evidence presented in Lown and Morgan (2006), the degree of credit rationing both on conventional loans (CR_C) and green loans (CR_G) relies on the financial health of both firms and banks. In particular, credit rationing increases as the debt service ratio of firms (dsr) increases,[17] as the bank leverage (lev_B) increases relative to its maximum acceptable value (lev_B^{max}) and as the capital adequacy ratio (CAR) decreases compared to its minimum acceptable value (CAR^{min}): [18]

$$CR_C = r\left(\overset{+}{dsr_{-1}}, \left(lev_{B-1} \overset{+}{-} lev_B^{max}\right), \left(CAR_{-1} \overset{-}{-} CAR^{min}\right)\right) + \varepsilon_{CR} \tag{26}$$

$$CR_G = l\left(\overset{+}{dsr_{-1}}, \left(lev_{B-1} \overset{+}{-} lev_B^{max}\right), \left(CAR_{-1} \overset{-}{-} CAR^{min}\right)\right) + \varepsilon_{CR} \tag{27}$$

As in the case of investment, we assume that credit rationing is also dependent on a random component, ε_{CR}, that follows a stochastic AR(1) process.

The bank leverage ratio is defined as:

[17] The debt service ratio is defined as the ratio of debt payment commitments (interest plus principal repayments) to profits before interest. Its key difference with the illiquidity ratio is that the latter takes into account the new flow of credit.

[18] In our simulations, the maximum bank leverage and the minimum capital adequacy ratio are determined based on the Basel III regulatory framework.

$$lev_B = \left(L_C + L_G + SEC_B + HPM\right) / K_B \tag{28}$$

where SEC_B is the government securities that banks hold, HPM is high-powered money and K_B is the capital of banks.

The capital adequacy ratio of banks is equal to:

$$CAR = K_B / \left[w_L\left(L_C + L_G\right) + w_S SEC_B\right] \tag{29}$$

where w_L and w_S are the risk weights on loans and securities respectively.

We assume that when the bank leverage ratio becomes higher than its maximum value and/or the capital adequacy ratio falls below its minimum value, the government steps in and bailouts the banking sector in order to avoid a financial collapse. The bailout takes the form of a capital transfer. This means that it has a negative impact on the fiscal balance and the government acquires no financial assets as a result of its intervention (see Popoyan et al., 2017 for a similar assumption). The bailout funds are equal to the amount that is necessary for the banking sector to restore the capital needed in order to comply with the regulatory requirements.

2.6. Central banks and green QE

Central banks determine the base interest rate, provide liquidity to commercial banks (via advances) and buy government securities (acting as residual purchasers). Moreover, in the context of QE programmes, they buy bonds issued by the firm sector. Currently, central banks do not explicitly distinguish between the holdings of conventional and green bonds. However, in order to analyse the implications of a green QE programme, we assume that central banks announce separately the amount of conventional bond and green bond purchases. The value of conventional corporate bonds held be central banks (B_{CCB}) is:

$$B_{CCB} = s_C B_{C-1} \tag{30}$$

where s_C is the share of total outstanding conventional bonds that central banks desire to keep on their balance sheet. Currently, this share is very low since the corporate bond purchases of central banks represent a very small proportion of the total bond market.

The central banks' holdings of corporate green bonds (B_{GCB}) are given by:

$$B_{GCB} = s_G B_{G-1} \tag{31}$$

where s_G is the share of total outstanding green bonds that central banks desire to keep on their balance sheet. We assume that this share is currently equal to zero since central banks do not implement green QE programmes.

The implementation of a green QE programme should not be viewed as a simple extension of the current corporate sector purchase programme of central banks. The current corporate QE programmes have as an aim to improve credit conditions in order to help central banks achieve their inflation targets and they are meant to be of temporary nature. On the contrary, a green QE would be a kind of industrial policy with a much longer-term commitment. Hence, the decision of central banks to conduct such a programme would require a re-consideration of their mandate or a different interpretation of their role in ensuring financial stability in economies that might face increasing climate-related financial risks. This is especially the case for the central banks of high-income countries, which have narrower mandates and a more strictly defined role in comparison with the central banks of low-income countries (see Campiglio et al., 2018).

3. Calibration, estimation and validation of the model

We have calibrated and estimated the DEFINE 1.0 model employing global data. Parameter values (a) have been econometrically estimated using panel data, (b) have been directly calibrated using related data, previous studies or reasonable values, or (c) have been indirectly calibrated such that the model matches the initial values obtained from the data or generates the baseline scenario. The related details are reported in the Online Appendix.[19]

The model is simulated for the period 2016-2115.[20] The aim of the simulations is to illuminate the long-run trends in the interactions between the financial system and climate change. Hence, no explicit attention is paid to short-run fluctuations and business cycles. In our simulations we focus

[19] The majority of our calibrations rely on data that refer to the global economy and the global ecosystem. For the econometric estimations (that have been made for our investment, consumption and labour productivity functions), we have used panel data for a large set of countries which, however, does not cover the whole global economy. In the econometric estimations the parameters have the expected sign and are statistically significant.
[20] The R code used for the simulations is available upon request.

on two specific sources of uncertainty:[21] (i) the uncertainty about the values of key parameters that capture the link between damages and the financial system; (ii) the uncertainty that stems from the stochastic AR(1) processes included in the investment credit rationing functions. In order to deal with the first source of uncertainty, we conduct a sensitivity analysis described in Section 4. In order to tackle the second source of uncertainty, we perform 200 Monte Carlo simulations and we report the across-run averages.

Our baseline scenario represents a 'business-as-usual' pathway whereby the global economy continues to expand in broad line with recent trends, and ecological efficiency improves moderately due to the continuation of technological changes and the implementation of some policies that promote green investment.[22] Some key features of our baseline scenario are shown in Table 5. It is assumed that the economy grows on average at a rate slightly lower than 2.7% till 2050; in other words, we postulate an economic expansion a little bit lower than the one observed over the last two decades or so.[23] The unemployment rate remains, on average, close to 6% till 2050. Drawing on the United Nations (2017) population projections (medium fertility variant), the population is assumed to grow at a declining rate, becoming equal to around 9.77bn people in 2050. Moreover, the default rate on corporate loans is assumed to remain, on average, close to its current level, which is slightly higher that 4%.

Table 5: Key features of the baseline scenario

Variable	Value/trend
Economic growth till 2050	slightly lower than 2.7% (on average)
Unemployment rate till 2050	slightly lower than 6% (on average)
Population in 2050	9.77bn
Labour force-to-population ratio in 2050	0.45
Default rate till 2050	slightly higher than 4% (on average)
CO_2 intensity in 2050 as a ratio of CO_2 intensity in 2016	around 0.9
Share of renewable energy in total energy in 2050	around 25%
Material intensity in 2050 as a ratio of material intensity in 2016	around 0.9
Energy intensity in 2050 as a ratio of energy intensity in 2016	around 0.7
Recycling rate in 2050 as a ratio of recycling rate in 2016	around 1.4
Annual green investment in the period 2016-2040	around US$1.1tn
Energy use in 2040 compared to 2016	around 1.4
Yield of conventional bonds	quite stable till around 2050
Yield of green bonds	declines slightly in the next decade or so

[21] A thorough investigation of all key sources of uncertainty is beyond the purpose of this paper.
[22] Carbon pricing is implicitly considered to be one of these policies.
[23] Based on data from World Bank.

CO_2 intensity (which captures the industrial emissions per unit of fossil-fuel energy) declines by 10% till 2050, for example due to the continuation in the replacement of coal with gas and the use of carbon capture and storage technologies.[24] The share of renewable energy increases to about 25% till 2050 (from about 14% which is the current level), while energy intensity is assumed to become approximately 30% lower in 2050 compared to its 2016 level. Material intensity and recycling rate also improve. The overall improvement in ecological efficiency indicators is associated with the accumulation of green capital. In our baseline scenario the annual green investment during the period 2016-2040 is equal to around US$1.1tn.[25] The annual use of energy is 40% higher in 2040 compared to 2016.[26]

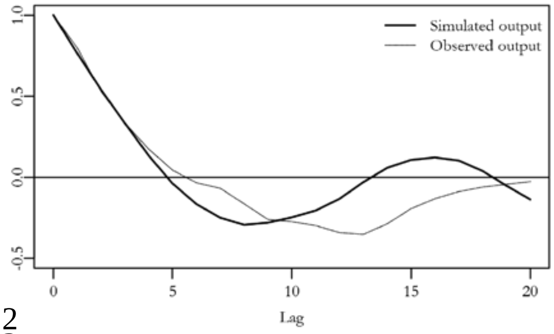
We also assume that the yield on the conventional bond market remains relatively stable till 2050, while the yield of green bonds improves in the next decade or so. The latter is a result of an increasing demand for green bonds that outstrips their supply, in line with recent trends (see, for example, Climate Bonds Initiative, 2017).

We do not expect that the structure of the time series data in the next decades will necessarily be the same with the structure of past times series. However, it is a useful exercise to compare the auto- and cross-correlation structure of our simulated data with the observed one in order to check whether the model produces data with reasonable time-series properties.[27] This is done in Fig. 1. Figs. 1a-1d show the auto-correlation structure of the cyclical component of the simulated and observed time series for output, consumption, investment and employment up to 20 lags. Figs. 1e-1h show the correlation between the cyclical component of output at time *t* and of output, investment, consumption and employment at time *t-lag*. The series are expressed in logs and the HP filter has been used to isolate the cyclical component. The simulated data refer to the baseline scenario and capture only the period 2016-2050 in order to avoid the significant disturbances to the data structures that are caused by climate change after 2050, when the 2°C threshold is passed.

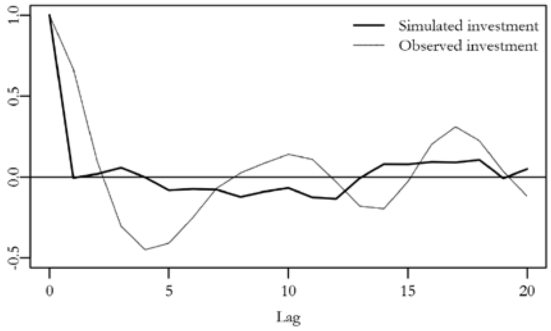
[24] For the importance of these factors in the determination of CO_2 intensity, see e.g. Peters et al. (2017).
[25] Note that IEA (2016, p. 82) estimates that the annual investment in renewables and energy efficiency that is necessary over the period 2016-2040 in order to avoid a global warming higher that 2°C is close to US$2tn. Recall that green investment in our model does not only include investment in renewables and energy efficiency: it also includes investment that improves material intensity and the recycling rate.
[26] In the Current Policies Scenario presented in IEA (2016) the energy use in 2040 is 43% higher compared to 2016.
[27] For similar validation exercises see Assenza et al. (2015) and Caiani et al. (2016).

Fig. 1: Auto-correlations and cross-correlations of observed and simulated data

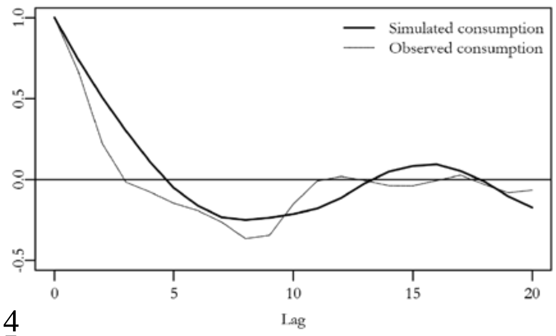
(a) Auto-correlation: output



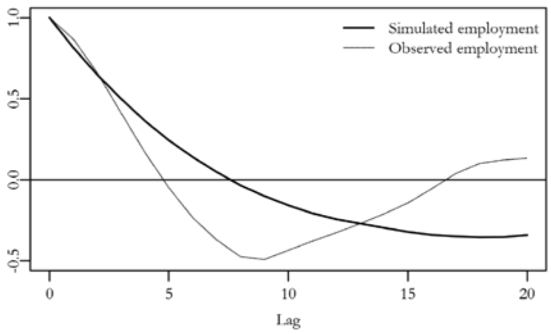
(b) Auto-correlation: investment



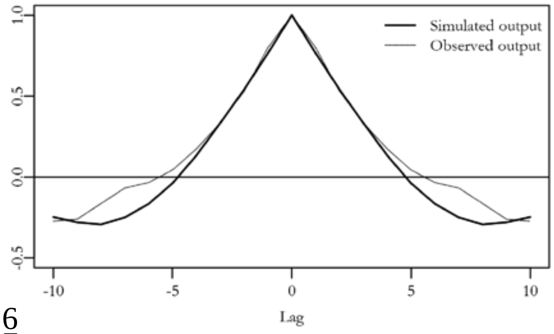
(c) Auto-correlation: consumption



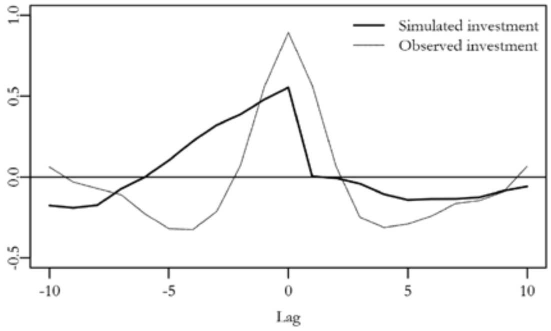
(d) Auto-correlation: employment



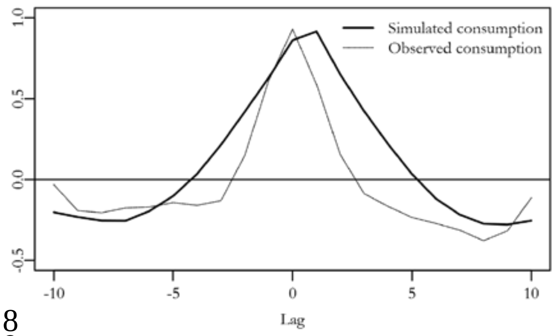
(e) Cross-correlation: output



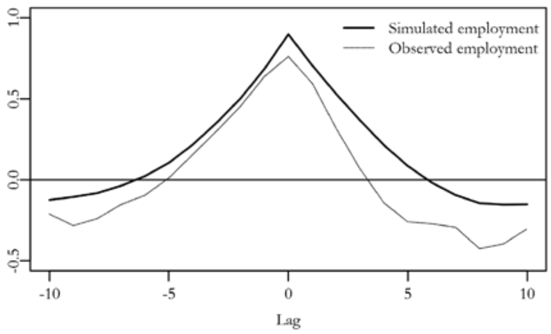
(f) Cross-correlation: investment



(g) Cross-correlation: consumption



(h) Cross-correlation: employment



Note: The series are expressed in logs and the HP filter has been used to isolate the cyclical component. The data for the observed variables have been taken from World Bank and refer to the global economy. Real output is available for the period 1960-2016, real consumption and real investment are available for the period 1970-2016 and employment is available for the period 1991-2016.

The auto-correlation structure of our simulated data is similar to the auto-correlation structure of the observed data. This is especially the case for the structure of our simulated output, which looks remarkably close to the empirically observed structure. Moreover, simulated investment, consumption and employment appear to be pro-cyclical, in tune with the empirical data, and their peak behaviour resembles the behaviour observed in the real data. These results suggest that our model generates data with empirically reasonable properties.

4. Climate change and financial stability

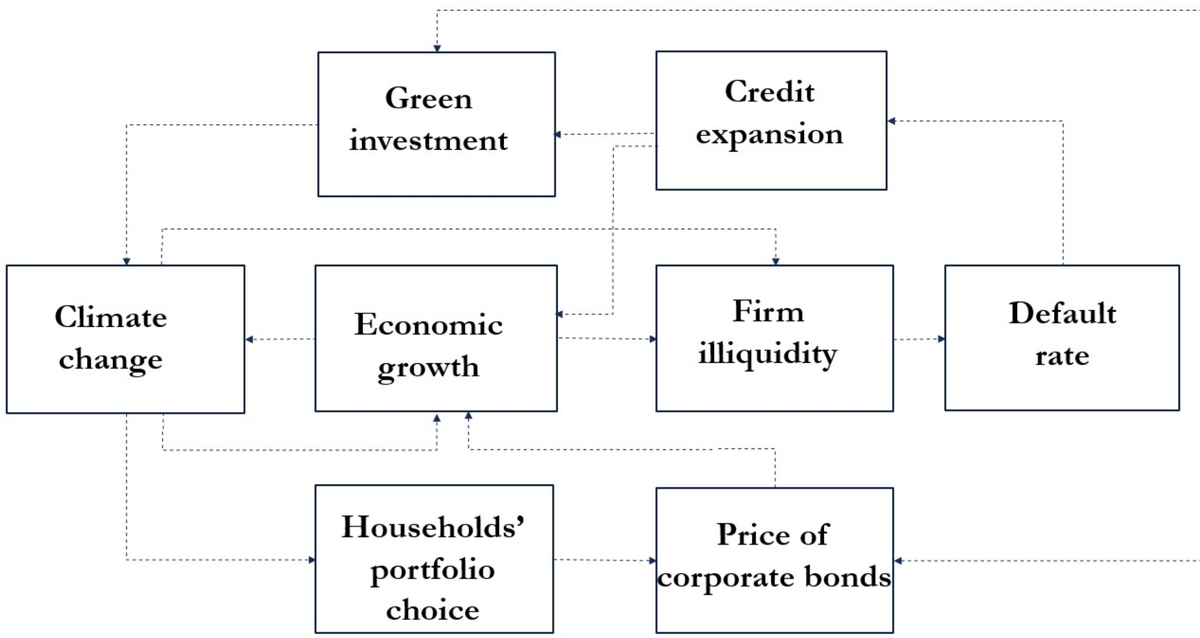
Let us first summarise the key effects of climate change on economic variables in our model. Climate damages reduce (i) consumption and investment demand, (ii) households' demand for conventional corporate bonds (increasing at the same time the demand for deposits and government securities), (iii) the labour-determined potential output (which is affected by labour productivity and labour force) and (iv) the capital-determined potential output (which is affected by capital stock and capital productivity). (i) and (ii) are affected by gross damages; in our baseline scenario we assume that the gross damages are 50% when $T = 6^o C$. On the other hand, (iii) and (iv) are affected by net damages, which in our baseline scenario are a relatively small proportion of gross damages. Climate damages also have a direct impact on the profitability of firms (since profits are affected by economic growth and the climate-induced depreciation of capital) and the rate of capacity utilisation (since the growth rate of output is not necessarily the same with the growth rate of capital-determined output). Both variables affect the desired investment of firms. Moreover, climate change influences the rate of employment since the growth rate of output is not necessarily the same with the labour-determined potential output.[28]

All these economic effects affect the stability of the financial system with feedback effects on the environment. Fig. 2 summarises the main channels through which climate change and financial stability interact. Fig. 3 plots the simulation results. In the baseline scenario CO_2 emissions increase significantly over the next decades (Fig. 3c). This rise is mainly driven by the exponential increase in output due to positive economic growth (Fig. 3a), the slow improvement in energy

[28] Note that capacity utilisation is given by Y/Y_K^*, where Y_K^* is the capital-determined potential output (equal to capital productivity times capital stock) and employment rate is given by Y/Y_N^* where Y_N^* is the labour-determined potential output (equal to labour productivity times labour force).

efficiciency and the low share of renewable energy in total energy (Fig 3b). Hence, CO_2 concentration in the atmposphere increases, leading to severe global warming: as Fig. 3d indicates, in 2100 temperature becomes about 4°C higher than pre-industrial levels.[29]

Fig. 2: Key channels through which climate change and financial stability interact in the model



The rise in atmospheric temperature leads to climate change damages. Accordingly, the growth rate of output starts declining (Fig. 3a). This slowdown of economic activity becomes more intense after the mid of the 21st century when temperature passes 2°C.[30] Declining economic growth and the desctruction of capital harms the profitability of firms (Fig. 3e) and deteriorates their liquidity, which in turn increases their rate of default (Fig. 3f) and thereby increases the bank leverage (Fig. 3g) and decreases the capital adequacy ratio.[31] The overall result is an increase in

[29] This increase in temperature in our baseline scenario is broadly in line with the results of key IAMs (see Nordhaus, 2016). Note that that the parameter values that we have used for the carbon cycle and temperature equations rely on the recent updates of the DICE (Dynamic Integrated Climate-Economy) model by Nordhaus (2016). These updates produce more pessimistic results about the path of atmpospheric temperature in the next decades. See also Bovari et al. (2018).

[30] Note that in 2100 the level of output in our baseline scenario is about 30% compared to a scenario in which there are no damages and economic growth continues to be close to its current level.

[31] The impact of climate damages on bank leverage is in line with the empirical evidence reported in Klomp (2014), which shows that natural disasters deteriorate the financial robustness of banks. Note that in our model the losses of firms due to the climate-induced destruction of their capital stock are not covered by the government or insurance companies.

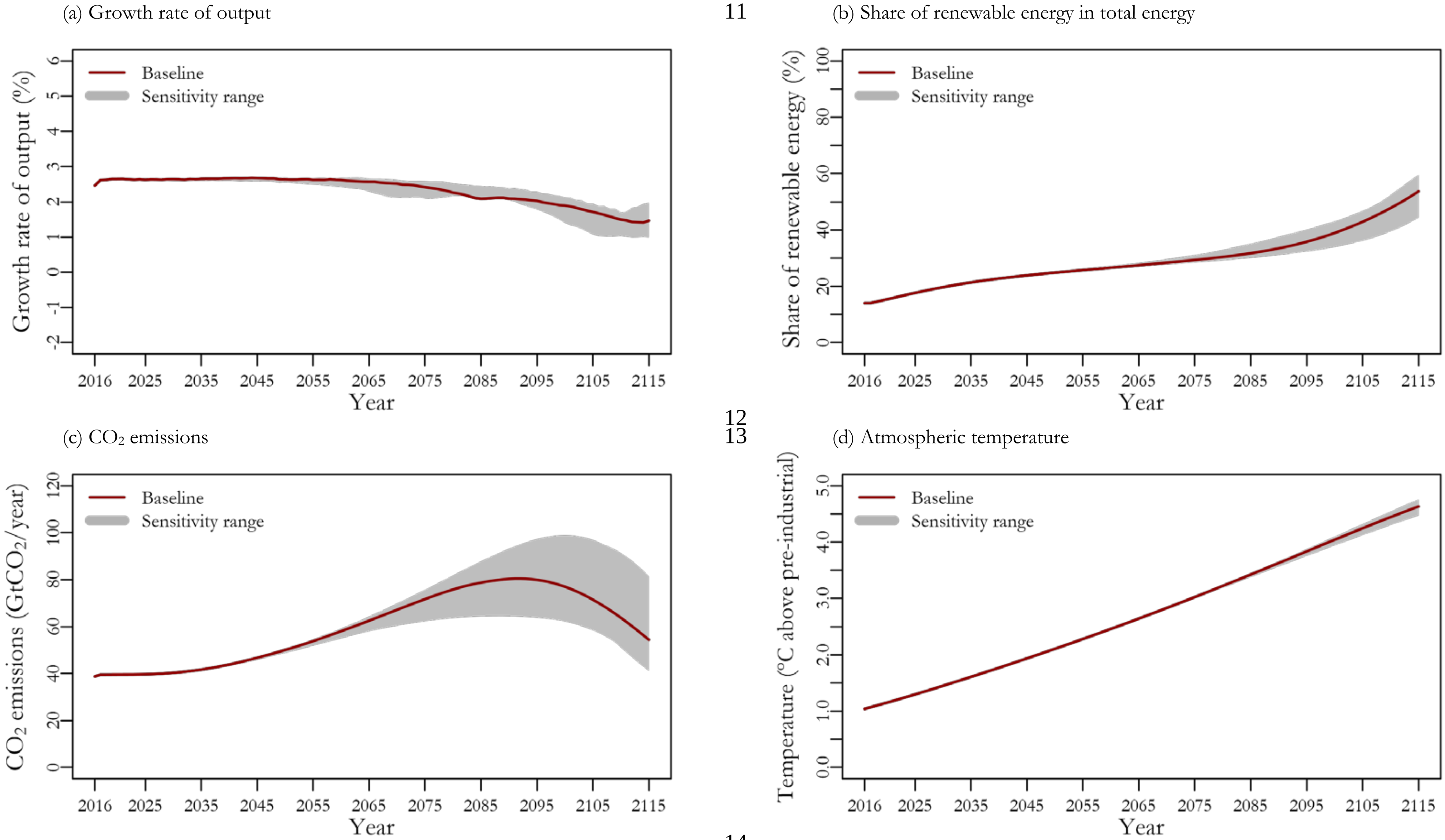
credit rationing, which feeds back into economic growth (Fig. 3a) and the profitability and liquidity of firms, giving rise to a vicious financial cycle. This also slows down the investment in green capital, disrupting the transition to a low-carbon and more ecologically efficient economy. Crucially, at some point in time the capital of banks becomes insufficient to cover the regulatory requirements. Thus, the government sector steps in and bailouts the banks with adverse effects on the public debt-to-output ratio (Fig. 3h). Note that the exponential increase in the public debt-to-output ratio is also expalined by (i) the reduction in tax revenues as a result of lower economic activity and (ii) the fact that the increase in public indebtedness causes a cumulative increase in interest payments that increases debt even further.

Furthermore, climate damages affect the liquidity preference of households. The destruction of capital and the decline in the profitability of firms induces a reallocation of household financial wealth from corporate bonds towards deposits and government securities, which are deemed much safer. This is shown in Fig. 3i. The result is a decline in the price of conventional bonds, which leads to a substantial increase in their yield in the last decades of our simulation period (Fig. 3j). This is an example of a climate-induced asset price deflation. Note that the exponential increase in the yield of bonds in the baseline scenario primarily stems from the convexity of damages: as global warming becomes more severe, the damages rise at an increasing rate.

The yield of green corporate bonds also increases in our baseline scenario, after the decline in the first years (Fig. 3k). However, the main reason behind this fall is not the decline in the demand for green bonds by households. This fall is primarily explained by the increase in the supply of green bonds since desired green investment continuously increases in our simulation period (Fig. 3l).

Bond price deflation has negative effects on economic growth because it reduces both the wealth-related consumption and the ability of firms to rely on the bond market in order to fund their desired investment. It also leads to less green investment, which affects adversely the improvement in ecological efficiency.

Fig. 3: Evolution of environmental, macroeconomic and financial variables, baseline scenario and sensitivity analysis



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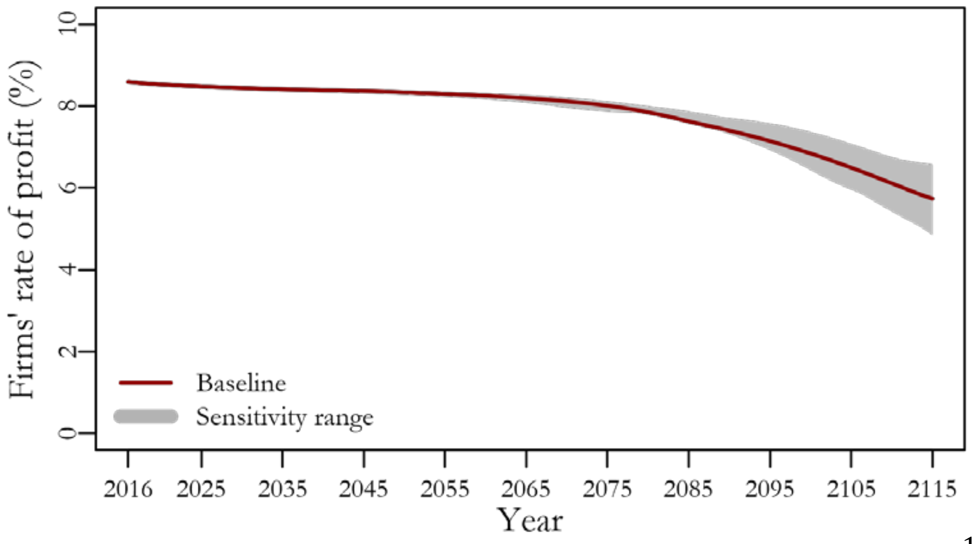
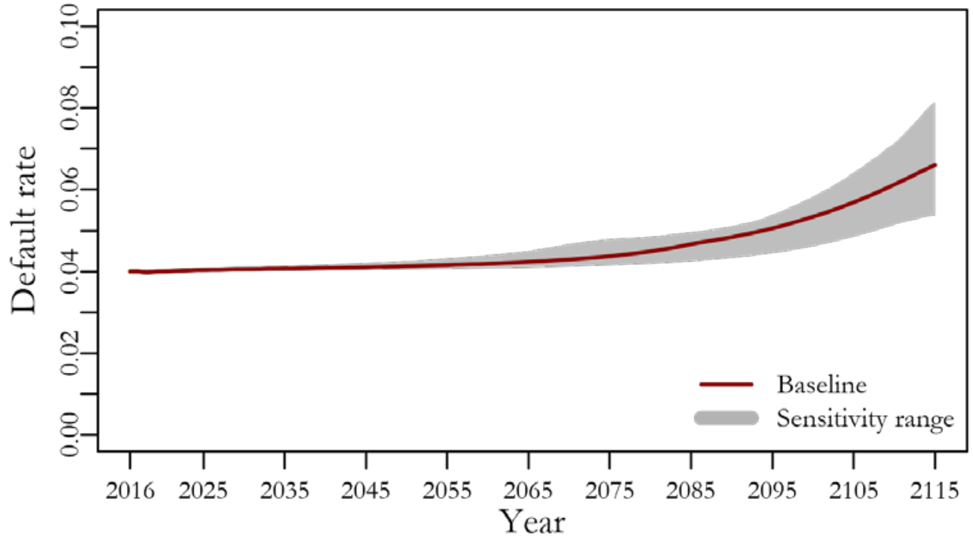
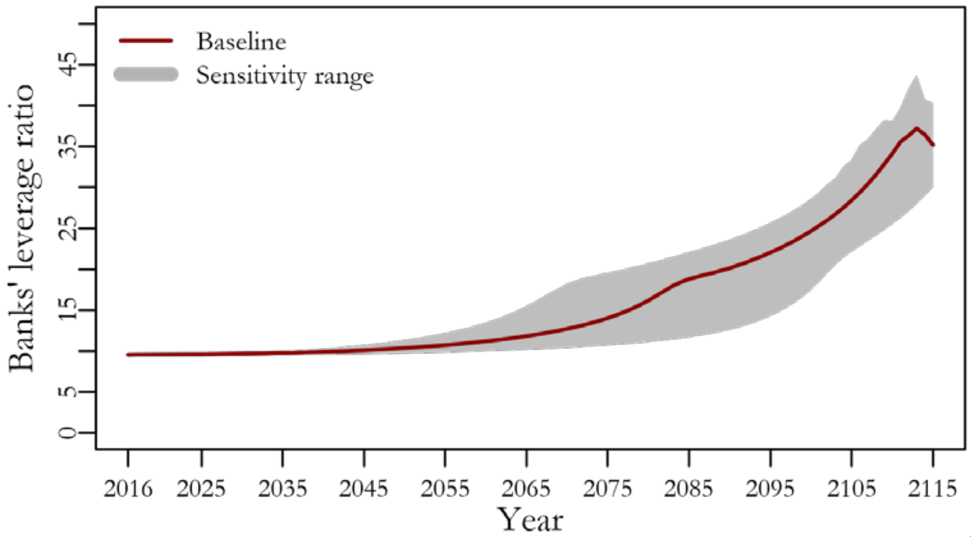
(e) Firms' rate of profit



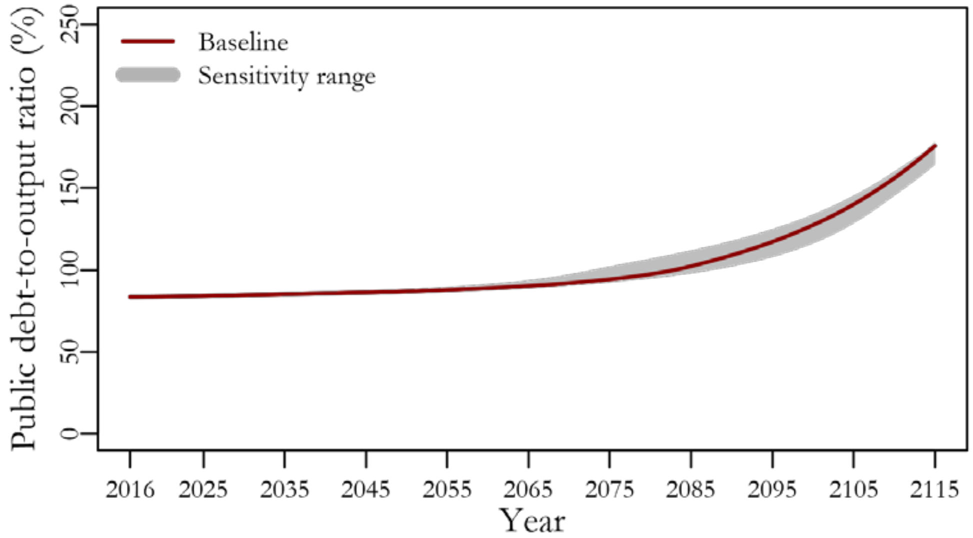
(f) Default rate on firms' loans



(g) Banks' leverage ratio



(h) Public debt-to-output ratio



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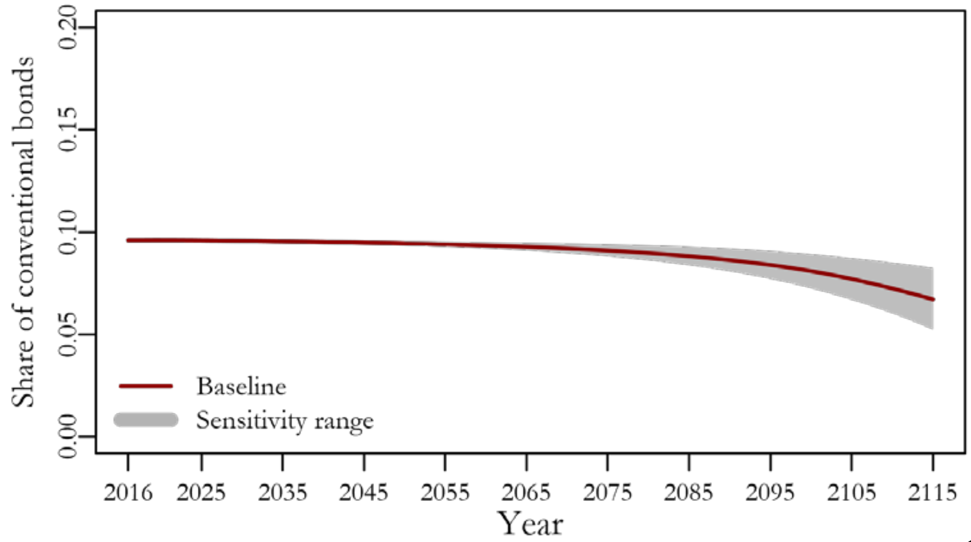
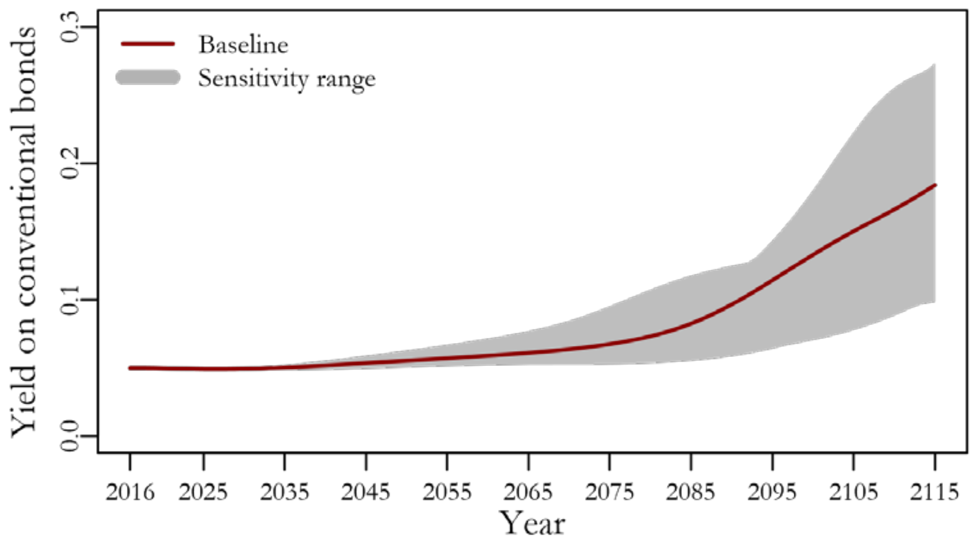
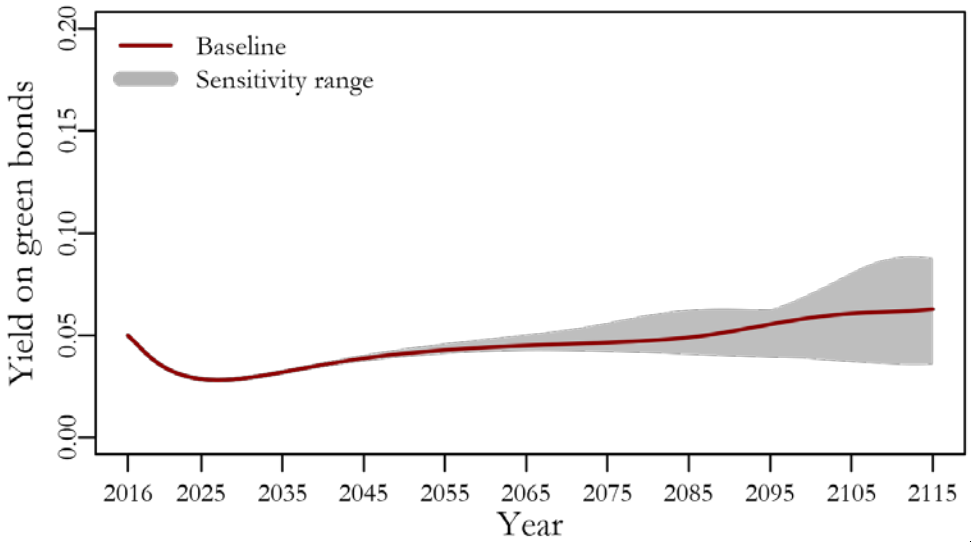
(i) Share of conventional corporate bonds in households' wealth



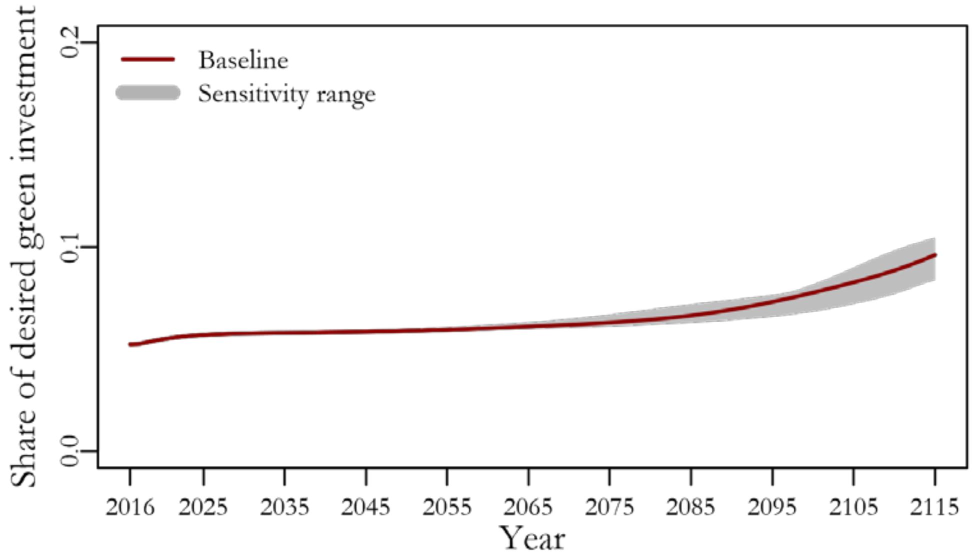
(j) Yield on conventional corporate bonds



(k) Yield on green corporate bonds



(l) Share of desired green investment in total investment



Note: The baseline scenario reports across-run averages from 200 Monte Carlo simulations. The values used in this scenario are reported in the Online Appendix. The sensitivity range relies on the 8 cases shown in Table 6. For each case, we run 200 Monte Carlo simulations and we keep the across-run averages. The sensitivity range is derived based on the annual minimum and maximum values of the averages among the 8 cases.

How does the baseline scenario change when key parameters are modified? Space limitations do not allow us to explore this question in detail. However, we conduct a sensitivity analysis that concentrates on the key parameters that are related to the responsiveness of the financial system to climate damages. These include (i) the sensitivity of the default rate to the illiquidity ratio (def_2), (ii) the sensitivity of credit rationing to the debt service ratio of firms, bank leverage and capital adequacy ratio ($l_2, l_3, l_4, r_2, r_3, r_4$) and (iii) the parameters of the portfolio choice that capture the sensitivity of the liquidity preference of households to the global warming damages ($\lambda_{10}^{'}, \lambda_{20}^{'}, \lambda_{40}^{'}$). In the sensitivity analysis, these parameters increase or decrease by 50% compared to their baseline values. As shown in Table 6, we consider 8 cases which capture different combinations in the percentage change of parameters (i), (ii) and (iii). For each case, we run 200 Monte Carlo simulations and we keep the across-run averages. The sensitivity range shown in Fig. 3 is derived based on the annual minimum and maximum values of the averages among the 8 cases.

The sensitivity analysis illustrates that the evolution of the default rate, the bank leverage ratio and the yield of conventional corporate bonds is affected by the changes in the parameter values (see Fig. 3f, Fig. 3g and Fig 3j). In particular, it turns out that the default rate increases (decreases) more quickly when its sensitivity to the illiquidity ratio is higher (lower) compared to the baseline. The same holds for the bank leverage ratio. In addition, the yield of conventional corporate bonds declines more rapidly when the portfolio choice of households is more responsive to climate change damages. However, despite the fact that the parameter values affect the severity and the time horizon of the climate-induced financial instability, the effects of climate change on financial stability are qualitatively similar.[32]

[32] Note that if we allow our simulations to continue after 2115 the share of renewable energy becomes at some point in time very close to 1, which leads to almost zero industrial CO_2 emissions. However, because of the inertia of the climate system, atmospheric temperature continues to increase for many decades.

Table 6: Values of parameters modified in the sensitivity analysis

Parameter	**Value in the baseline scenario**	**Percentage change (%) compared to the baseline scenario**							
		Case I	Case II	Case III	Case IV	Case V	Case VI	Case VII	Case VIII
Parameter of the default rate function (related to the sensitivity of the default rate to the illiquidity ratio of firms) (def_2)	7.81	+50%	-50%	+50%	-50%	+50%	-50%	+50%	-50%
Parameter of the function of credit rationing on green loans (related to the sensitivity of credit rationing to the default rate) (l_2)	2.08	+50%	-50%	-50%	+50%	+50%	-50%	-50%	+50%
Parameter of the function of credit rationing on green loans (related to the sensitivity of credit rationing to the leverage ratio of banks) (l_3)	0.04	+50%	-50%	-50%	+50%	+50%	-50%	-50%	+50%
Parameter of the function of credit rationing on green loans (related to the sensitivity of credit rationing to the capital adequacy ratio of banks) (l_4)	2.08	+50%	-50%	-50%	+50%	+50%	-50%	-50%	+50%
Parameter of the function of credit rationing on conventional loans (related to the sensitivity of credit rationing to the default rate) (r_2)	2.08	+50%	-50%	-50%	+50%	+50%	-50%	-50%	+50%
Parameter of the function of credit rationing on conventional loans (related to the sensitivity of credit rationing to the leverage ratio of banks) (r_3)	0.04	+50%	-50%	-50%	+50%	+50%	-50%	-50%	+50%
Parameter of the function of credit rationing on conventional loans (related to the sensitivity of credit rationing to the capital adequacy ratio of banks) (r_4)	2.08	+50%	-50%	-50%	+50%	+50%	-50%	-50%	+50%
Parameter of households' portfolio choice (λ_{10}')	0.10	+50%	-50%	-50%	+50%	-50%	+50%	+50%	-50%
Parameter of households' portfolio choice (λ_{20}')	-0.20	+50%	-50%	-50%	+50%	-50%	+50%	+50%	-50%
Parameter of households' portfolio choice (λ_{40}')	0.10	+50%	-50%	-50%	+50%	-50%	+50%	+50%	-50%

5. Effects of a green QE programme

In this section we analyse how our results change when a green QE programme is implemented. We suppose that in 2020 central banks around the globe decide that they will purchase 25% of the outstanding green bonds and they commit themselves that they will keep the same share of the green bond market over the next decades. We also assume that the proportion of conventional corporate bonds held by central banks remains equal to its current level.[33]

[33] We find that the effects of a green QE programme do not differ significantly if we assume that central banks stop holding conventional corporate bonds.

Experimentation with various parameter values has shown that the parameter that plays a key role in determining the effectiveness of a green QE programme is the sensitivity of the share of desired green investment to the divergence between the green bond yield and the conventional bond yield (β_2) – see Eq. (9). The higher the value of β_2 the more firms' green investment responds to a monetary policy-induced decline in the yield of green bonds. Consequently, in our simulations we consider a green QE (baseline) scenario whereby β_2 is equal to its baseline value but also some green QE scenarios in which β_2 is allowed to take a number of values below and above its baseline value.

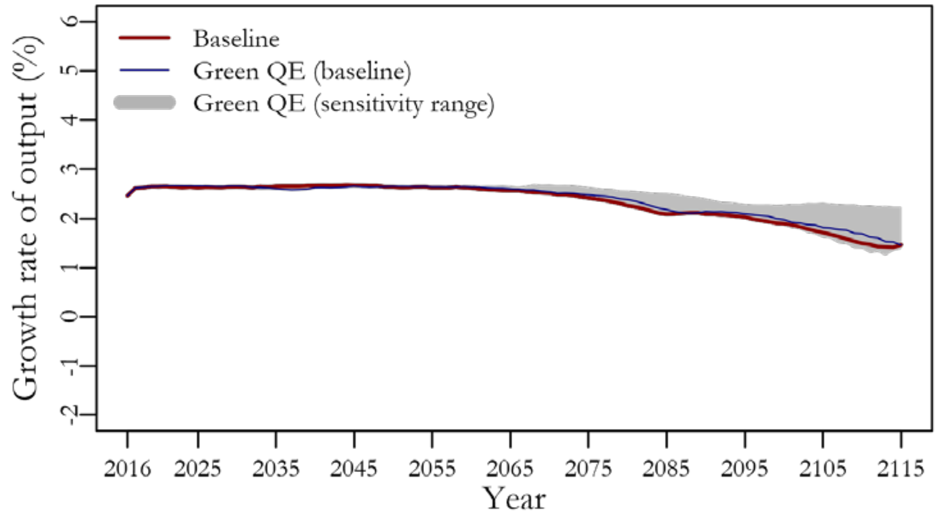
The effects of the green QE programme are portrayed in Fig. 4.[34] The green QE sensitivity range captures how the effects of a green QE programme are modified when β_2 changes. As Fig. 4k shows, green QE boosts the price of green corporate bonds, reducing their yield. This has various positive implications for climate change and financial stability. Regarding climate change, the resulting reduction in the green bond yield leads to a lower cost of borrowing for firms and a lower reliance on bank lending. This increases overall investment, including green investment. More importantly, since the yield of green bonds declines relative to the yield of conventional bonds (Figs. 4j and 4k), the share of desired green investment in total investment goes up (Fig. 4l). As firms invest more in green capital, the use of renewable energy increases (Fig. 4b). This leads to lower CO_2 emissions and slower global warming from what would otherwise be the case.

It should, however, be pointed out that in our simulations green QE cannot by itself prevent a substantial rise in atmospheric temperature: even with the optimistic value of β_2, global warming is not significantly lower than 4ºC at the end of the century. There are two key reasons for that. First, the interest rate is just one of the factors that affect green investment. Therefore, a decline in the green bond yield is not sufficient to bring about a substantial rise in green investment. Second, a higher β_2 is conducive to lower damages, allowing economic activity to expand more rapidly in the optimistic green QE scenario (Fig. 4a). This higher economic activity places upward pressures on CO_2 emissions (Fig. 4c).

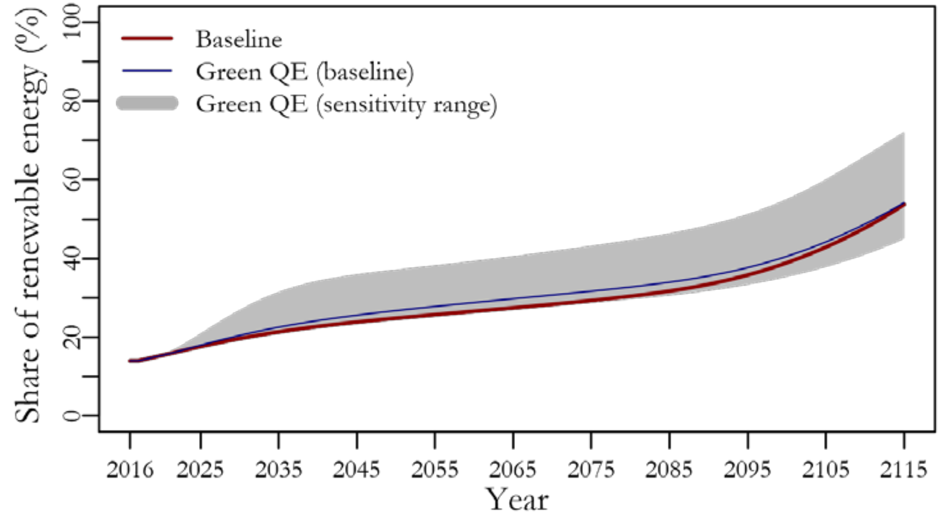
[34] Note that different values of β_2 would produce a different baseline scenario. Hence, the baseline scenario in which $\beta_2 = 1$ is not directly comparable with the scenarios reflected in the green QE range since in these scenarios β_2 is different from 1.

Fig. 4: Effects of the implementation of a green QE programme

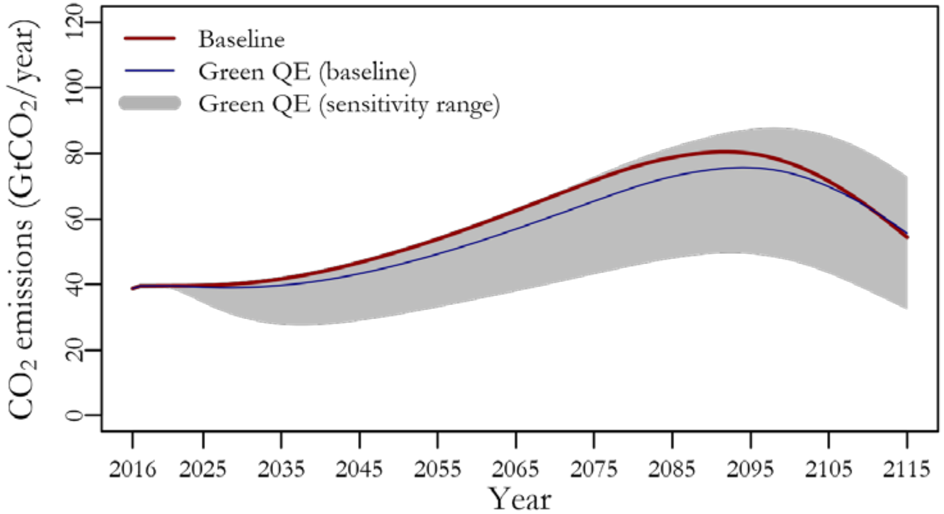
(a) Growth rate of output



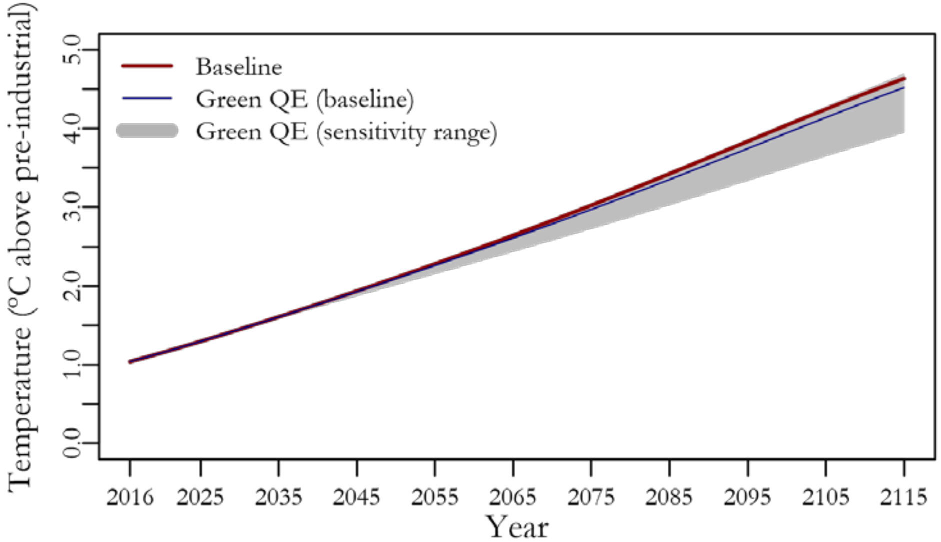
(b) Share of renewable energy in total energy



(c) CO_2 emissions



(d) Atmospheric temperature



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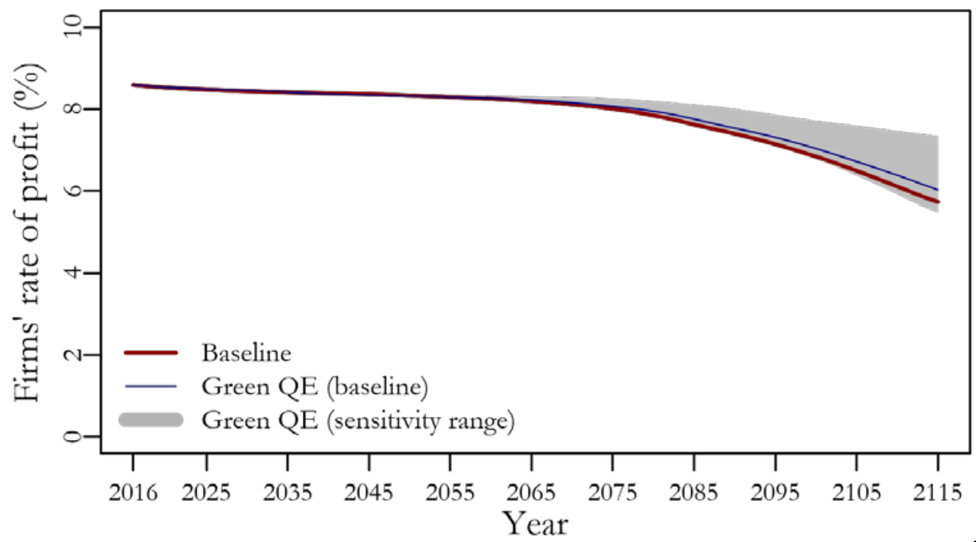
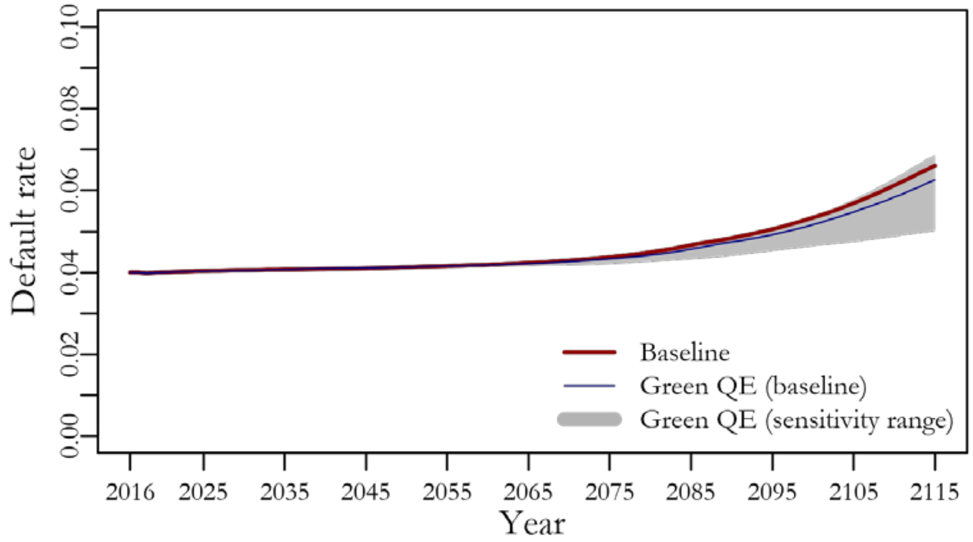
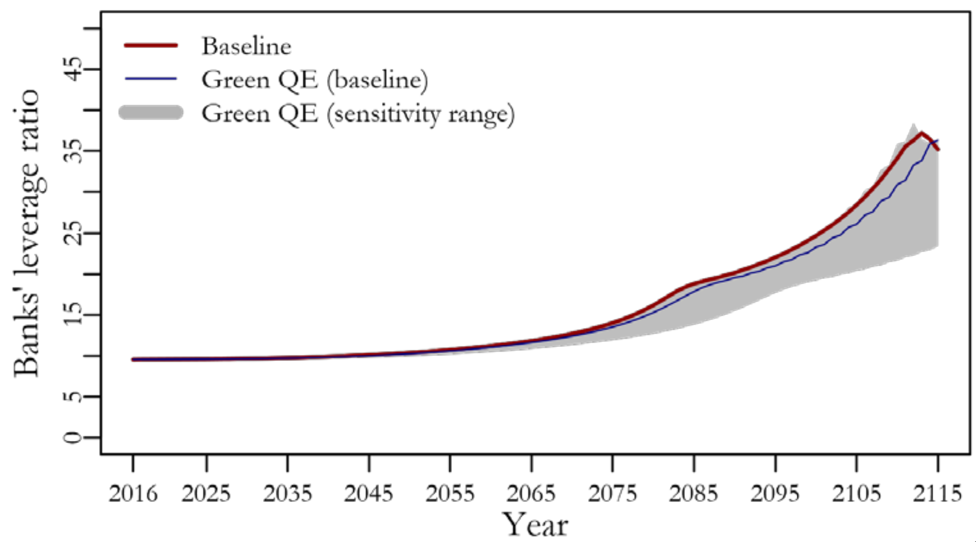
(e) Firms' rate of profit



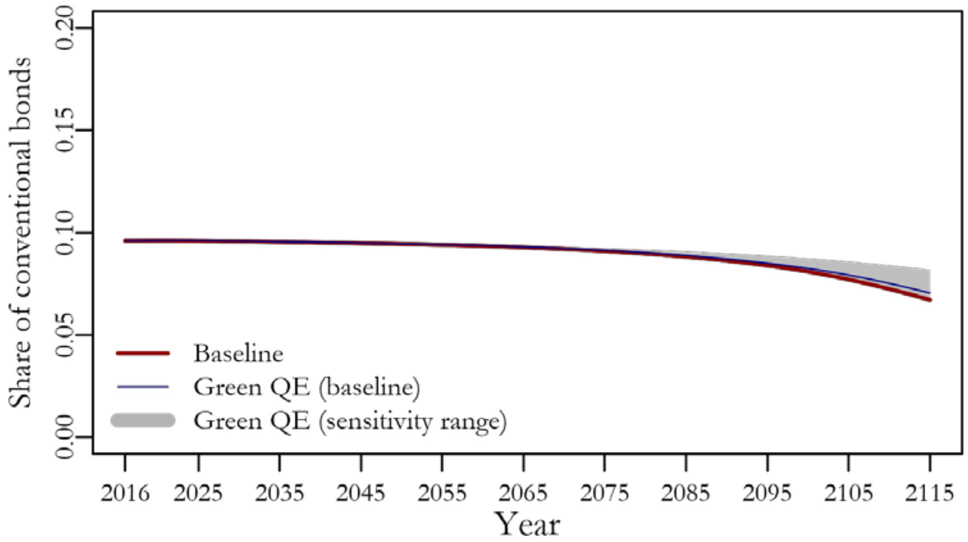
(f) Default rate on firms' loans



(g) Banks' leverage ratio



(h) Public debt-to-output ratio



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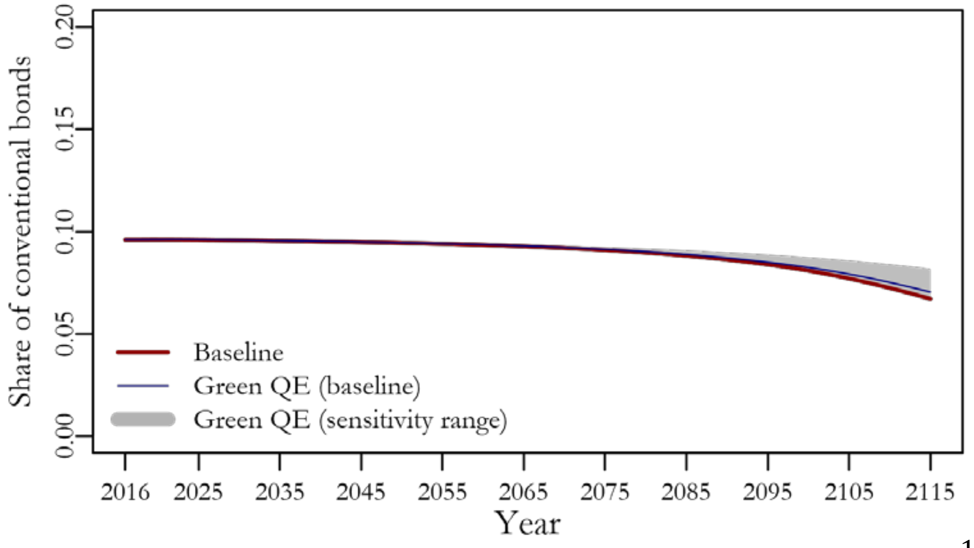
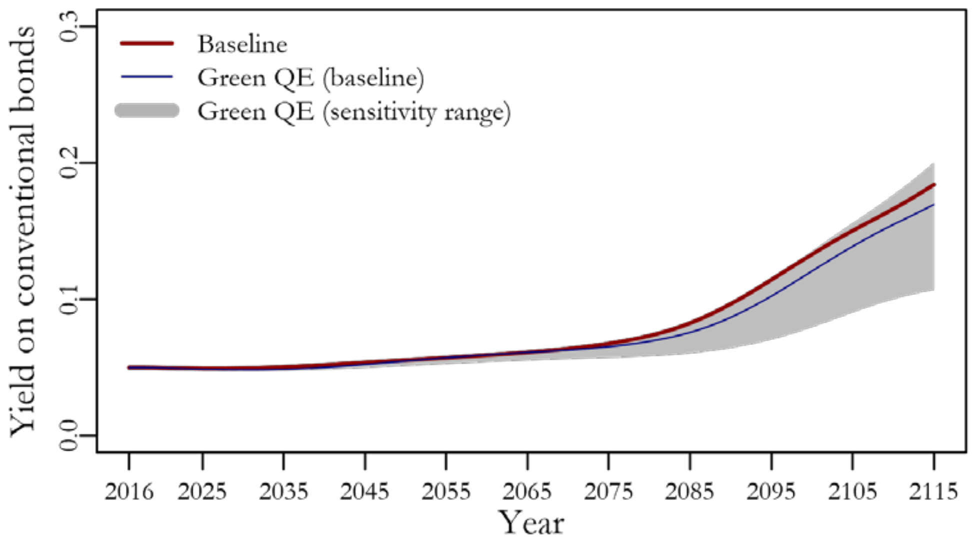
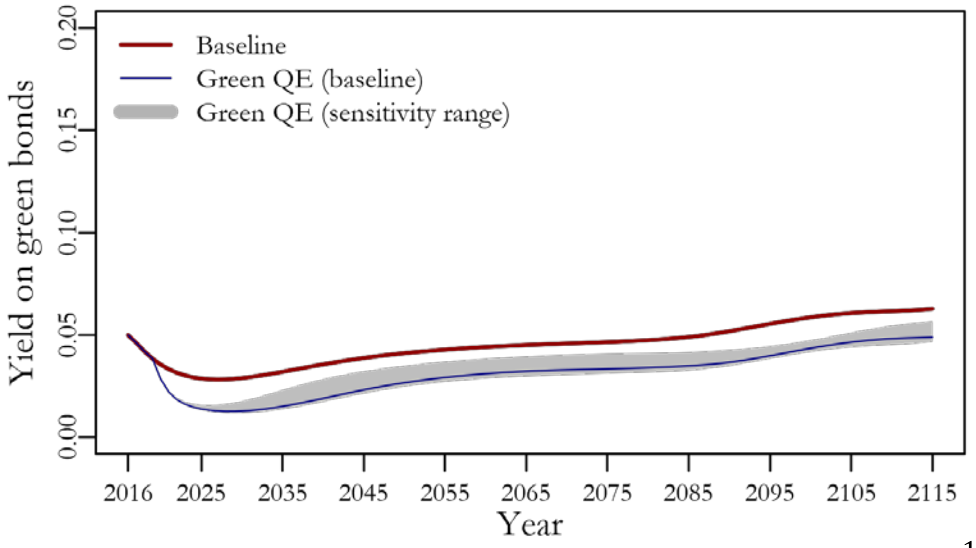
(i) Share of conventional corporate bonds in households' wealth



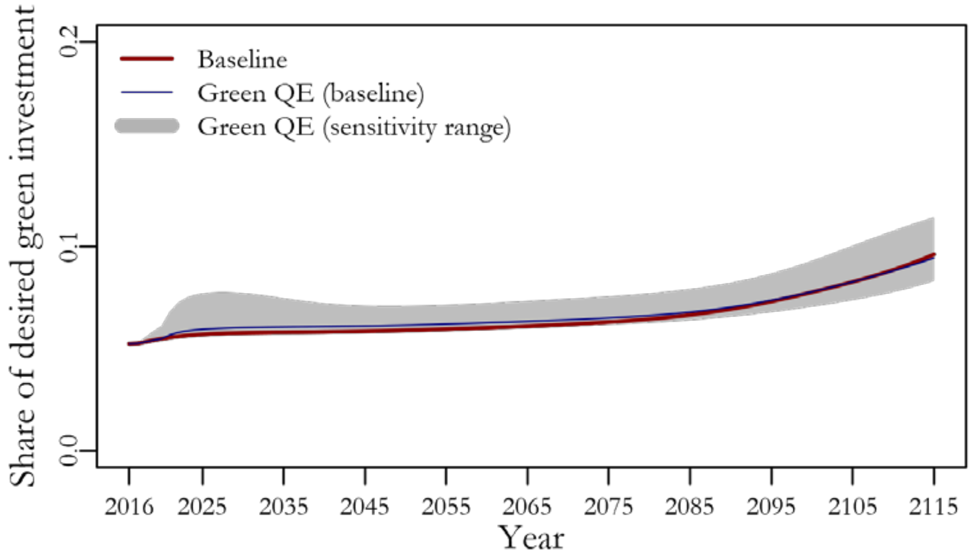
(j) Yield on conventional corporate bonds



(k) Yield on green corporate bonds



(l) Share of desired green investment in total investment



Note: The baseline scenario reports across-run averages from 200 Monte Carlo simulations. The values used in this scenario are reported in the Online Appendix. In Green QE (baseline) the implementation of a green QE programme (captured by an increase in s_G *from 0 to 0.25) starts in 2020 and the sensitivity of the desired green investment to the divergence between the green bond yield and the conventional bond yield (*β_2*) is equal to 1, as in the baseline scenario. The sensitivity range for the green QE scenario is derived based on a range of values for* β_2 *between 0.5 and 4. For each of these values, we run 200 Monte Carlo simulations and we keep the across-run averages. The sensitivity range is derived based on the annual minimum and maximum values of the averages among the different values of* β_2*.*

Regarding financial stability, green QE increases firm profitability and reduces the liquidity problems of firms. This makes the default rate and the bank leverage lower compared to the baseline (Figs. 4f and 4g); it also reduces the public debt-to-output ratio (Fig. 4h). These beneficial effects on financial stability stem from (i) the reduction in economic damages as a result of slower global warming and (ii) the lower reliance of firms' green investment on bank lending. A higher value of β_2 reinforces generally the financial stability effects of green QE. However, the decline in the yield of green bonds is lower compared to the baseline green QE scenario (Fig. 4k). The reason is that firms issue more green bonds in order to fund their higher desired green investment. For a given demand for green bonds, this tends to reduce the bond price, leading to a higher yield.

6. Conclusion

The fundamental changes that are expected to take place in the climate system in the next decades are likely to have severe implications for the stability of the financial system. The purpose of this article was to analyse these implications by using a stock-flow-fund ecological macroeconomic model. Emphasis was placed on the effects of climate change damages on the financial position of firms and asset price deflation. The model was estimated and calibrated using global data and simulations were conducted for the period 2016-2115.

Our simulation analysis for the interactions between climate change and financial stability produced three key results. First, by destroying the capital of firms and reducing their profitability and liquidity, climate change is likely to increase rate of default of corporate loans that could harm the stability of the banking system. Second, the damages caused by climate change can lead to a portfolio reallocation that can cause a gradual decline in the price of corporate bonds. Third, climate-induced financial instability might adversely affect credit expansion, exacerbating the negative impact of climate change on economic activity. The sensitivity analysis illustrated that these results do not change qualitatively when key parameter values related to the financial system are modified.

The article also investigated how a green QE programme could reduce the risks imposed on the financial system by climate change. The QE that has been examined in the paper is of a very different nature compared to the current QE programmes: it has a long-run horizon and it is a kind of industrial policy rather than a cyclical tool. The simulation results showed that, by increasing the price of green corporate bonds, the implementation of such a green QE programme can reduce climate-induced financial instability and restrict global warming. However, as expected, green QE is not by itself capable of preventing a substantial reduction in atmospheric temperature. Even with an optimistic assumption about the sensitivity of green investment to the divergence between the green bond yield and the conventional bond yield, global warming is still severe. Hence, many other types of environmental policies need to be implemented in conjunction with a green QE programme in order to keep atmospheric temperature close to 2 °C and prevent climate-induced financial instability. These could include traditional green fiscal policies (such as carbon taxes and green public investment), other green finance policies apart from QE (such as green loans subsidies and green differentiated capital requirements) and regulatory interventions that would induce more environmentally friendly consumption norms and methods of production. The investigation of the economic, financial and environmental implications of such policies is left for future research.

Supplementary material to this article can be found online at: <add URL>

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