Climate Policy, Financial Frictions, and Transition Risk[*]

Stefano Carattini[†] Garth Heutel[‡] Givi Melkadze[§]

May 2023

Abstract

We study climate and macroprudential policies in an economy with financial frictions. Using a dynamic stochastic general equilibrium model featuring both a pollution market failure and a market failure in the financial sector, we explore transition risk – whether ambitious climate policy can lead to macroeconomic instability. It can, but the risk can be alleviated through macroprudential policies – taxes or subsidies on banks' assets. Then, we explore efficient climate and macroprudential policy in the long run and over business cycles. The presence of financial frictions affects the steady-state value and dynamic properties of the efficient carbon tax.

JEL Classifications: E32; G18; Q58

Keywords: Carbon taxes; Business cycles; Financial frictions; Stranded assets; Transition risk; Macroprudential policy

---

[*] We thank the editor and two anonymous referees for very useful suggestions. We also thank Andrew Feltenstein, Stephie Fried, Margaret Insley, Soojin Kim, Jorge Martinez-Vazquez, Aude Pommeret, Jonathan Smith, Martin Uribe, and participants at seminars and conferences, including at the Bank of Canada, Bank of France, Dalhousie University, the Halle Institute for Economic Research, Paris Dauphine University, South East Asian Central Banks Research and Training Centre, University of Auckland, Vanderbilt University, and the ASSA 2021 Annual Meetings, AERE 2021 Summer Conference, and NBER 2022 Spring Meetings for helpful comments. All authors acknowledge support from the Alliance for Market Solutions. Carattini acknowledges support from the Grantham Foundation for the Protection of the Environment through the Grantham Research Institute on Climate Change and the Environment and from the ESRC Centre for Climate Change Economics and Policy as well as from the Swiss National Science Foundation, grant number PZ00P1_180006/1.

[†] Georgia State University, CESifo, and University of St. Gallen. Email: scarattini@gsu.edu.

[‡] Georgia State University and NBER. Email: gheutel@gsu.edu.

[§] Georgia State University. Email: gmelkadze@gsu.edu.

1 Introduction

Achieving the Paris Agreement's goal to maintain global temperature increases within 2°C above pre-industrial levels will likely demand ambitious and quick climate policy action, rather than the gradual "ramp-up" approach to policy favored by some integrated assessment models like DICE. Such an ambitious and sudden policy may create macroeconomic risks given the financial sector's investment in fossil fuel reserves and polluting industries. A non-trivial fraction of financial intermediaries' asset portfolios is currently represented by carbon-intensive assets at a high risk of becoming "stranded," i.e. losing most of their economic value. This risk is what Mark Carney's influential speech at Lloyd's (Carney 2015) identified as "transition risk," stemming from unanticipated ambitious climate action. Could a climate policy large and sudden enough to achieve the 2°C goal cause a recession because of the financial sector's exposure to risky assets? And if so, could some other policy mitigate this risk?

Beyond its impact on transition risk, the financial sector can have important implications for the efficient design of climate policy in the long run and over business cycles. The Great Recession has illustrated that financial and credit market frictions play a crucial role in driving business cycles and has emphasized the need for macroprudential regulation to manage financial stability risk (Gertler and Kiyotaki 2010, Bernanke 2019). Both the Great Recession and the COVID-19 recession have demonstrated that carbon emissions are sensitive to economic activity. Given market failures associated with both greenhouse gas pollution and financial frictions, and given banks' exposure to carbon-intensive assets, understanding the interactions between climate policy and macroprudential policy is important for the efficient design of such policies.

The purpose of this paper is to study how the presence of financial market frictions affects the efficient design of climate policy and the possibility of transition risk. We answer the following two questions: (i) Could a sudden and ambitious climate policy shock create transition risk, and can macroprudential policy alleviate this risk? (ii) How do financial frictions affect the efficient design of climate policy and macroprudential financial policy in the long run and over business cycles? We develop a dynamic stochastic general equilibrium (DSGE) model with "brown" (polluting) and "green" (non-polluting) production sectors and two sources of inefficiencies: a pollution externality and financial frictions in a banking sector. We allow for two types of policies: a carbon tax to target the climate externality, and macroprudential policies in the form of a tax or a subsidy on banks' assets to target financial frictions.

At the core of our model are banks that raise deposits from households and make loans to non-financial firms in green and brown sectors. The firms in turn rely on bank credit to finance capital purchases. Financial frictions between banks and depositors constrain the amount of investment in the economy by banking sector equity (or net worth). When banks are in financial stress (i.e., when their net worth is low), real economic activity falls. This is a newly-identified channel through which climate policy can impact the economy.

We calibrate the model to U.S. data and run two sets of simulations. First, we consider the response of the economy to an exogenous abrupt introduction of ambitious climate policy, and we study how this response can be mitigated using macroprudential policies. These simulations address the threat of transition risk induced by climate policy. By "transition risk," we specifically mean the threat that the sudden introduction of a climate policy may lead to macroeconomic instability via the financial sector. However, our model can also accommodate shocks of a different nature with similar implications, such as sudden changes in consumer behaviors, or courts forcing carbon-intensive firms to drastically reduce emissions.

Second, we solve for the efficient policy responses (the Ramsey problem) both in the long run (the steady state) and in response to business cycles generated by exogenous productivity shocks (real business cycles). These simulations address how the pollution externality and the financial frictions interact in the design of efficient policies. We consider both the first-best case, where both a carbon tax and macroprudential policies are available, and second-best cases where some policies are constrained. To assess the role of financial stability risk, we compare economies both with and without financial frictions.

Our first set of simulations shows that transition risk is possible – ambitious climate action can trigger instability in the banking sector – and that macroprudential policy can alleviate this risk. Without financial frictions, an unanticipated introduction of a permanent carbon tax triggers a transition away from brown production and towards green production. With financial frictions, the same carbon tax can lead to a contraction in both the green and brown sectors – a recession. Due to financial instability in the banking sector, climate policy has a negative spillover effect on the green sector. The carbon tax lowers the market value of carbon-intensive assets (asset stranding). Because of their exposure to these assets, banks experience equity losses and are forced to cut lending to both brown and green producers.

The extent of transition risk depends on banks' exposure to carbon-intensive assets at the time of climate action. Therefore, we consider macroprudential policy tools that shift banks' portfolio composition away from brown assets to mitigate the transition risk. Financial regulators, acting within their financial stability mandates, can reduce banks' exposure to climate-sensitive industries and mitigate the risk of a disorderly transition to a low carbon economy. That is, central banks and financial regulators can limit transition risk now to prevent the need to delay, on financial stability grounds, ambitious climate policy, when the opportunity for more stringent policy would present itself. We stress that these simulations are not intended to show that "ambitious climate policy will cause a recession," but rather that prudent financial regulation can ensure that ambitious climate policy does *not* cause a recession. The argument that the threat of macroeconomic instability should prevent climate policy from being enacted thus ignores the ability of macroprudential policy to eliminate that threat.

It is worth comparing our way of modelling macroprudential policies – taxes or subsidies on banks' assets – to Basel-type capital requirements, which are a more common approach to financial regulation in advanced economies. Broadly, capital requirements impose limits on banks' leverage ratios. In our model, the financial friction itself imposes an endogenous leverage constraint on banks. Given this constraint, the taxes and subsidies on banks' assets that we model incorporate, in a tractable way, climate-related factors in macroprudential regulation. For example, a tax on brown assets encourages banks to shift their portfolios away from carbon-intensive sectors. This tax policy closely mimics a capital requirement policy that introduces positive risk-weights on banks' brown assets (e.g., a "brown-penalizing" factor) within the Basel framework, which would also discourage banks from lending to carbon-intensive firms.

In our second set of simulations, we solve for the efficient carbon tax and macroprudential policy, both in the long run (the steady state) and over business cycles driven by productivity shocks. The steady-state results demonstrate the importance of the interaction of the two market failures. Without financial frictions, the carbon tax brings about the first best by reducing emissions. With financial frictions, and when the only available policy instrument is the carbon tax, the second-best carbon tax is lower than its first-best level. This is because the inefficiency from financial frictions works in the opposite direction as the climate externality – the financial frictions lead to underproduction, and the pollution externality leads to overproduction. When the only available policy instrument is a uniform macroprudential policy – a tax or subsidy on banks' assets that is the same for brown and green assets – then output is higher than in the unregulated equilibrium, but pollution is also higher. The regulator uses macroprudential policy to primarily tackle financial frictions with little effect on the climate externality. Using macroprudential policy alone as a substitute for climate policy is not very effective. This is true even when the regulator can use a differentiated macroprudential policy – a tax or subsidy on banks' assets that can be different for brown and green assets. Under the second-best differentiated macroprudential policy, pollution is not much lower than it is under the second-best uniform macroprudential policy. When both a carbon tax and macroprudential policy are available, then the first-best outcome can be achieved. Hence, the implementation of macroprudential policy is not only useful in dealing with transition risk, but also later on, to complement climate policy with the goal of leading to an efficient level of economic activity and emissions.

Our finding that macroprudential policy alone is not very effective at addressing climate change, while not central to our analyses, is still very policy relevant, as it calls into question recent attempts by regulators to use central banks to address climate change. For example, the UK government since 2021 mandates the Bank of England to guide the economy towards net-zero carbon goals, as described in the 2021 budget address to parliament by the Chancellor of the Exchequer (Sunak 2021).

Additional simulations vary the timing of policy implementation, for instance with the carbon tax being announced several periods in advance, policy being implemented more gradually, either with a phase-in of the carbon tax or with macroprudential policy preceding the carbon tax, or carbon taxes following a stochastic process so that the economy is repeatedly surprised by climate policy shocks to mimic climate policy uncertainty. Generally, these additional simulations reinforce the main finding that macroprudential policies can be designed in such a way that they can mitigate transition risk.

The business cycle results also demonstrate the importance of accounting for both market failures. In response to a negative total factor productivity shock, when financial frictions are present, the efficient carbon tax falls by more than when those frictions are absent. As a result, emissions are less procyclical when financial frictions are present. When macroprudential policies are available, emissions are more procyclical than when the carbon tax is the only available instrument. In the absence of a carbon tax, macroprudential policies (both uniform and differentiated) yield more procyclical emissions than the first best.

Our paper contributes to several strands of literature. We contribute to a growing theoretical literature on climate policy and stranded assets. Van der Ploeg and Rezai (2020) and Rozenberg, Vogt-Schilb, and Hallegatte (2020) show that unanticipated changes in climate policy may result in the stranding of carbon-intensive capital.[1] We also contribute to an emerging

---

[1] See also reviews by Monasterolo (2020) and Semienuk et al. (2021). There is also growing empirical literature studying climate policy and stranded assets, such as Carattini and Sen (2019), Sen and von Schickfus (2020), and Ramelli et al. (2021). Van der Ploeg (2020) provides a review of the inability of financial markets to fully price climate risks.

literature analyzing the role of central banks and macroprudential authorities in tackling climate change, including Campiglio (2016) and Böser and Colesanti Senni (2020). Further, our paper is related to an established literature in macroeconomics allowing for financial frictions, building on the seminal work by Bernanke and Gertler (1989) and Kiyotaki and Moore (1997). This literature, which largely responded to the Great Recession, identifies credit market frictions and disruptions in the banking sector as an important source of macroeconomic fluctuations (Meh and Moran 2010, Jermann and Quadrini 2012, Christiano and Ikeda 2013, Brunnermeier and Sannikov 2014, Iacoviello 2015; see also Brunnermeier, Eisenbach, and Sannikov 2013 for an extensive survey of the literature on macroeconomic models with financial frictions). Finally, we contribute to the literature that studies macroprudential regulation of the financial sector (e.g., Gertler, Kiyotaki, and Queralto 2012, Angeloni and Faia 2013, Collard et al. 2017, De Paoli and Paustian 2017, Jeanne and Korinek 2020). Our way of modelling macroprudential policy instruments as taxes and subsidies on banks' assets is most similar to that of Gertler, Kiyotaki, and Queralto (2012) and De Paoli and Paustian (2017).

Methodologically, our paper combines two strands of the DSGE literature. The first adds an environmental component to a DSGE model (which has been called an E-DSGE model) to study climate and other environmental policies under business cycles, including Fischer and Springborn (2011), Heutel (2012), and Dissou and Karnizova (2016).[2] Second, our paper relates to the literature addressing the role of financial frictions in driving macroeconomic dynamics, using a banking sector DSGE model from Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). Our model combines a standard DSGE real business cycle model with an environmental component (as in the E-DSGE literature) and with banking financial frictions (as in Gertler and Kiyotaki 2010 and Gertler and Karadi 2011).

Two concurrent studies by Diluiso et al. (2021) and Benmir and Roman (2020) also combine

---

[2] See Fischer and Heutel (2013) and Annicchiarico et al. (2021) for surveys of this literature. Golosov et al. (2014) also develop a DSGE model with an environmental externality but do not study business cycles. Gallic and Vermandel (2020) develop a DSGE model of climate and weather shocks, but without pollution or pollution policy.

an E-DSGE model with a banking sector and financial frictions based on Gertler and Karadi (2011) to address a related set of research questions. As we do, Diluiso et al. (2021) study transition risk stemming from climate policy, but unlike our paper, they do not study first-best or second-best efficient policy design via the Ramsey optimization problem. In addition, our results on transition risk differ substantially from theirs, given the relative focus each paper places on the type of transition. Diluiso et al. (2021) conclude that "even for very ambitious climate targets, transition risks are limited for a credible, exponentially growing carbon price." However, the main concern of central banks and policymakers is an unanticipated sudden policy shock, rather than a gradual one, potentially leading to a "hard landing," where a large portion of the economy is exposed to transition risk (Battiston et al. 2017, ECB 2021). While both studies ultimately consider both gradual and abrupt transitions, each study's contribution lies with their main focus, ours being on the abrupt rather than gradual transition (see also Annicchiarico et al. 2021 for a broader discussion).

Our paper differs from Benmir and Roman (2020) in several important dimensions. First, Benmir and Roman (2020) do not analyze climate-policy-driven financial stability risk. Instead, one of their main findings is that the efficiency of carbon tax in reducing emissions "heavily depends on the abatement efficiency (i.e. low transition cost)" controlled by an exogenous parameter in the abatement cost function. This result is intuitive but is unrelated to the issue of climate-related financial risks – the main focus of our study and the main concern of central banks and financial authorities. Second, Benmir and Roman (2020) find that the carbon tax needed to achieve the goal of the Paris Agreement yields substantial welfare losses in the long run. On the contrary, our efficient carbon tax, while powerful enough to reduce emissions by 40%, brings about welfare gains in the long run (as one would expect from addressing the climate externality). Finally, Benmir and Roman (2020) only study second-best Ramsey-efficient climate policy, while we also analyze first-best policy and importantly, second-best macroprudential policies, in the steady state as well as over the business cycle.

Several other E-DSGE papers also consider macroeconomic policies and the interaction between macroeconomic and environmental policies. Annicchiarico and Di Dio (2015, 2017) and Economides and Xepapadeas (2018) add a new-Keynesian specification of price rigidities to an E-DSGE model to study monetary policy. Chan (2020) compares fiscal and monetary policies to climate policies. As mentioned earlier, like our paper, Diluiso et al. (2021) and Benmir and Roman (2020) also combine an E-DSGE model with financial frictions and macroprudential policy, as do Ferrari and Nispi Landi (2023).

The paper proceeds as follows. Section 2 presents the model, and Section 3 describes the calibration. Sections 4 and 5 present our simulation results. In Section 4, we assess the transition risk of climate-policy-induced recession by presenting the response to an unanticipated exogenous emissions tax, both with and without financial frictions, and with and without macroprudential policies. Section 5 considers efficient policy design by presenting results from the Ramsey problems, both first-best and second-best, in both the deterministic steady state and in response to exogenous productivity shocks. Section 6 concludes.

2 Model

We consider a closed economy consisting of households, a government, and four types of firms – financial intermediaries (banks), capital producers, and non-financial goods-producing "green" and "brown" firms. The economy features two sources of inefficiency. The first is a standard environmental externality: brown firms do not internalize how their individual production decisions affect the pollution stock and thus aggregate output. The second source of inefficiency comes from financial market frictions: the moral hazard problem between banks and depositors constrains the amount of credit in the economy by banks' net worth. Since bankers cannot issue new equity when constrained, credit is undersupplied, and shocks to the economy are inefficiently amplified through the standard financial accelerator mechanism. To address these inefficiencies, we model two types of policies: climate policy, in the form of a carbon tax, and macroprudential policies, in the form of taxes or subsidies on banks' assets.

2.1 Households

We follow Gertler and Karadi (2011) in formulating the household sector. There is a continuum of identical households of measure unity. Each household has a continuum of a unit measure of family members. A fraction $(1-\iota)$ of members are workers, and a fraction ι are bankers. Workers supply labor hours to non-financial firms in brown and green production sectors and return wage income to the household. Each banker manages a financial intermediary (a bank) and transfers dividends to the household. There is perfect consumption insurance within the household. The household consumes and saves. Households cannot save by directly lending to productive firms. Rather, they can only save through depositing funds in banks.

A representative household chooses consumption C_t, savings in the form of bank deposits D_t, and sector-specific labor hours, L_t^b and L_t^g, to maximize

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\eta} \left(C_t - \varpi \frac{\left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L} \right]^{\frac{1+\xi}{1+\rho_L}}}{1+\xi} \right)^{1-\eta} \right\}, \tag{1}$$

subject to the budget constraint,

$$C_t + D_t = w_t^b L_t^b + w_t^g L_t^g + R_{t-1} D_{t-1} + \Xi_t + \Pi_t + T_t, \tag{2}$$

where w_t^b and w_t^g are wage rates in brown and green sectors, R_{t-1} is a non-contingent interest rate on bank deposits, Ξ_t are net dividends from banks, Π_t denotes profits from the ownership of non-financial firms, and T_t is a lump-sum transfer from the government. The parameter $\beta \in (0,1)$ is the household's subjective discount factor, $\varpi > 0$ is a labor disutility parameter, and $\eta > 0$ controls the curvature of the utility function.

The specification of labor hours in the utility function follows Horvath (2000) and allows for imperfect labor substitutability between the sectors. In every period the representative household is endowed with one unit of time. Denote by $L_t \equiv \left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L}\right]^{\frac{1}{1+\rho_L}}$ total (composite) hours worked in period t. When $\rho_L = 0$, labor hours in brown and green sectors are perfect substitutes. When $\rho_L > 0$, labor hours are imperfect substitutes across the sectors. The parameter ξ is the inverse of the Frisch elasticity of the labor hours aggregator. This preference specification, based on Greenwood-Hercowitz-Huffman (1988), eliminates wealth effects, and so in Appendix F we will consider robustness to an alternate specification of preferences.

Let $M_{t,t+1} \equiv \beta \frac{U_{c,t+1}}{U_{c,t}}$ be the household's stochastic discount factor, where $U_{c,t} = \left(C_t - \varpi \frac{L_t^{1+\xi}}{1+\xi}\right)^{-\eta}$ is the marginal utility of consumption in period t. Then households' optimal consumption and sector-specific labor supply decisions are characterized by standard first order conditions:

$$\mathbb{E}_t\left(M_{t,t+1} R_t\right) = 1, \tag{3}$$

$$\varpi L_t^{\xi-\rho_L}\left(L_t^i\right)^{\rho_L} = w_t^i, \quad \text{for } i = \{g, b\}. \tag{4}$$

2.2 Bankers

Each banker manages a financial intermediary (a bank). The banker offers loans to non-financial firms by combining her own net worth with external funds raised from households in the form of deposits. In particular, at time t, an individual banker j purchases securities $S_{j,t}^i$, at unit price Q_t^i, issued by final good producing firms in sector $i = \{g, b\}$. These securities are claims on the gross rate of return on sector-specific capital. The government can levy macroprudential taxes (or subsidies if negative) τ_t^i, $i = \{g, b\}$, on banks' assets. We allow these taxes to potentially differ across brown and green assets, which would capture the scenario in which a supervisory authority takes into account environmental aspects in bank capital regulation.

These taxes or subsidies capture some of the proposed policies in bank regulatory frameworks, e.g., brown penalizing and green supporting factors. Taxes on banks' assets require information about firms' emissions, unlike carbon taxes, which can be implemented upstream. But we consider this a feasible policy in the context of rapidly expanding mandatory climate-related disclosures. For instance, in the United Kingdom all large firms must disclose carbon emissions under the Streamlined Energy and Carbon Reporting scheme, while in the United States large polluters must report carbon emissions to the Environmental Protection Agency under the Greenhouse Gas Reporting Program. In March 2022, the U.S. Securities and Exchange Commission (SEC) also proposed a climate disclosure rule that, if approved, would require all publicly traded firms in the United States to disclose carbon emissions, and whose implications for the design of macroprudential policy are discussed in Carattini et al. (2022).

The banker finances the expenditure side of her balance sheet with net worth $N_{j,t}$ and newly issued deposits $D_{j,t}$. Thus, the individual bank's balance sheet or flow-of-funds constraint in time t is given by

$$(1+\tau_t^b)Q_t^b S_{j,t}^b + (1+\tau_t^g)Q_t^g S_{j,t}^g = D_{j,t} + N_{j,t}. \tag{5}$$

Denote by $R_{k,t}^b$ and $R_{k,t}^g$ the time t realized gross rates of return on banks' brown and green assets, respectively. The individual bank's net worth evolves according to

$$N_{j,t+1} = R_{k,t+1}^b Q_t^b S_{j,t}^b + R_{k,t+1}^g Q_t^g S_{j,t}^g - R_t D_{j,t}. \tag{6}$$

As in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011), we introduce the following moral hazard problem to limit banks' ability to obtain external funds: After raising deposits and purchasing assets at time t, a banker managing the bank can choose to divert an exogenous fraction κ of total assets for personal use (i.e., transfer the funds to his/her own household). The cost to the banker from diverting the funds is that the depositors can shut down the bank after recovering the remaining $(1-\kappa)$ fraction of assets. Recognizing the possibility of bankers "running away," depositors will thus lend to banker j only if she has incentives to operate honestly.

Let $V_{j,t}$ denote the franchise (or continuation) value of the bank at the end of period t. Then for the depositors (households) to be willing to deposit money with banker j, the following incentive constraint must be satisfied,

$$V_{j,t} \geq \kappa(Q_t^b S_{j,t}^b + Q_t^g S_{j,t}^g). \tag{7}$$

Households are willing to lend to a bank as long as the bank's franchise value $V_{j,t}$, which measures the present discounted value of future profits from operating honestly, is larger than the gains from diverting funds. This inequality always holds, so in equilibrium, bankers never actually "run away" or divert funds.

At the end of each period, a banker exits the business with exogenous probability $1-\gamma$, following a common assumption in the financial frictions literature, which guarantees that banks never accumulate enough internal funds to avoid the need for external finance. Upon exit, a banker transfers her retained earnings to her family in the form of dividends and becomes a worker.[3] Surviving bankers reinvest all their net worth. Since bankers are members of households, they maximize the expected present value of their terminal wealth (or future dividend payouts to households). A banker chooses asset holdings in green and brown production sectors $S_{j,t}^i$, $i = \{g, b\}$, and deposits $D_{j,t}$ to maximize

$$V_{j,t} = \mathbb{E}_t \left\{ \sum_{\widetilde{\tau}=t+1}^{\infty} (1-\gamma)\, \gamma^{\widetilde{\tau}-t-1} M_{t,\widetilde{\tau}} N_{j,\widetilde{\tau}} \right\}, \tag{8}$$

subject to (5), (6) and (7), where $M_{t,\widetilde{\tau}}$ is the households' stochastic discount factor $M_{t,\widetilde{\tau}} \equiv \beta^{\widetilde{\tau}-t} \frac{U'_{c,\widetilde{\tau}}}{U'_{c,t}}$. Appendix A contains a detailed characterization of the bank's problem and associated optimality conditions. Here we discuss key equations.

---

[3] The number of bankers that become workers in every period is thus $(1-\gamma)\,\iota$. To keep the relative proportion of each group fixed over time, we assume that the same number of workers randomly become bankers in every period.

In the Appendix, we show that the bank's value function is linear in individual net worth,

$$V_{j,t} = \varphi_t N_{j,t}, \tag{9}$$

where $\varphi_t \geq 1$ is the time-varying shadow value of a bank's net worth, common across banks. Combining (9) with (7), we can express the incentive constraint as

$$Q_t^b S_{j,t}^b + Q_t^g S_{j,t}^g \leq \frac{\varphi_t}{\kappa} N_{j,t}. \tag{10}$$

Bank's assets cannot exceed a fraction $\frac{\varphi_t}{\kappa}$ of its equity capital. In our calibrated model, this constraint will always bind in the proximity of the steady state. Aggregating (10) at equality over the entire banking sector yields

$$Q_t^b S_t^b + Q_t^g S_t^g = \frac{\varphi_t}{\kappa} N_t. \tag{11}$$

This is the key equation capturing the negative financial accelerator and the inefficiency arising from the financial sector. When banks are financially constrained, the demand for capital in the economy $\left(Q_t^b S_t^b + Q_t^g S_t^g\right)$ is restricted by the amount of financial intermediaries' aggregate net worth (N_t). Shocks to the economy get amplified through fluctuations in the banking sector's equity capital. Bankers do not internalize this effect that their net worth has on the economy – this is analogous to a second externality – and thus the equilibrium is inefficient.

Banks' optimal portfolio decision leads to the following standard no-arbitrage condition between green and brown loans,

$$\mathbb{E}_t \left\{ \Omega_{t+1} \left[R_{k,t+1}^b - \left(1 + \tau_t^b\right) R_t \right] \right\} = \mathbb{E}_t \left\{ \Omega_{t+1} \left[R_{k,t+1}^g - \left(1 + \tau_t^g\right) R_t \right] \right\}, \tag{12}$$

where $\Omega_{t+1} \equiv M_{t,t+1} \left(1 - \gamma + \gamma \varphi_{t+1}\right)$ is the bankers' effective stochastic discount factor. That is, the expected discounted excess returns on the banks' green and brown assets, taking into account the tax (dis)advantage of each type of asset, have to be equalized. Equation (12) illustrates how macroprudential policy affects banks' demand for brown versus green assets. For example, all else equal, a higher τ_t^b lowers the expected excess return on brown loans relative to green. For equation (12) to hold again with the higher τ_t^b, the required return on brown assets ($R_{k,t+1}^b$) has to increase, tightening the supply of brown loans. Therefore, through macroprudential taxes a regulator can affect the relative supply of different types of loans in the economy.

Banks that exit the business are replaced by an equal number of new banks, with each of them receiving a small initial start-up transfer $\frac{\zeta}{1-\gamma}\sum_{i=\{g,b\}} Q_t^i S_t^i$ from the households. Thus, the aggregate banking sector's net worth evolves according to

$$N_{t+1} = \gamma \left[\sum_{i=\{g,b\}} R_{k,t+1}^i Q_t^i S_t^i - R_t D_t \right] + \zeta \sum_{i=\{g,b\}} Q_t^i S_t^i, \tag{13}$$

and the net dividend payouts to households are

$$\Xi_{t+1} = (1-\gamma) \left[\sum_{i=\{g,b\}} R_{k,t+1}^i Q_t^i S_t^i - R_t D_t \right] - \zeta \sum_{i=\{g,b\}} Q_t^i S_t^i. \tag{14}$$

As is common in the financial frictions literature, we define credit spread a difference between the expected rate of return on a given type of asset and the risk-free rate, $\text{spread}_t^i \equiv \mathbb{E}_t\left(R_{k,t+1}^i - R_t\right),\ i \in \{b,g\}$. The aggregate banking sector leverage ratio is the value of banks' total assets over net worth, $\text{lev}_t \equiv \frac{Q_t^b S_t^b + Q_t^g S_t^g}{N_t}$, and the portfolio share of brown assets is denoted by $s_t^b \equiv \frac{Q_t^b S_t^b}{Q_t^b S_t^b + Q_t^g S_t^g}$.

2.3 Goods-Producing Firms

Two types of representative firms produce green and brown output. Brown production entails emissions as a byproduct, while green production does not. Both production sectors rely on the banking sector to obtain funds to purchase capital.

2.3.1 Production Technology

Pollution negatively affects productivity in both green and brown sectors. Both types of firms operate a Cobb-Douglas production technology with capital $\left(K_{t-1}^{i}\right)$ and labor (L_t^i) inputs,

$$Y_t^i = \left[1 - d\left(X_t\right)\right] A_t \left(K_{t-1}^{i}\right)^{\alpha^i} \left(L_t^i\right)^{1-\alpha^i}, \tag{15}$$

where $\alpha^i \in (0,1)$ is a parameter, X_t is the pollution stock in the economy, $d\left(\cdot\right) \in (0,1)$ is an increasing damage function, and A_t denotes the aggregate stochastic total factor productivity (TFP),

$$\log A_t = \rho_A \log A_{t-1} + \sigma_A \varepsilon_{A,t}, \quad \varepsilon_{A,t} \sim \mathcal{N}\left(0,1\right). \tag{16}$$

Green and brown goods are imperfect substitutes for each other. The aggregate final consumption good Y_t is a constant elasticity of substitution aggregate of sectoral outputs,

$$Y_t = \left[\left(\pi^b\right)^{\frac{1}{\rho_Y}} \left(Y_t^b\right)^{\frac{\rho_Y-1}{\rho_Y}} + \left(1-\pi^b\right)^{\frac{1}{\rho_Y}} \left(Y_t^g\right)^{\frac{\rho_Y-1}{\rho_Y}}\right]^{\frac{\rho_Y}{\rho_Y-1}}, \tag{17}$$

where $\rho_Y > 0$ is the elasticity of substitution parameter, and π^b is the weight on brown input in the final good production. The demand functions for the two types of output are

$$Y_t^b = \pi^b \frac{Y_t}{\left(p_t^b\right)^{\rho_Y}}, \; Y_t^g = \left(1-\pi^b\right) \frac{Y_t}{\left(p_t^g\right)^{\rho_Y}}, \tag{18}$$

where p_t^b and p_t^g denote relative prices of brown and green goods. The final consumption good is numeraire, and its price is normalized to 1.

2.3.2 Brown Sector

Production in the brown sector entails emissions as a byproduct. The pollution stock X_t evolves according to

$$X_t = \delta_X X_{t-1} + e_t + e_t^{\mathrm{row}}, \tag{19}$$

where e_t denotes current-period domestic emissions and e_t^{row} is emissions imposed from the rest of the world. Domestic emissions depend on production in the brown sector $\left(Y_t^b\right)$ and the fraction of emissions abated μ_t,

$$e_t = \left(1 - \mu_t\right) Y_t^b. \tag{20}$$

Emissions abatement is costly. Abating the fraction μ_t of emissions costs Z_t units of the final good,

$$Z_t = \theta_1 \mu_t^{\theta_2} Y_t^b. \tag{21}$$

The specification of emissions and abatement cost functions are similar to Nordhaus (2008), Heutel (2012), and Barrage (2020). An environmental externality arises because the representative brown firm does not internalize how its production affects both green and brown output through the pollution stock X_t and associated damages $d\left(X_t\right)$.

At the end of period t final goods firms in the brown sector purchase capital K_t^b from capital producers at market price Q_t^b. Following Gertler and Karadi (2011), the firms finance their capital purchases by issuing financial claims S_t^b to banks. Each claim is priced at the same price $\left(Q_t^b\right)$ as capital so that $Q_t^b K_t^b = Q_t^b S_t^b$. After production takes place in time $t+1$, the firm can sell the undepreciated capital $\left(1 - \delta^b\right) K_t^b$ on the market at price Q_{t+1}^b. There are no financing frictions between firms and banks, and the firms offer a state-contingent payoff $R_{k,t+1}^b$ on securities owned by the financial intermediaries.

Brown firms are subject to an emissions tax τ_t^e imposed by the government. Their time t

realized profits are

$$\Pi_t^b = p_t^b Y_t^b - \tau_t^e e_t - Z_t - w_t^b L_t^b - R_{k,t}^b Q_{t-1}^b K_{t-1}^b + \left(1-\delta^b\right) Q_t^b K_{t-1}^b. \tag{22}$$

The optimality conditions with respect to labor $\left(L_t^b\right)$ and abatement (μ_t) are:

$$w_t^b = \left(1-\alpha^b\right) \frac{Y_t^b}{L_t^b} \left[p_t^b - \theta_1 \mu_t^{\theta_2} - \tau_t^e \left(1-\mu_t\right)\right], \tag{23}$$

$$\tau_t^e = \theta_1 \theta_2 \mu_t^{\theta_2 - 1}. \tag{24}$$

A state-contingent return on brown assets, satisfying the optimality condition, is given by

$$R_{k,t}^b = \frac{\alpha^b \frac{Y_t^b}{K_{t-1}^b} \left[p_t^b - \theta_1 \mu_t^{\theta_2} - \tau_t^e \left(1-\mu_t\right)\right] + \left(1-\delta^b\right) Q_t^b}{Q_{t-1}^b}. \tag{25}$$

2.3.3 Green Sector

Similar to brown firms, green firms rely on bank credit to purchase sector-specific capital K_t^g at price Q_t^g. They also hire labor L_t^g from households at wage rate w_t^g. The green firms' optimality conditions imply

$$w_t^g = \left(1-\alpha^g\right) \frac{p_t^g Y_t^g}{L_t^g}, \tag{26}$$

and

$$R_{k,t}^g = \frac{\alpha^g \frac{p_t^g Y_t^g}{K_{t-1}^g} + \left(1-\delta^g\right) Q_t^g}{Q_{t-1}^g}. \tag{27}$$

2.4 Capital Firms

Capital is sector-specific and immobile across sectors. Competitive capital-producing firms build green and brown capital goods subject to convex capital adjustment costs. Producing I_t^i, $i = \{g, b\}$, units of sector-specific new capital goods requires $\left(1 + \frac{\phi^i}{2}\left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2\right) I_t^i$ units of the final good, where the parameter $\phi^i \geq 0$ controls the size of the adjustment cost (Christiano, Eichenbaum, and Evans 2005).

Denote by Q_t^i the price of new sector-specific capital goods. The capital producers solve

$$\max_{\{I_t^i\}_{i=\{g,b\}}} \mathbb{E}_0 \sum_{t=0}^{\infty} M_{0,t} \sum_{i=\{g,b\}} \left[Q_t^i I_t^i - \left(1 + \frac{\phi^i}{2} \left(\frac{I_t^i}{I_{t-1}^i} - 1 \right)^2 \right) I_t^i \right]. \tag{28}$$

The first order optimality condition associated with this problem is

$$Q_t^i = 1 + \frac{\phi^i}{2} \left(\frac{I_t^i}{I_{t-1}^i} - 1 \right)^2 + \phi^i \left(\frac{I_t^i}{I_{t-1}^i} - 1 \right) \frac{I_t^i}{I_{t-1}^i} - \mathbb{E}_t \left\{ M_{t,t+1} \phi^i \left(\frac{I_{t+1}^i}{I_t^i} - 1 \right) \left(\frac{I_{t+1}^i}{I_t^i} \right)^2 \right\}, \quad i = \{g, b\}. \tag{29}$$

Sector-specific capital stock evolves according to

$$K_t^i = \left(1 - \delta^i\right) K_{t-1}^i + I_t^i, \text{ for } i = \{g, b\}, \tag{30}$$

where δ^i is the depreciation rate of capital.

2.5 Government

The government simply transfers net revenues from the carbon tax and the macroprudential policies to households in a lump-sum manner,

$$T_t = \tau_t^e e_t + \tau_t^b Q_t^b S_t^b + \tau_t^g Q_t^g S_t^g. \tag{31}$$

3 Calibration

A period in the model corresponds to one quarter. The model parameters can be divided into three categories: standard real business cycle (RBC) parameters, parameters related to financial frictions, and parameters related to climate externalities. Table 1 summarizes the calibrated values. The calibration is based on the baseline scenario when all policy instruments are zero ($\tau_t^e = \tau_t^b = \tau_t^g = 0$).

We choose standard values for the subjective discount factor $\beta = 0.9975$ (which implies an annualized risk-free rate of 1% in the steady state), the risk aversion parameter, $\eta = 2$, the Frisch elasticity of labor supply, $\frac{1}{\xi} = 1$, and the capital depreciation rate, $\delta^b = \delta^g = 0.025$. We set the capital share in green production α^g to 0.33. We allow the brown sector to be slightly more capital intensive, $\alpha^b = 0.35$.[4] Both of these values are commonly used in the RBC literature. The parameter controlling for inter-sectoral elasticity of substitution between labor hours (ρ_L) is set to 1. This is the estimate found by Horvath (2000) using sectoral labor hours data from the U.S. As is common in the RBC literature, we set the labor disutility parameter ϖ so that the fraction of time spent working in the steady state is $\frac{1}{3}$.

For the elasticity of substitution between green and brown output, we rely on empirical estimates in Papageorgiou, Saam, and Schulte (2013) and set $\rho_Y = 2$. We choose the share of brown output in the production of final consumption good $\left(\pi^b\right)$ to target the steady-state ratio of green-to-total capital stock of 0.60.[5] The implied value, $\pi^b = 0.332$, is also consistent with the fact that income share of green sector to total output is about 70%. The persistence and standard deviation of the aggregate TFP shock are set at the standard RBC values, $\rho_A = 0.95$, $\sigma_A = 0.007$. The investment adjustment cost parameter for both sectors (ϕ^i) is 10. These values are in line with the parameter values also used in the environmental DSGE literature (e.g., Heutel 2012, Annicchiarico and Di Dio 2015).[6]

We calibrate the environmental part of the model based on the most recent version of the

---

[4] For instance, Antweiler, Copeland, and Taylor (2001) and Fullerton and Heutel (2007) find that the dirty sector is slightly more capital intensive than the clean sector.

[5] This yields a slightly lower ratio of green-to-total capital stock than in some other studies, e.g. Fried, Novan and Peterman (2021) calibrate a ratio of about 0.80. Since nearly all production uses at least some polluting inputs, it is inevitably somewhat arbitrary to impose a strict cutoff between a green and brown sector.

[6] These values also imply that the standard deviations of simulated (HP-filtered) series are consistent with business cycle stylized facts. Aggregate investment is much more volatile than output, $\sigma(I)/\sigma(Y) = 2.3$; consumption is less volatile than output, $\sigma(C)/\sigma(Y) = 0.7$; the standard deviation of output series $\sigma(Y) = 1.4\%$.

DICE model (Nordhaus 2018). While DICE models damage as a function of temperature, where temperature is affected by the carbon stock through a dynamic climate model, here we simplify and model damages directly as a function of carbon $d\left(X_t\right)$. The climate damage function takes a quadratic form $d\left(X_t\right) = d_0 + d_1 X_t + d_2 X_t^2$. We calibrate the damage function using a methodology similar to that of Gibson and Heutel (2020),[7] and we arrive at the parameter values $\widehat{d_0} = -0.026$, $\widehat{d_1} = 3.61e-5$, and $\widehat{d_2} = 1.44e-8$.

In the parameterized damage function, pollution stock (X_t) is measured in gigatons of carbon, while in our model, the units are abstract. To map the empirical estimates into the model, we set the steady-state pollution level to 1172 GtC, which is the mean value of the carbon stock over the first 250 years of the simulation in the DICE optimal tax scenario.[8] We consider this scenario, rather than starting at the current real-world level of the carbon stock, because our exercise requires a high enough level of pollution stock and damages in order for the carbon tax to have a substantial magnitude. This is because pollution damages in DICE are growing as a result of TFP growth, which is absent in our DSGE model.[9] This implies that at the steady state, damages are of 3.6% of output (i.e., $d(X_{ss,\text{model}}) = 0.036$). It also implies (as we will show in the results) that the steady-state level of the efficient carbon tax is about \$17 per ton of carbon dioxide, which is just slightly less than the social cost of carbon found by Nordhaus (2017) when using DICE.

Since other studies using other integrated assessment models (IAMs) or other methodologies argue for higher social costs of carbon (e.g., Ricke et al. 2018, Pindyck 2019), our model can be understood as a conservative approach based on DICE. If anything, higher social costs of

---

[7] Like Gibson and Heutel (2020), we run the climate portion of the DICE model for various exogenous levels of atmospheric carbon stock, then evaluate the resulting temperature and damages for each level, and fit the damage function based on the results. But unlike Gibson and Heutel (2020), we calculate temperature and damages based only on the long-run stable equilibrium that the climate reaches in DICE; i.e. we exclude the first several periods for burn-in.

[8] That is, we compute $d_{\text{scale}} = \frac{X_{ss,\text{model}}}{1172}$ and rescale the empirical estimates accordingly: $d_1 = \frac{\widehat{d_1}}{d_{\text{scale}}}$ and $d_2 = \frac{\widehat{d_2}}{d_{\text{scale}}^2}$.

[9] Later, in a sensitivity analysis, we will also run simulations calibrated to the current real-world level of the carbon stock.

carbon would lead to stronger shocks to the economy if ambitious climate policy is abruptly implemented. The same applies to carbon tax rates obtained following a cost-effectiveness approach, as in Stiglitz et al. (2017) and IMF (2019).

The abatement cost function is also parameterized following Nordhaus (2018). We set the exponent θ_2 to 2.6 – the same value as in Nordhaus (2018). To calibrate the coefficient θ_1, we take into account two considerations: First, the abatement cost coefficient is a decreasing function of time in DICE, representing growth in abatement technology, though it is constant in our model. Second, in our model, the abatement cost applies only to the brown sector, while in DICE, it is calibrated as a share of total GDP. As in our strategy for the steady-state pollution stock calibration, we take the mean value of the abatement coefficient from DICE over the first 250 years of the simulation, and then we rescale it to account for the fact that it applies just to the brown sector.[10] The resulting value of θ_1 is 0.0334. The pollution decay parameter δ_X is set to 0.9965 following Gibson and Heutel (2020). Emissions from the rest of the world are assumed to be constant over time $e_t^{\text{row}} = e^{\text{row}}$. Consistent with the fact that the U.S. emits about one-sixth of global carbon dioxide, we set e^{row} to equal five times the steady-state value of domestic emissions.

We set the bank survival rate γ to 0.972 as in Gertler and Karadi (2011), implying that, on average, bankers survive for about 9 years. We choose the values for the fraction of funds that can be diverted (κ) and transfer parameter (ζ) to match the steady-state leverage ratio of the banking sector of 5 and annualized credit spreads (both on brown and green assets) of 90 basis points. This implies the parameter values $\kappa = 0.3313$, $\zeta = 0.0029$, which are in line with the ones used in Gertler and Karadi (2011) and Gertler and Kiyotaki (2010).

---

[10] The mean value of the abatement cost coefficient for the first 250 years of DICE simulation is 0.015. We multiply this value by the ratio $\frac{Y_{ss}}{Y_{ss}^b}$ to obtain the adjusted θ_1.

4 Climate action and transition risk

In this section, we study transition dynamics to a low-carbon economy, and we assess the risk of policy-induced recession and the potential for macroprudential policy to address it.[11] We consider a surprise introduction of a permanent emissions tax of 17.2 dollars per ton of CO_2, which is the efficient steady-state carbon price in our model. We can think of this scenario as one in which, after decades of delayed and insufficient action, there is a sudden shift in the global political environment resulting in the implementation of ambitious climate policy.

The carbon tax that we consider is lower than those recommended by Stiglitz and Stern (2017) and the IMF (2019), which argue that a global carbon tax within the \$40-\$80 range would be necessary to achieve the temperature trajectory consistent with the Paris Agreement. If anything, a higher carbon tax would lead to a larger shock to the economy when ambitious climate policy is abruptly implemented, making our approach conservative or accommodating expectations of a positive carbon tax rate among agents. That is, our experiment can also be seen as a carbon tax shock of 17.2 dollars per ton of CO_2 above expectations, i.e., a surprise increase of 17.2 dollars in the carbon tax rate that agents had priced in.

The economy starts in the baseline deterministic steady state (with no policies of either type, climate or macroprudential). In time period (quarter) 5, the economy is surprised by the introduction of a permanent emissions tax.[12] We focus on the transition dynamics in which the economy has perfect foresight about its future path after the tax has been introduced. In this section we ignore productivity shocks. We compare results from our baseline model (described above) to a model that does not have a banking sector and thus does not have financial frictions.[13] This comparison allows us to gauge the importance of financial frictions

---

[11] We solve the model numerically using the Dynare package developed by Adjemian et al. (2011).

[12] The \$17.2 per ton of CO_2 tax shock corresponds to an increase in τ_t^e from 0 to 0.0192. To obtain dollar amounts we perform a back-of-the-envelope calculation in which we set the steady state level of aggregate output in the baseline model to be equal to the U.S. GDP (\$20 trillion) and the steady state emissions to the level of emissions consistent with the pollution stock of 1172 GtC.

[13] The model without financial frictions is a two-sector environmental DSGE model in which households directly lend capital to non-financial firms with no agency problem between households and firms.

in the macroeconomic effects of a carbon price shock.

Figure 1 plots the transition dynamics in response to the exogenous carbon tax. Solid lines show the dynamics of our baseline model with financial frictions presented in Section 2. Dashed lines show the dynamics of the model without financial frictions. Each simulation starts in the steady state of the given model. In response to the carbon tax, emissions fall by about 40% (Panel (a)), with or without financial frictions. The next two panels show that the economy with financial frictions experiences a deeper recession: investment and output fall by more than they do in the economy without financial frictions. In the long run, once this permanent carbon tax is implemented and the economy makes a transition to the new post-tax steady state, aggregate output and welfare will increase. This is because the tax is set at the level such that in the steady state it perfectly internalizes the climate externality. Just as in the DICE model, when this Pigouvian tax induces the first-best level of abatement, total output and total welfare are both higher than under the no-policy case, since the reduction in emissions that the tax brings about enhances growth in the long run. However, the focus of the simulations in this section is on the transition, so we present relatively short to medium term economic dynamics (i.e., the first 20 periods after the carbon tax has been put in place).[14]

The remaining panels of Figure 1 illustrate the mechanisms behind the climate-policy-induced financial crisis. Panel (d) shows that the banking sector's net worth quickly falls by about 13% before rebounding. These equity losses in the banking sector occur because of falling asset prices (particularly on brown assets) from the emissions tax. With financial frictions, undercapitalized banks are forced to cut lending to both brown and green sectors (e.g., brown and green credit spreads rise). Tighter credit supply implies that both brown and green capital fall (Panels (e) and (f)). Without financial frictions, the economy moves away from

---

[14] Early in the transition, output falls even in the economy without financial frictions because the carbon tax lowers equilibrium labor hours, and even though damages also fall, the former effect dominates. Once the new post-tax steady state is reached, aggregate output is higher than the initial steady state, and green production expands while brown production contracts. Because of the very slow decay rate of the carbon pollution stock (a quarterly decay rate of less than one-half of one percent, calibrated based on a half-life of 50 years), it takes several hundred periods for the economy to reach this new steady state.

brown and towards green investment, and green capital expands as a result. The green sector and the economy overall experience a deeper and more prolonged recession in the economy with financial frictions, since the frictions slow the transition from brown to green production.

We next ask whether macroprudential regulation can mitigate this transition risk by reducing banks' exposure to brown assets. Suppose that prior to the introduction of the emissions tax, the regulator enacts a tax-and-subsidy scheme on brown and green assets to shift banks' steady-state portfolio composition away from brown assets. We set $\tau^b = 0.005$ and $\tau^g = -0.003$, which reduces the share of brown assets in banks' portfolios from 40% to 32.4%.[15]

Figure 2 shows the same transition dynamics as in Figure 1 for the economy with financial frictions but also includes the dynamics after the introduction of the macroprudential policies. Each simulation starts in the steady state with no carbon policy but with or without the macroprudential policies. These policies can mitigate the severity of the transition risk. Aggregate investment and output fall by less with the macroprudential policy than without it, which is expected since the banks' portfolios have shifted away from brown assets due to the macroprudential policies. The percentage reduction in emissions is about the same under each case, though these are presented as percentage reductions from the initial steady state, and the initial steady-state emissions differ between the two cases, with emissions being higher without macroprudential policy. Since the banking sector is now less exposed to the brown sector, equity losses are milder and credit issued to the firms falls by less. With the macroprudential policy, green economic activity experiences a milder slowdown and faster recovery.

Figures A1 and A2 in the Appendix present additional variables under the simulations presented in Figures 1 and 2, respectively. In Appendix D and Figures A3 through A9, we present various sensitivity analyses, including simulations that consider other assumptions about the timing of policy introduction and simulations varying parameter values related to technology and climate variables.

---

[15] Aoki et al. (2018) also use this type of tax-subsidy scheme on banks' balance sheets to model macroprudential policies.

5 Efficient climate and macroprudential policies

In Section 4, we studied the financial sector's role for transition risk induced by an abrupt implementation of climate policy, and the role of macroprudential policy to mitigate that risk. In those simulations, we focused on exogenous policies. This section explores the interactions between financial frictions and environmental externalities and their implications for efficient policy design. When both a carbon tax τ_t^e and a uniform macroprudential tax $\tau_t^b = \tau_t^g$ (subsidy if negative) on banks' assets are available, the policymaker can fully undo both types of distortions. We refer to this Ramsey-efficient policy mix and the associated allocations as the "first best." Using the first best as a benchmark, we also consider second-best policies, that is, when one of the instruments is absent from a policy toolbox. We also consider the case where the policymaker can use a differentiated macroprudential policy, setting separate taxes on different types of assets (green or brown) in banks' portfolio ($\tau_t^b \neq \tau_t^g$).

5.1 Steady state

Table 2 reports the deterministic steady-state outcomes of key variables in the models with and without financial frictions across different policy scenarios. The first two columns report steady-state outcomes in the model without financial frictions, under the no-policy scenario and with the efficient emissions tax. Columns 3 and 4 consider similar policy scenarios in the model with financial frictions, and the remaining columns also consider macroprudential policies. The units of the emissions tax are in dollars per ton of CO_2, where we convert the arbitrary units of the DSGE model to these real-world units using the strategy described in the calibration section above. The macroprudential taxes, climate damages, and credit spreads are in percentages. The welfare losses are in terms of compensating variation in consumption that equates the steady-state welfare under a given policy scenario to that of the first-best outcome. The remaining variables in Table 2 are presented in arbitrary model units.

In the absence of an emissions tax, firms do not internalize the negative climate externality, pushing emissions up to inefficiently high levels in both economies, with and without financial frictions. In the model with financial frictions, this effect is counteracted by the inefficiently low production as bank lending to firms is constrained by the presence of financial frictions. The two sources of market failure work in opposite directions, so unregulated steady-state emissions are lower with financial frictions than without them.

Without financial frictions, the efficient steady-state emissions tax is 0.0192 in abstract DSGE units, which corresponds to 17.2 dollars per ton of CO_2.[16] With financial frictions, the second-best carbon tax (absent any macroprudential policies) is 13.8 dollars per ton of CO_2. Because the financial frictions work in the opposite direction of the climate externality, the presence of financial frictions implies that the carbon tax would be lower. This lower tax in the model with financial frictions is enough to bring the steady-state emissions and climate damages almost to their efficient levels. The second column is a first-best outcome, since without financial frictions the only externality is pollution, and it is corrected through the Pigouvian tax. The fourth column is a second-best outcome; there are two sources of market inefficiencies (pollution externality and financial frictions) but only one instrument (the emissions tax) to address them.

The last three columns report deterministic steady-state outcomes in the baseline model (with both a pollution externality and financial frictions) when macroprudential policy instruments are available. The fifth column is the case where only a uniform macroprudential policy (i.e., $\tau_t^b = \tau_t^g$) is available, and the sixth column allows for differentiated macroprudential policies. The last column is the first-best scenario, with both types of instruments available.

When only a uniform macroprudential policy is available, since financial frictions limit the level of economic activity to inefficiently low levels, the policymaker subsidizes banks to increase

---

[16] We arrive at this calculation in the following way. As described earlier, we set our model's steady-state pollution stock to correspond to 1172 GtC. The law of motion of the pollution stock implies that this steady-state stock level corresponds to a quarterly flow of 0.684 GtC of emissions. The efficient carbon tax in dollars per ton of CO_2 is from the following conversion formula: tax in dollars per ton of CO_2 = tax in arbitrary model units × [20 trillion USD/ annual output in arbitrary model units] × [emissions in arbitrary model units/ 0.684 GtC] / [3.67 tons CO_2/ ton of carbon].

credit supply to the economy. That is, the second-best policy recapitalizes the banking sector by setting $\tau^b_{ss} = \tau^g_{ss} = -0.0019$. As a result, banks' net worth, credit spreads and aggregate output are all brought closer to their first-best levels. This second-best macroprudential policy, however, implies much higher emissions than the first best due to increased economic activity. The steady-state emissions are about 60% higher than their first-best level, implying more severe future climate damages.[17]

In column 6, the regulator can set differentiated macroprudential policies and thus take environmental factors into account. Without an emissions tax, the planner subsidizes green loans more than brown loans; the second-best steady-state taxes on brown and green assets are $\tau^b_{ss} = -0.0014$ and $\tau^g_{ss} = -0.0022$, respectively. As a result, emissions are lower relative to the case with the uniform macroprudential policy, but the difference is very small (1.4%). When only macroprudential policies are available, the gains from pushing economic activity closer to its first-best level largely outweigh the costs from increased climate damages. Macroprudential policies alone are not effective at tackling climate change. Additional steady-state variable values are presented in Table A1 in the Appendix, and Appendix E and Figure A10 describe the sensitivity of the steady-state results to various parameters.

5.2 Dynamics

Next, we study the implications of pollution externalities and financial frictions for Ramsey-optimal dynamic policies in response to productivity shocks. We consider impulse responses to a one-standard-deviation negative shock to aggregate productivity.

---

[17] Using the atmospheric modeling module of DICE, we can translate these differences in steady-state emissions into temperature changes. We equate the unregulated simulation to DICE's baseline no-policy simulation. Under the first-best in our model, steady-state emissions are 34% lower than in the unregulated scenario, so in DICE we exogenously reduce emissions in each period 34% lower than in the baseline. For each simulation, we calculate the peak temperature change given by DICE. Under our first-best simulation, the peak temperature is 1°C lower than it is under the unregulated baseline. Under the second-best simulations with only macroprudential policies, emissions are 7% higher than the unregulated baseline, and the peak temperature is 0.1°C higher than the unregulated baseline.

Figure 3 shows the impulse responses of key variables in the economies with and without financial frictions under the efficient emissions tax policy (without macroprudential policies). Each simulation starts at the steady state that includes the Ramsey-efficient emissions tax under that model. Similar to the standard RBC model, a negative TFP shock has a contractionary effect on the economy: aggregate investment and output fall.

Consistent with the previous findings in the E-DSGE literature, the efficient emissions tax and emissions are both procyclical. Financial frictions affect the dynamics of the efficient carbon tax. In the economy with financial frictions, the efficient emissions tax falls by much more in response to the negative shock, so that emissions actually increase on impact (Figure 3, Panels (b) and (c)). The procyclicality of emissions is thus dampened.

The second-best emissions tax falls more with financial frictions because the financial frictions inefficiently amplify the macroeconomic aggregates' responses to the negative TFP shock via banks' net worth. A decline in productivity reduces banks' net worth by lowering the realized return on assets. Given the lower level of equity, the banking sector becomes more constrained in its ability to raise deposits and lend to firms. The tighter credit supply, which results in widening of credit spreads, further amplifies the decline in investment and output. Since here the policymaker is equipped with only one instrument – the emissions tax – she uses this instrument to address both the pollution externality and the financial frictions. In response to the negative productivity shock, the planner cuts the emissions tax more aggressively to mitigate the fall in banks' net worth and credit supply. In the unregulated equilibrium, banks' net worth and capital investment decline by more in response to the negative TFP shock. When a macroprudential policy instrument is also available, the Ramsey planner uses the emissions tax to exclusively deal with the pollution externality and the macroprudential instrument to address the financial frictions. Appendix Figure A11 presents the impulse responses of additional variables for this simulation.

Figure 4 plots impulse responses when macroprudential policies are available. We consider the second-best policies when only a uniform macroprudential policy is available but no emissions tax (solid lines), the second-best policies when differentiated macroprudential policy is available but no emissions tax (dotted lines), and the first-best policies when both an emissions tax and macroprudential policies are available (dashed lines). When an emissions tax is available, macroprudential policies do not need to be differentiated to achieve the first best, so we consider just uniform macroprudential policies in this case.

For the two second-best policies, the responses to these policies are barely distinguishable from each other. In both cases, emissions fall by more than they do in the first best, while investment, output, net worth, and credit spreads dynamics closely replicate the first-best responses. This suggests that from the Ramsey-efficiency perspective, second-best macroprudential taxes do not address negative pollution externalities over the business cycle. The intuition behind this result is that climate damages, which affect net output, are driven by the pollution stock – a very slow-moving variable over the business cycle. Therefore, the Ramsey planner with only macroprudential taxes can let emissions fluctuate more than optimally in response to mean-reverting productivity shocks without incurring much efficiency losses in investment and output.

The two second-best policies (uniform and differentiated macroprudential policies) are barely distinguishable from each other for the same reason that the steady states under these two policies (shown in the second- and third-to-last columns of Table 2) are barely distinguishable from each other. Allowing for differentiated policy lets the regulator subsidize green assets at a higher rate than brown assets, but the efficient degree of differentiation is very small. A larger spread between these two macroprudential policy magnitudes would decrease emissions more, but it would create additional distortions in credit markets that would outweigh any climate benefits. Therefore, in Figure 4 we see nearly-identical impulse responses of emissions and other outcomes under these two policy scenarios. This feature again demonstrates that macroprudential policies alone are ineffective in combating climate change.

For the first-best policy, the planner uses the emissions tax to solely address the climate externality and the macroprudential policy to stabilize the banking sector. The efficient tax on banks' assets is procyclical. When the economy is in a recession, the policymaker subsidizes banks' asset purchases, thereby propping up asset prices and bank equity. The policymaker is thus able to fully stabilize credit spreads at their efficient level. The procyclical nature of a macroprudential tax levied on banks' assets is similar in nature to countercyclical bank capital buffers advocated by the Basel III framework and adopted by financial regulators in many countries. On impact, the subsidy increases from its steady-state level of -0.22% to about -2%. As a result, banks' net worth greatly stabilized, falling by only 11% versus 20% in the absence of the macroprudential policy. Appendix Figure A12 presents the impulse responses of additional variables for this simulation.

6 Conclusion

Reaching the Paris Agreement's goal of keeping global warming within 2°C above pre-industrial levels requires aggressive policy action. Central banks and financial regulators have recently expressed concern that such a policy action could trigger transition risk, possibly leading to a policy-driven recession. To minimize this transition risk, regulators have started expanding their set of tools to include new macroprudential policies specifically tailored to green and brown assets. Preventing transition risk is important, as is preventing the risk that ambitious climate action is not implemented when the opportunity finally presents itself.

We develop a DSGE model of an economy with two key market failures: a climate externality and financial frictions. The model addresses the issues of transition risk and of the efficient design of climate and macroprudential policies in the long run and over business cycles. We simulate the transition in response to an exogenous carbon tax, both with and without macroprudential policies. We also simulate efficient climate and macroprudential policy in the long run and over business cycles. Our results show that macroprudential policies can reduce the risk of a recession following a major climate policy. Further, by addressing financial frictions, macroprudential policies can also support economic growth once climate policy is in place. However, macroprudential policies alone, without a climate policy, perform poorly in addressing the climate externality.

Like other DSGE models, ours makes several simplifying assumptions that could be relaxed in future work to address other questions. For example, our model contains a representative agent and thus does not address concerns about equity or distributional issues; instead, we could model heterogeneous agents or multiple sectors (as discussed in Annicchiarico et al. 2021). Further, our calibration is based on the DICE model, one of several integrated assessment models that could be used for this exercise.

Important policy implications follow from our study. Introducing macroprudential policy today can prevent a potential recession tomorrow, or the need to forgo ambitious climate policy because of transition risks. Climate and macroprudential policies work best when used as complements, rather than substitutes. Each policy addresses a distinct market failure. Our paper can guide current efforts by central banks and financial regulators to minimize the transition risk from climate policy and ensure efficient outcomes in the long run and over business cycles.

References

Adjemian, S., Bastani, H., Juillard, M., Mihoubi, F., Perendia, G., Ratto, M. and Villemot, S.: 2011, Dynare: Reference manual, version 4.

Angeloni, I. and Faia, E.: 2013, Capital regulation and monetary policy with fragile banks, *Journal of Monetary Economics* **60**(3), 311–324.

Annicchiarico, B., Carattini, S., Fischer, C. and Heutel, G.: 2021, Business cycles and environmental policy: Literature review and policy implicatinos, *National Bureau of Economic Research Working Paper* **29032**.

Annicchiarico, B. and Di Dio, F.: 2015, Environmental policy and macroeconomic dynamics in a new Keynesian model, *Journal of Environmental Economics and Management* **69**, 1–21.

Annicchiarico, B. and Di Dio, F.: 2017, GHG emissions control and monetary policy, *Environmental and Resource Economics* **67**(4), 823–851.

Antweiler, W., Copeland, B. R. and Taylor, M. S.: 2001, Is free trade good for the environment?, *American Economic Review* **91**(4), 877–908.

Aoki, K., Benigno, G. and Kiyotaki, N.: 2018, Monetary and financial policies in emerging markets. Mimeo.

Barrage, L.: 2020, Optimal dynamic carbon taxes in a climate–economy model with distortionary fiscal policy, *The Review of Economic Studies* **87**(1), 1–39.

Battiston, S., Mandel, A., Monasterolo, I., Schütze, F. and Visentin, G.: 2017, A climate stress-test of the financial system, *Nature Climate Change* **7**(4), 283.

Benmir, G. and Roman, J.: 2020, Policy interactions and the transition to clean technology, *Centre for Climate Change Economics and Policy Working Paper 368.*

Bernanke, B. and Gertler, M.: 1989, Agency costs, net worth, and business fluctuations, *American Economic Review* **79**(1), 14–31.

Bernanke, B. S.: 2018, The real effects of disrupted credit: Evidence from the global financial crisis, *Brookings Papers on Economic Activity* **2018**(2), 251–342.

Bianchi, J.: 2016, Efficient bailouts?, *American Economic Review* **106**(12), 3607–3659.

Böser, F. and Colesanti Senni, C.: 2020, Emission-based interest rates and the transition to a low-carbon economy, *Working Paper 20/337*, CER-ETH - Center of Economic Research (CER-ETH) at ETH Zurich.

Brunnermeier, M. K., Eisenbach, T. and Sannikov, Y.: 2013, *Macroeconomics with Financial Frictions: A Survey*, Cambridge University Press, New York.

Brunnermeier, M. K. and Sannikov, Y.: 2014, A macroeconomic model with a financial sector, *American Economic Review* **104**(2), 379–421.

Campiglio, E.: 2016, Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy, *Ecological Economics* **121**, 220–230.

Carattini, S., Hertwich, E., Melkadze, G. and Shrader, J. G.: 2022, Mandatory disclosure is key to address climate risks, *Science* **378**(6618), 352–354.

Carattini, S. and Sen, S.: 2019, Carbon taxes and stranded assets: Evidence from Washington state, *Working Paper 7785*, CESifo Group Munich.

Carney, M.: 2015, Breaking the tragedy of the horizon–climate change and financial stability, *Speech given at Lloyd's of London.*

Chan, Y. T.: 2020, Are macroeconomic policies better in curbing air pollution than environmental policies? A DSGE approach with carbon-dependent fiscal and monetary policies, *Energy Policy* **141**, 111454.

Christiano, L. J., Eichenbaum, M. and Evans, C. L.: 2005, Nominal rigidities and the dynamic effects of a shock to monetary policy, *Journal of Political Economy* **113**(1), 1–45.

Christiano, L. J. and Ikeda, D.: 2013, *Government Policy, Credit Markets, and Economic Activity*, Studies in Macroeconomic History, Cambridge University Press, p. 226–331.

Collard, F., Dellas, H., Diba, B. and Loisel, O.: 2017, Optimal monetary and prudential policies, *American Economic Journal: Macroeconomics* **9**(1), 40–87.

De Paoli, B. and Paustian, M.: 2017, Coordinating monetary and macroprudential policies, *Journal of Money, Credit and Banking* **49**(2-3), 319–349.

Diluiso, F., Annicchiarico, B., Kalkuhl, M. and Minx, J. C.: 2021, Climate actions and macro-financial stability: The role of central banks, *Journal of Environmental Economics and Management* **110**, 102548.

Dissou, Y. and Karnizova, L.: 2016, Emissions cap or emissions tax? A multi-sector business cycle analysis, *Journal of Environmental Economics and Management* **79**, 169–188.

ECB: 2021, Financial stability review, *European Central Bank* .

Economides, G. and Xepapadeas, A.: 2018, Monetary policy under climate change, *CESifo Working Paper Series* **7021**.

Ferrari, A. and Nispi Landi, V.: 2023, Whatever it takes to save the planet? Central banks and unconventional green policy, *Macroeconomic Dynamics* **forthcoming**.

Fischer, C. and Heutel, G.: 2013, Environmental macroeconomics: Environmental policy, business cycles, and directed technical change, *Annual Review of Resource Economics* **5**(1), 197–210.

Fischer, C. and Springborn, M.: 2011, Emissions targets and the real business cycle: Intensity targets versus caps or taxes, *Journal of Environmental Economics and Management* **62**(3), 352–366.

Fried, S., Novan, K. and Peterman, W. B.: 2021, The macro effects of climate policy uncertainty, *FEDS Working Paper 2021-18*.

Fullerton, D. and Heutel, G.: 2007, The general equilibrium incidence of environmental taxes, *Journal of Public Economics* **91**(3-4), 571–591.

Gallic, E. and Vermandel, G.: 2020, Weather shocks, *European Economic Review* **124**, 103409.

Gertler, M. and Karadi, P.: 2011, A model of unconventional monetary policy, *Journal of Monetary Economics* **58**(1), 17–34.

Gertler, M. and Kiyotaki, N.: 2010, Financial intermediation and credit policy in business cycle analysis, *Handbook of Monetary Economics*, Vol. 3, Elsevier, pp. 547–599.

Gertler, M., Kiyotaki, N. and Queralto, A.: 2012, Financial crises, bank risk exposure and government financial policy, *Journal of Monetary Economics* **59**, S17–S34.

Gibson, J. and Heutel, G.: 2020, Pollution and labor market search externalities over the business cycle, *Working Paper 27445*, National Bureau of Economic Research.

Golosov, M., Hassler, J., Krusell, P. and Tsyvinski, A.: 2014, Optimal taxes on fossil fuel in general equilibrium, *Econometrica* **82**(1), 41–88.

Greenwood, J., Hercowitz, Z. and Huffman, G. W.: 1988, Investment, capacity utilization, and the real business cycle, *American Economic Review* **78**(3), 402–417.

Heutel, G.: 2012, How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks, *Review of Economic Dynamics* **15**(2), 244–264.

Horvath, M.: 2000, Sectoral shocks and aggregate fluctuations, *Journal of Monetary Economics* **45**(1), 69–106.

Iacoviello, M.: 2015, Financial business cycles, *Review of Economic Dynamics* **18**(1), 140–163.

IMF: 2019, Fiscal monitor: How to mitigate climate change, *Technical report*, IMF, Washington, DC.

Jeanne, O. and Korinek, A.: 2020, Macroprudential regulation versus mopping up after the crash, *The Review of Economic Studies* **87**(3), 1470–1497.

Jermann, U. and Quadrini, V.: 2012, Macroeconomic effects of financial shocks, *American Economic Review* **102**(1), 238–71.

Kiyotaki, N. and Moore, J.: 1997, Credit cycles, *Journal of Political Economy* **105**(2), 211–248.

Meh, C. A. and Moran, K.: 2010, The role of bank capital in the propagation of shocks, *Journal of Economic Dynamics and Control* **34**(3), 555–576.

Monasterolo, I.: 2020, Climate change and the financial system, *Annual Review of Resource Economics* **12**(1), 299–320.

Nordhaus, W.: 2008, *A question of balance: Weighing the options on global warming policies*, Yale University Press.

Nordhaus, W.: 2018, Evolution of modeling of the economics of global warming: Changes in the DICE model, 1992–2017, *Climatic Change* **148**(4), 623–640.

Nordhaus, W. D.: 2017, Revisiting the social cost of carbon, *Proceedings of the National Academy of Sciences* **114**(7), 1518–1523.

Papageorgiou, C., Saam, M. and Schulte, P.: 2017, Substitution between clean and dirty energy inputs: A macroeconomic perspective, *Review of Economics and Statistics* **99**(2), 281–290.

Pindyck, R. S.: 2019, The social cost of carbon revisited, *Journal of Environmental Economics and Management* **94**, 140–160.

Ramelli, S., Wagner, A. F., Zeckhauser, R. J. and Ziegler, A.: 2021, Investor rewards to climate responsibility: Stock-price responses to the opposite shocks of the 2016 and 2020 U.S. elections, *The Review of Corporate Finance Studies* **10**(4), 748–787.

Ricke, K., Drouet, L., Caldeira, K. and Tavoni, M.: 2018, Country-level social cost of carbon, *Nature Climate Change* **8**(10), 895–900.

Rozenberg, J., Vogt-Schilb, A. and Hallegatte, S.: 2020, Instrument choice and stranded assets in the transition to clean capital, *Journal of Environmental Economics and Management* **100**, 102183.

Semieniuk, G., Campiglio, E., Mercure, J.-F., Volz, U. and Edwards, N. R.: 2021, Low-carbon transition risks for finance, *WIREs Climate Change* **12**(1), e678.

Sen, S. and von Schickfus, M.-T.: 2020, Climate policy, stranded assets, and investors' expectations, *Journal of Environmental Economics and Management* **100**, 102277.

Stiglitz, J. E., Stern, N., Duan, M., Edenhofer, O., Giraud, G., Heal, G. M., la Rovere, E. L., Morris, A., Moyer, E., Pangestu, M. et al.: 2017, Report of the High-level Commission on Carbon Prices, *Carbon Pricing Leadership Coalition*.

Sunak, R.: 2021, Budget Speech 2021, *Technical report*, HM Treasury.

van der Ploeg, F. and Rezai, A.: 2020, Stranded assets in the transition to a carbon-free economy, *Annual Review of Resource Economics* **12**(1).

van der Ploeg, R.: 2020, Macro-financial implications of climate change and the carbon transition, *Working Paper*, ECB Forum on Central Banking.

Tables and Figures

Table 1: Calibration

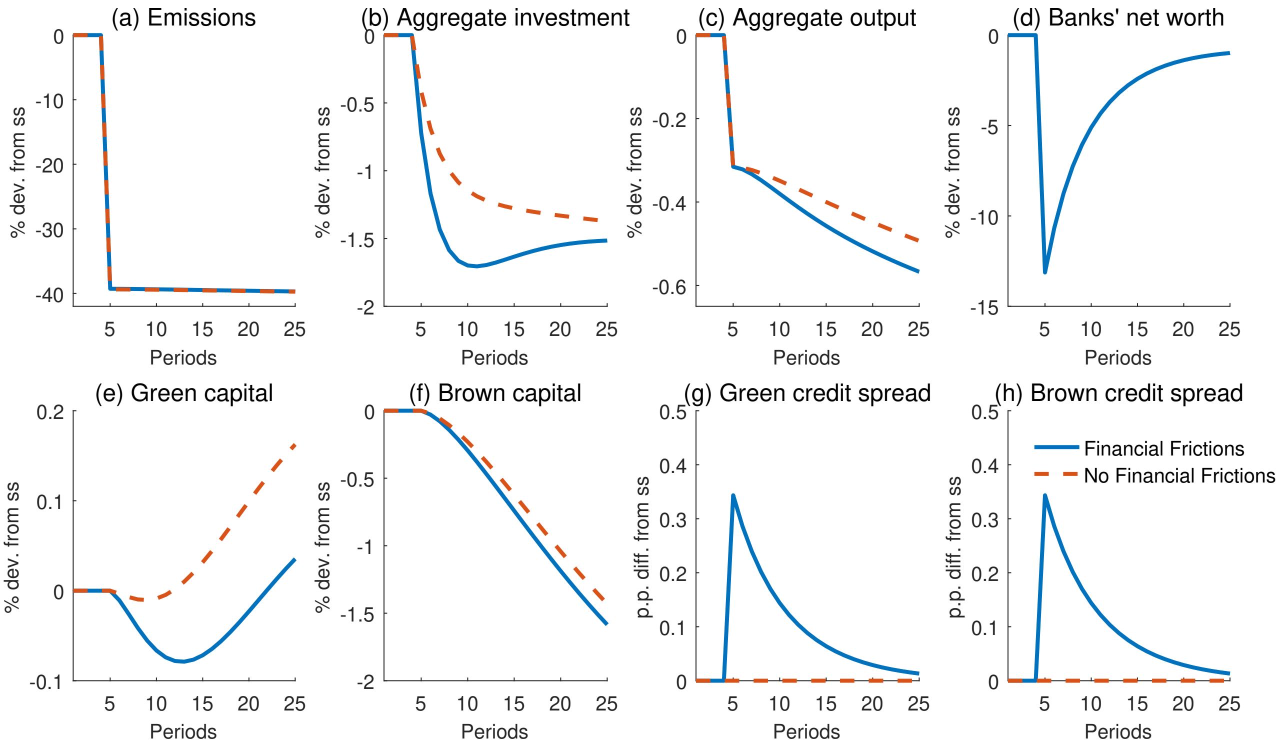
Parameter	Value	Description
RBC parameters		
β	0.9975	Discount factor
η	2	Risk aversion
ξ	1	Frisch elasticity of labor hours
ϖ	8.9544	Labor disutility
ρ_L	1	Intrasectoral CES of labor hours
α^b	0.35	Capital share in 'brown' production
α^g	0.33	Capital share in 'green' production
δ^b, δ^g	0.025	Capital depreciation rate
ϕ^b, ϕ^g	10	Investment adjustment cost
ρ_A	0.95	Persistence of aggregate TFP shocks
σ_A	0.007	Std. dev. of innovations to TFP
Environmental parameters		
θ_1	0.0334	Abatement cost function parameters
θ_2	2.6	
d_0	-0.026	Damage function parameters
d_1	3.6613e-5	
d_2	1.4812e-8	
δ_X	0.9965	Pollution decay
e^{row}	3.3705	Emissions in the ROW
ρ_Y	2	CES between 'green' and 'brown' outputs
π^b	0.332	Share of 'brown' output
Banking sector parameters		
κ	0.3313	Fraction of divertable assets
γ	0.972	Bankers' survival rate
ζ	0.0029	Proportional transfer to new bankers

Table 2: Steady state

	No financial frictions		Financial frictions				
	No policy	Emissions tax only	No policy	Emissions tax only	Uniform macro-prudential policies only ($\tau^b = \tau^g$)	Differentiated macropru-dential policies only ($\tau^b \neq \tau^g$)	Emissions tax and uniform macroprudential policies
Emissions tax ($ per ton)	0	17.2	0	13.8	0	0	17.2
Tax on brown assets (%)	–	–	0	0	-0.19	-0.14	-0.22
Tax on green assets (%)	–	–	0	0	-0.19	-0.22	-0.22
Aggregate output	1.622	1.629	1.502	1.507	1.601	1.601	1.629
Climate damages (%)	3.72	3.15	3.61	3.15	3.70	3.69	3.15
Emissions	0.729	0.443	0.674	0.442	0.720	0.714	0.443
Banks' net worth	–	–	3.410	3.386	3.862	3.864	3.957
Green credit spread (%)	0	0	0.225	0.225	0.038	0.007	0
Brown credit spread (%)	0	0	0.225	0.225	0.038	0.084	0
Welfare loss (% CV)	0.76	0	1.58	1.06	0.86	0.84	0

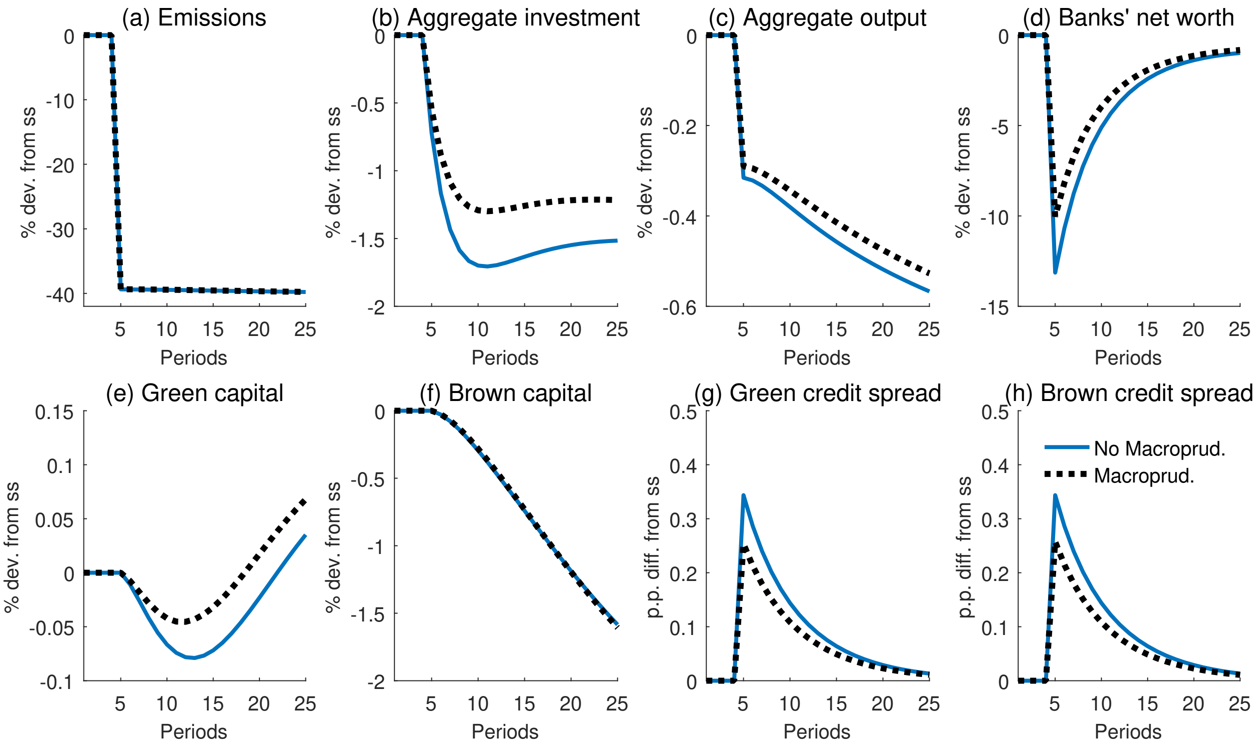
Note: This table shows the steady state values of selected variables in the economies with and without financial frictions under different policy scenarios. The units of the emissions tax are dollars per ton of CO_2, based on the calibration described in the text. Tax rates on banks' assets and credit spreads are in percentages. Climate damages are in percent of output. Welfare loss is in terms of compensating consumption variation relative to the first-best allocations. All other variables are in arbitrary model units.

Figure 1: Transition dynamics to a low carbon economy



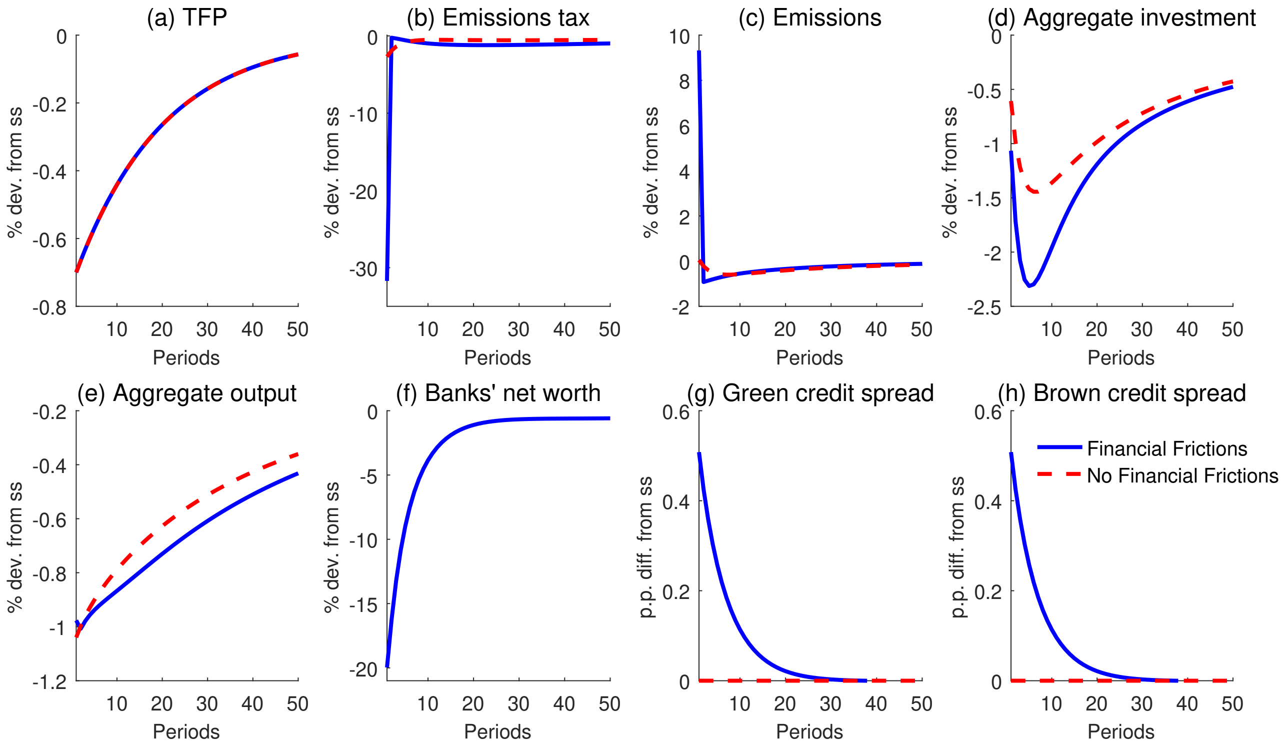
Note: This figure shows the transition dynamics in response to an unanticipated introduction of the permanent emissions tax of about 17 dollars per ton of CO_2 in the economies with and without financial frictions. Each simulation begins at the no-policy steady state under the given model.

Figure 2: Transition to a low carbon economy with macroprudential policy



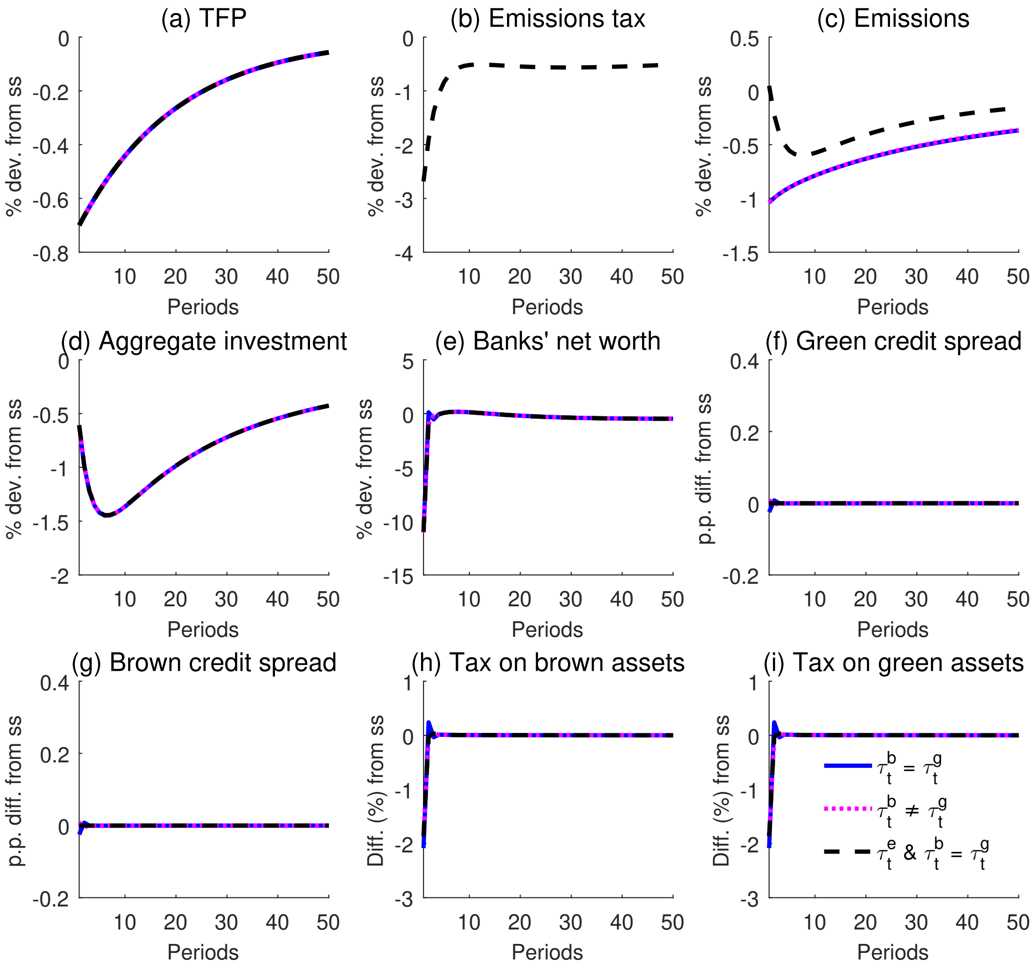
Note: This figure plots the transition dynamics in the model with financial frictions to the same emissions tax shock as in Figure 1 under two scenarios: (i) No macroprudential policy (solid lines); (ii) with macroprudential policy (dashed lines). Macroprudential policy is such that it lowers banks' steady-state exposure to the brown sector from 40% (baseline calibration) to 32.4%. Deviations are calculated relative to the respective initial steady states. Each simulation begins at the steady state with no emissions policy under the given model.

Figure 3: The Ramsey-efficient dynamic emissions tax



Note: This figure plots the impulse responses to a one-standard-deviation negative TFP shock under the Ramsey-efficient emissions tax policy in the economies (i) with financial frictions (solid lines) and (ii) without financial frictions (dashed lines). Each simulation begins at the steady state that includes the Ramsey-efficient emissions tax under the given model.

Figure 4: Ramsey-efficient dynamic policies under different sets of instruments



Note: This figure plots the impulse responses to a one-standard-deviation negative TFP shock in the baseline model with Ramsey-efficient policies when (i) only uniform tax on banks' assets ($\tau_t^b = \tau_t^g$) is available (solid lines); (ii) only differentiated taxes on banks' brown (τ_t^b) and green (τ_t^g) assets are available (dotted lines); (iii) emissions tax (τ_t^e) and a uniform tax on banks' assets ($\tau_t^b = \tau_t^g$) are available (dashed lines). Each simulation begins at the steady state that includes the specified policy combination.

Online Appendix

A Details on banks' optimization problem

We formulate the banker's optimization problem in recursive form. First, using the flow of funds constraint (5) to replace deposits $D_{j,t}$, we can express the evolution of bank's net worth (6) as

$$N_{j,t+1} = \left[R^b_{k,t+1} - \left(1+\tau^b_t\right) R_t\right] Q^b_t S^b_{j,t} + \left[R^g_{k,t+1} - \left(1+\tau^g_t\right) R_t\right] Q^g_t S^g_{j,t} + R_t N_{j,t}. \tag{A1}$$

The banker's optimization problem in recursive form then becomes:

$$V_{j,t} = \max_{S^b_{j,t}, S^g_{j,t}} \mathbb{E}_t \left\{\left[\left(1-\gamma\right) M_{t,t+1} N_{j,t+1} + \gamma M_{t,t+1} V_{j,t+1}\right]\right\}, \tag{A2}$$

subject to the incentive constraint (7) and the evolution of net worth (A1).

We guess and later verify that the value function is linear in net worth $N_{j,t}$,

$$V_{j,t} = \varphi_t N_{j,t}, \tag{A3}$$

where φ_t is the time-varying coefficient common across banks. It is convenient to define the variables:

$$\chi^b_t \equiv \mathbb{E}_t \left[\Omega_{t+1} \left(R^b_{k,t+1} - \left(1+\tau^b_t\right) R_t\right)\right], \tag{A4}$$

$$\chi^g_t \equiv \mathbb{E}_t \left\{\Omega_{t+1} \left[R^g_{k,t+1} - \left(1+\tau^g_t\right) R_t\right]\right\}, \tag{A5}$$

$$\nu_t \equiv \mathbb{E}_t \left[\Omega_{t+1} R_t\right], \tag{A6}$$

where $\Omega_{t+1} \equiv M_{t,t+1}\left(1-\gamma+\gamma\varphi_{t+1}\right)$ can be interpreted as the banker's effective stochastic discount factor; χ^b_t and χ^g_t are the expected discounted (tax adjusted) excess returns on brown and green assets, respectively, relative to deposits, and ν_t is the expected discounted cost of raising an additional unit of deposits.

Using the definitions (A4) −(A6), the conjecture (A3), and (A1), we can rewrite the Bellman equation (A2) as

$$V_{j,t} = \max_{S^b_{j,t}, S^g_{j,t}} \left\{\chi^b_t Q^b_t S^b_{j,t} + \chi^g_t Q^g_t S^g_{j,t} + \nu_t N_{j,t}\right\}. \tag{A7}$$

The incentive constraint (7) then becomes,

$$\chi_t^b Q_t^b S_{j,t}^b + \chi_t^g Q_t^g S_{j,t}^g + \nu_t N_{j,t} \geq \kappa \left(Q_t^b S_{j,t}^b + Q_t^g S_{j,t}^g \right). \tag{A8}$$

The Lagrangian function for this problem is

$$\pounds_t = \left(\chi_t^b Q_t^b S_{j,t}^b + \chi_t^g Q_t^g S_{j,t}^g + \nu_t N_{j,t} \right) (1 + \lambda_t) - \lambda_t \kappa \left(Q_t^b S_{j,t}^b + Q_t^g S_{j,t}^g \right), \tag{A9}$$

where λ_t is the Lagrange multiplier on the incentive constraint (A8). The first order optimality conditions are:

$$(1 + \lambda_t) \chi_t^b = \lambda_t \kappa, \tag{A10}$$

$$(1 + \lambda_t) \chi_t^g = \lambda_t \kappa, \tag{A11}$$

$$\lambda_t \left[\chi_t^b Q_t^b S_{j,t}^b + \chi_t^g Q_t^g S_{j,t}^g + \nu_t N_{j,t} - \kappa \left(Q_t^b S_{j,t}^b + Q_t^g S_{j,t}^g \right) \right] = 0, \text{ with } \lambda_t \geq 0. \tag{A12}$$

Combining the FOCs (A10) and (A11) yields $\chi_t^b = \chi_t^g$, which gives equation (12) in the main text,

$$\mathbb{E}_t \left\{ \Omega_{t+1} \left[R_{k,t+1}^b - \left(1 + \tau_t^b \right) R_t \right] \right\} = \mathbb{E}_t \left\{ \Omega_{t+1} \left[R_{k,t+1}^g - \left(1 + \tau_t^g \right) R_t \right] \right\}. \tag{A13}$$

From (A10) we also have $\lambda_t = \frac{\chi_t^b}{\kappa - \chi_t^b}$. The incentive constraint (A8) binds whenever the Lagrange multiplier $\lambda_t > 0$, or when $0 < \chi_t^b < \kappa$. In our realistic parametrization of the model, the incentive constraint always binds in a local region of the steady state. When the incentive constraint binds, the amount of bank's assets is limited by bank's equity capital,

$$Q_t^b S_{j,t}^b + Q_t^g S_{j,t}^g = \frac{\nu_t}{\kappa - \chi_t^b} N_{j,t}. \tag{A14}$$

Using (A14) and the optimality conditions we can verify our conjecture (A3):

$$V_{j,t} = \varphi_t N_{j,t} = \chi_t^b \frac{\nu_t}{\kappa - \chi_t^b} N_{j,t} + \nu_t N_{j,t} = \frac{\kappa \nu_t}{\kappa - \chi_t^b} N_{j,t}, \tag{A15}$$

$$\Rightarrow \varphi_t = \frac{\kappa \nu_t}{\kappa - \chi_t^b}. \tag{A16}$$

Since χ_t^b, χ_t^g and ν_t only depend on aggregate variables, φ_t is not individual bank-specific either. Aggregating (A14) across banks, and after imposing (A16), gives equation (11) in the main text.

B Full set of equilibrium conditions

$$L_t = \left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L}\right]^{\frac{1}{1+\rho_L}}, \tag{B1}$$

$$M_{t,t+1} = \beta \frac{\left(C_{t+1} - \varpi \frac{L_{t+1}^{1+\xi}}{1+\xi}\right)^{-\eta}}{\left(C_t - \varpi \frac{L_t^{1+\xi}}{1+\xi}\right)^{-\eta}}, \tag{B2}$$

$$1 = \mathbb{E}_t\left(M_{t,t+1} R_t\right), \tag{B3}$$

$$w_t^i = \varpi L_t^{\xi-\rho_L}\left(L_t^i\right)^{\rho_L}, \quad \text{for } i = \{g, b\}, \tag{B4}$$

$$\chi_t^b = \mathbb{E}_t\left[\Omega_{t+1}\left(R_{k,t+1}^b - \left(1+\tau_t^b\right) R_t\right)\right], \tag{B5}$$

$$\chi_t^g = \mathbb{E}_t\left[\Omega_{t+1}\left(R_{k,t+1}^g - \left(1+\tau_t^g\right) R_t\right)\right], \tag{B6}$$

$$\nu_t = \mathbb{E}_t\left[\Omega_{t+1} R_t\right], \tag{B7}$$

$$\Omega_{t+1} = M_{t,t+1}\left(1-\gamma+\gamma\varphi_{t+1}\right), \tag{B8}$$

$$\chi_t^b = \chi_t^g, \tag{B9}$$

$$\varphi_t = \frac{\kappa \nu_t}{\kappa - \chi_t^b}, \tag{B10}$$

$$Q_t^b S_t^b + Q_t^g S_t^g = \frac{\nu_t}{\kappa - \chi_t^b} N_t, \tag{B11}$$

$$N_{t+1} = \gamma\left[\sum_{i=\{g,b\}} R_{k,t+1}^i Q_t^i S_t^i - R_t D_t\right] + \zeta \sum_{i=\{g,b\}} Q_t^i S_t^i, \tag{B12}$$

$$D_t = (1+\tau_t^b) Q_t^b S_t^b + (1+\tau_t^g) Q_t^g S_t^g - N_t, \tag{B13}$$

$$Y_t = \left[\left(\pi^b\right)^{\frac{1}{\rho_Y}}\left(Y_t^b\right)^{\frac{\rho_Y-1}{\rho_Y}} + \left(1-\pi^b\right)^{\frac{1}{\rho_Y}}\left(Y_t^g\right)^{\frac{\rho_Y-1}{\rho_Y}}\right]^{\frac{\rho_Y}{\rho_Y-1}}, \tag{B14}$$

$$Y_t^i = \left[1 - d\left(X_t\right)\right] A_t \left(K_{t-1}^i\right)^{\alpha^i}\left(L_t^i\right)^{1-\alpha^i}, \text{ for } i = \{g, b\}, \tag{B15}$$

$$p_t^b = \left(\frac{\pi^b Y_t}{Y_t^b}\right)^{\frac{1}{\rho_Y}}, \tag{B16}$$

$$p_t^g = \left(\frac{\left(1-\pi^b\right) Y_t}{Y_t^g}\right)^{\frac{1}{\rho_Y}}, \tag{B17}$$

$$X_t = \delta_X X_{t-1} + e_t + e_t^{\text{row}}, \tag{B18}$$

$$e_t = (1 - \mu_t) Y_t^b, \tag{B19}$$

$$Z_t = \theta_1 \mu_t^{\theta_2} Y_t^b, \tag{B20}$$

$$w_t^b = \left(1 - \alpha^b\right) \frac{Y_t^b}{L_t^b} \left[p_t^b - \theta_1 \mu_t^{\theta_2} - \tau_t^e (1 - \mu_t)\right], \tag{B21}$$

$$\tau_t^e = \theta_1 \theta_2 \mu_t^{\theta_2 - 1}, \tag{B22}$$

$$R_{k,t}^b = \frac{\alpha^b \frac{Y_t^b}{K_{t-1}^b} \left[p_t^b - \theta_1 \mu_t^{\theta_2} - \tau_t^e (1 - \mu_t)\right] + \left(1 - \delta^b\right) Q_t^b}{Q_{t-1}^b}, \tag{B23}$$

$$w_t^g = (1 - \alpha^g) \frac{p_t^g Y_t^g}{L_t^g}, \tag{B24}$$

$$R_{k,t}^g = \frac{\alpha^g \frac{p_t^g Y_t^g}{K_{t-1}^g} + (1 - \delta^g) Q_t^g}{Q_{t-1}^g}, \tag{B25}$$

$$\begin{aligned} Q_t^i = {} & 1 + \frac{\phi^i}{2} \left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2 + \phi^i \left(\frac{I_t^i}{I_{t-1}^i} - 1\right) \frac{I_t^i}{I_{t-1}^i} + \\ & - \mathbb{E}_t \left\{ M_{t,t+1} \phi^i \left(\frac{I_{t+1}^i}{I_t^i} - 1\right) \left(\frac{I_{t+1}^i}{I_t^i}\right)^2 \right\}, \text{for } i = \{g, b\}, \end{aligned} \tag{B26}$$

$$K_t^i = \left(1 - \delta^i\right) K_{t-1}^i + I_t^i, \text{ for } i = \{g, b\}, \tag{B27}$$

$$Q_t^i S_t^i = Q_t^i K_t^i, \quad \text{for } i = \{g, b\}, \tag{B28}$$

$$Y_t = C_t + \sum_{i=\{g,b\}} I_t^i + Z_t + \sum_{i=\{g,b\}} \frac{\phi^i}{2} \left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2 I_t^i. \tag{B29}$$

Given government policies $(\tau_t^e, \tau_t^b, \tau_t^g)$ and exogenous total factor productivity (A_t), a competitive equilibrium is described by the stochastic sequences of endogenous variables $\mathbf{J}_t \equiv [\left\{L_t^i, K_t^i, I_t^i, Y_t^i, S_t^i, w_t^i, R_{k,t}^i, Q_t^i, p_t^i\right\}_{i=g,b}, C_t, M_{t,t+1}, L_t, Y_t, Z_t, \mu_t, e_t, X_t, N_t, D_t, R_t, \chi_t^b, \chi_t^g, \nu_t, \varphi_t, \Omega_{t+1}]$ that satisfy the system of equations B1-B29.

C The Ramsey-efficient policy problem

For a given set of available instruments (e.g., only τ_t^e; only $\tau_t^b = \tau_t^g$; τ_t^b and τ_t^g; τ_t^e and $\tau_t^b = \tau_t^g$) the Ramsey planner solves:

$$\max_{\{\mathbf{J}_t,\text{ and a given set of instruments}\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\eta} \left(C_t - \varpi \frac{\left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L} \right]^{\frac{1+\xi}{1+\rho_L}}}{1+\xi} \right)^{1-\eta} \right\}, \tag{C1}$$

subject to the constraints of the competitive equilibrium (i.e., equations B1-B32). As is common in the literature, we take the 'timeless perspective' approach to implement the solution to the Ramsey problem; the policymaker is able to commit to a state-contingent dynamic policy announced in time 0. We implement the solution in Dynare.

D Transition risk: Sensitivity analysis

In this section, we present more simulations extending the simulations exploring transition risk from Section 4, though we vary the assumptions about the timing of the policies and parameter values.

Figure A3 contrasts the abrupt implementation of an exogenous carbon tax to a gradual, ramp-up approach, which is typically recommended by IAMs like DICE. A surprise carbon tax is introduced in period 5. Under the gradual simulation, the tax rate starts low and increases linearly to the efficient level (17.2 dollars per ton) by period 25 and permanently stays at that efficient level thereafter. The experiment illustrates that gradual "ramp-up" causes a milder recession and avoids the sudden drop in output caused by the abrupt tax increase. The decrease in green capital is much less severe under the gradual tax, and the level of green capital rises above the original steady-state level much more quickly.

In the next simulation, presented in Figure A4, we consider how the preannouncement of a carbon tax, rather than its sudden implementation, affects the results. In these simulations, the carbon tax of 17.2 dollars per ton is announced in period 5 (unexpectedly), but it does not take effect until period 10. Because asset prices are forward looking, the negative effects of the announcement on asset prices, banks' net worth, and investment are immediate, albeit milder than in the baseline scenario. The recession is milder with the pre-announcement, and green production and capital also fall by less.

Both of the previous sets of simulations explore how the timing of the carbon tax can affect the transition and possibly alleviate the threat of a recession. Of course, the timing of climate policy is often constrained by political economy elements, so a gradual implementation might be an inferior solution to implementing macroprudential policy, which allows for abrupt implementations as well. Climate damages are also higher with gradual implementation, in terms of eventual temperature increase.

In the next set of simulations that we explore here, we instead investigate the timing of the macroprudential policies. In the results presented in the main text and presented in Figure 2, the macroprudential policy is in place before the carbon tax is enacted, and the initial steady state of the simulations with the macroprudential policy is the steady state that includes that policy. In Figure A5 we instead introduce the macroprudential policies at the same time as the introduction of the carbon tax (period 5). In these simulations, the magnitudes of the macroprudential policies are identical to those in Figure 2, though the timing differs.

Figure A5 demonstrates that the macroprudential policies are still quite effective at ameliorating the impact of the recession – aggregate investment falls by less and rebounds much more quickly, and aggregate output does not fall as much.

We consider the case where macroprudential policy is introduced first and then, after some time, but before the new steady state is reached, the climate policy shock hits the economy. Figure A6 shows the transition dynamics in response to an unexpected introduction of permanent macroprudential policies in period 2 and then the permanent emissions tax in period 11. The figure illustrates that macroprudential policy pushes bank equity up, resulting in higher aggregate investment spending. Aggregate output also expands slightly before the emissions tax is introduced. At the time of the introduction of climate policy, the share of brown capital in the economy is about 36% and, therefore, banks' balance sheets are less exposed to the carbon tax shock relative to the case with no macroprudential policy. As a result, bank equity capital falls by less in response to the emissions tax shock. With macroprudential policy in place, aggregate investment and output fall by less. In addition, macroprudential policy helps green capital expand from the very beginning of the transition.

The next set of simulations considers the case when emissions tax shock follows an AR(1) stochastic process as described in Figure A7. The previous simulations assumed perfect foresight after the tax policy is introduced. Figure A7 shows the results of the stochastic simulations when agents in the economy are repeatedly surprised by carbon tax shocks in periods 5, 15, and 25. Qualitatively, the results are very similar to the experiments with the one time, unexpected introduction of a permanent carbon tax. Macroprudential policies are again effective at mitigating the transition risks.

We next present results under an alternate calibration in which we calibrate our pollution values based on the current real-world carbon stock, rather than the carbon stock taken from a long-run average under a run of DICE. As described in the text, our initial calibration was done to ensure a high enough carbon tax would result, given that the relatively high carbon tax in DICE arises from TFP growth, which is absent in our model. In this alternative calibration presented here, the steady-state pollution stock corresponds to 851 GtC. With the recalibration under this assumption, the first-best steady-state carbon tax is now just about 10 dollars per ton of CO_2. Figure A8 shows that the results are qualitatively very similar to baseline calibration, but the smaller carbon tax shock implies smaller transition effects. Note that even when we start the simulation in the low-pollution-stock steady state, if we hit the model with the carbon tax of the same size as in our baseline calibration, the results are also quantitatively almost the same as in the baseline.

Figure A9 further explores the sensitivity of the transition dynamics in the model with financial frictions (solid lines in Figure 1) to parameter values. Specifically, we vary two parameters that are relevant in the transition to a low carbon economy: (i) the elasticity of substitution parameter between brown and green inputs, ρ_Y, and the abatement cost parameter, θ_1. In the baseline calibration these parameters are set to $\rho_Y = 2$ and $\theta_1 = 0.0334$. In the sensitivity exercises we consider a lower degree of substitutability, $\rho_Y = 1.2$, and higher abatement cost, $\theta_1 = 0.15$. We vary these parameters one at a time comparing the results with the baseline calibration under the same carbon tax shock. Figure A9 shows that under the alternative parameter values, the results are qualitatively very similar to the baseline case. Note that these sensitivity results are monotonic in the parameters' values.

Quantitatively, with the lower substitutability between brown and green inputs (dashed lines), aggregate output and investment fall by less, largely because of the smaller decline in brown production in response to the introduction of the carbon tax. However, with the low elasticity of substitution, the green sector experiences a more severe and prolonged recession as it is harder for the economy to move away from brown production. The responses of banks' net worth and credit spreads are not very different from the baseline case. When abatement cost is high (dotted lines), emissions do not fall nearly as much as in the baseline and the economy experiences a more severe recession throughout the transition. Since it is too costly to abate, brown firms scale down their production leading to lower overall economic activity. The effects of the carbon tax shock on banks' net worth and credit supply are again similar to the baseline calibration.

E Steady-state Ramsey-efficient policies: Sensitivity analysis

Here we present the results from sensitivity analyses varying two parameters that control the degree of distortions due to financial frictions. Figure A10 shows how the second-best steady-state carbon tax varies when we exogenously change the parameters ζ (Panel (a)) and κ (Panel (b)). We vary banks' transfer parameter ζ from its baseline value to higher values and the agency problem parameter κ from its baseline to lower values. The parameter ζ is the banks' transfer parameter; a higher ζ means that exogenous transfers from households to banks increase, which directly increases banks' net worth. Banks can thus intermediate more capital to the economy. The base case calibrated value of ζ is 0.0029. As we increase this parameter, it reduces the steady-state distortion in allocations coming from the financial frictions. When ζ is about 0.00846, the second-best emissions tax is the same as the first-best tax (\$17.2 per ton), meaning that the inefficiencies from the financial friction in the steady state have been eliminated.

The parameter κ is the agency problem parameter; a lower κ means that incentives to divert funds for banks are lower, so depositors are willing to lend more to the banks. As a result, banks can extend more credit to the economy. The base case calibrated value of κ is 0.3313. As we reduce this parameter, it reduces the distortion from financial frictions. Again, there is a low enough value for κ (about 0.1135) for which the second-best emissions tax is the same as first-best tax.

Table A2 further explores the sensitivity of the steady state results with respect to other selected technology and climate parameters. Specifically, we consider (i) lower value of substitutability parameter ($\rho_Y = 1.2$) between green and brown goods, (ii) higher value of abatement cost parameter ($\theta_1 = 0.15$), and (iii) higher output damages from pollution stock. For the latter experiment we scale up the pollution damage term in equation (15) to $zd(X_t)$ and set $z = 1.5$ in the sensitivity analysis.

Table A2 shows that compared to the baseline calibration, the second-best emissions tax is lower with the lower substitutability between brown and green inputs and with the higher abatement cost (columns 1 and 2). These two parameters do not have quantitatively noticeable effects on the second-best differentiated macroprudential policies (columns 4 and 5). With the higher pollution damages (i.e., 5.3% of steady-state output in the unregulated economy) both the first and second-best emissions taxes are higher (columns 3 and 9) compared to the baseline. The larger climate damages also result in much smaller subsidy for brown loans (column 6) as the pollution externality is now quantitatively more important and the prudential regulator takes it into account more. In fact, when climate damages are large enough, e.g. when $z = 4$ which implies the steady-state damages of 13%, the Ramsey regulator imposes a positive tax (albeit small) on brown loans and subsidy on green.

F Robustness to preference specification

In the baseline calibration, the households' period utility function is of Greenwood-Hercowitz-Huffman (1988) (GHH) form, eliminating wealth effects on labor supply. This preference specification is commonly used in models with financial frictions to allow for reasonable fluctuations in labor hours without explicitly modeling price rigidities and labor market frictions that would otherwise significantly complicate the model (see e.g., Gertler et al. 2012 or Bianchi 2016). In this section, we confirm that all our main findings still hold under a utility function that is additively separable in consumption and (composite) labor hours and thus allows for wealth effects on labor supply:

$$U(C_t, L_t^g, L_t^b) = \frac{C_t^{1-\eta}}{1-\eta} - \varpi \frac{\left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L}\right]^{\frac{1+\xi}{1+\rho_L}}}{1+\xi} \tag{F1}$$

After re-calibrating the model with these separable preferences, all the parameter values, except for the labor disutility parameter ϖ, remain the same as in the baseline calibration (see Table 2). We set the labor disutility parameter $\varpi = 7.7337$ to target the steady-state labor hours of $\frac{1}{3}$, as we did in the baseline calibration.

Table A3 shows the steady-state results under various policy scenarios, as in Table 2, but now with household preferences given by equation (F1). The results are very similar to our baseline findings with the GHH preferences.

Figures A13 through A16 focus on transition dynamics and Ramsey efficient dynamic policies under the separable utility function. Qualitatively, the results are the same as in our baseline calibration. Quantitatively, allowing for the wealth effect on labor supply smooths out the effects of shocks. During the transition to a low-carbon economy, households' labor supply does not fall as much as in the case with the GHH preferences, and this mitigates the fall in aggregate output. It is still the case that ambitious climate policy action, without macroprudential policies, triggers equity losses in the banking sector and disrupts credit supply. Banks are forced to pull back their lending from the green sector which lowers green capital in the short- to medium-term (Figure A13), similar to the baseline scenario (Figure 1). Macroprudential policy again alleviates the transition risk stemming from ambitious climate policy (Figure

A14).

Similarly, with the wealth effect on labor supply, the negative TFP shock has a milder effect on the economic activity and banks' net worth. This implies that, with financial frictions, the second-best Ramsey efficient tax falls by less under the separable utility function compared to the baseline GHH preferences (Figure A15). The Ramsey-efficient second-best dynamic macroprudential policies are also very similar to the base-case results (Figure A16).

Table A1: Steady state: Additional variables

	No financial frictions			Financial frictions				
	No policy	Emissions tax only		No policy	Emissions tax only	Uniform macro-prudential policies only ($\tau^b = \tau^g$)	Differentiated macroprudential policies only ($\tau^b \neq \tau^g$)	Emissions tax and uniform macroprudential policies
Consumption	1.124	1.131		1.076	1.080	1.116	1.116	1.131
Green output	0.914	0.924		0.848	0.855	0.903	0.908	0.924
Brown output	0.729	0.725		0.674	0.670	0.720	0.714	0.725
Green investment	0.299	0.301		0.256	0.257	0.291	0.295	0.301
Brown investment	0.199	0.196		0.171	0.168	0.194	0.190	0.196
Labor in green prod.	0.273	0.274		0.263	0.264	0.271	0.272	0.274
Labor in brown prod.	0.213	0.211		0.205	0.204	0.212	0.211	0.211
Pollution stock	1171.4	1089.4		1155.6	1089.4	1168.6	1166.9	1089.4

Note: This table shows the steady state values of selected variables in the economies with and without financial frictions under different policy scenarios. All variables are in arbitrary model units.

Table A2. Steady state: Sensitivity to parameters

	Financial frictions								
	Emissions tax only			Differentiated macroprud. only			Emissions tax and uniform macroprud.		
	$\rho_Y = 1.2$	$\theta_1 = 0.15$	$z = 1.5$	$\rho_Y = 1.2$	$\theta_1 = 0.15$	$z = 1.5$	$\rho_Y = 1.2$	$\theta_1 = 0.15$	$z = 1.5$
Emissions tax (\$ per ton)	13.5	9.0	21.3	0	0	0	16.8	17.3	24.7
Tax on brown assets (%)	0	0	0	-0.15	-0.14	-0.11	-0.22	-0.22	-0.22
Tax on green assets (%)	0	0	0	-0.22	-0.22	-0.22	-0.22	-0.22	-0.22

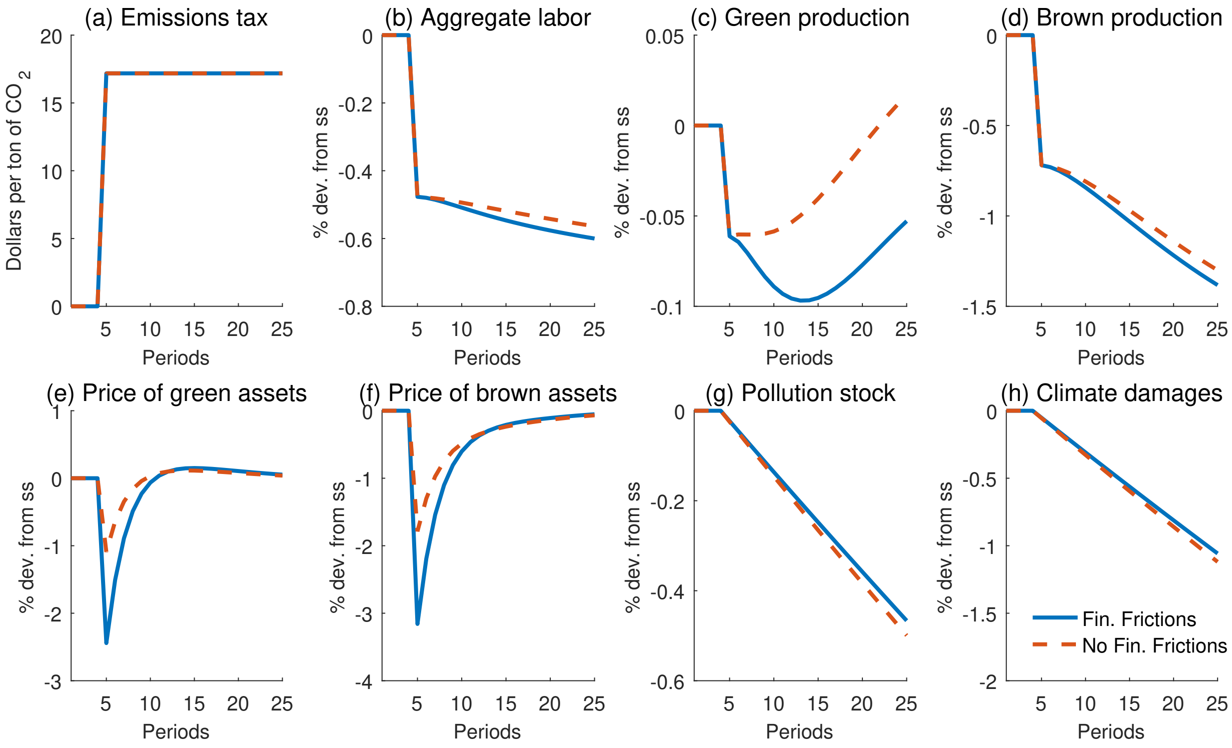
Note: This table shows sensitivity of Ramsey-efficient policies to different parameters in the economy with financial frictions. Parameter ρ_Y controls the elasticity of substitution between green and brown goods. θ_1 controls the cost of abatement, and z is the scalar controlling output damages from pollution; That is, for this sensitivity exercise we use z to scale the damage function as $zd(X_t)$.

Table A3: Steady state: Separable preferences

	No financial frictions		Financial frictions				
	No policy	Emissions tax only	No policy	Emissions tax only	Uniform macro-prudential policies only ($\tau^b = \tau^g$)	Differentiated macroprudential policies only ($\tau^b \neq \tau^g$)	Emissions tax and uniform macroprudential policies
Emissions tax ($ per ton)	0	16.6	0	14.4	0	0	16.6
Tax on brown assets (%)	–	–	0	0	-0.20	-0.15	-0.22
Tax on green assets (%)	–	–	0	0	-0.20	-0.22	-0.22
Aggregate output	1.576	1.577	1.502	1.503	1.566	1.566	1.577
Climate damages (%)	3.68	3.13	3.61	3.13	3.67	3.66	3.13
Emissions	0.709	0.434	0.674	0.435	0.704	0.698	0.434
Banks' net worth	–	–	3.410	3.376	3.787	3.788	3.831
Green credit spread (%)	0	0	0.225	0.225	0.030	0.000	0
Brown credit spread (%)	0	0	0.225	0.225	0.030	0.075	0
Welfare loss (% CV)	0.61	0	1.27	0.76	0.68	0.67	0

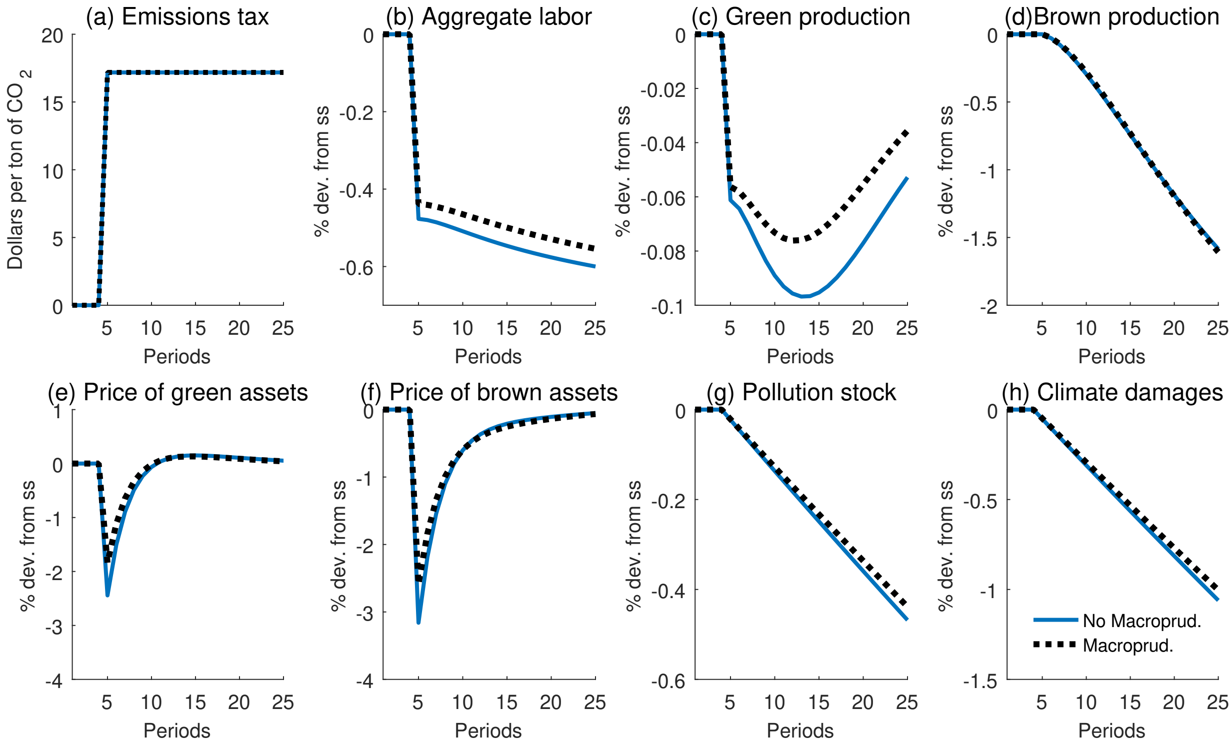
Note: This table shows the steady state values of selected variables in the economies with and without financial frictions under different policy scenarios. The units of the emissions tax are dollars per ton of CO_2, based on the calibration described in the text. Tax rates on banks' assets and credit spreads are in percentages. Climate damages are in percent of output. Welfare loss is in terms of compensating consumption variation relative to the first-best allocations. All other variables are in arbitrary model units. The households' utility function is given by equation (F1).

Figure A1: Transition to a low carbon economy: Additional variables



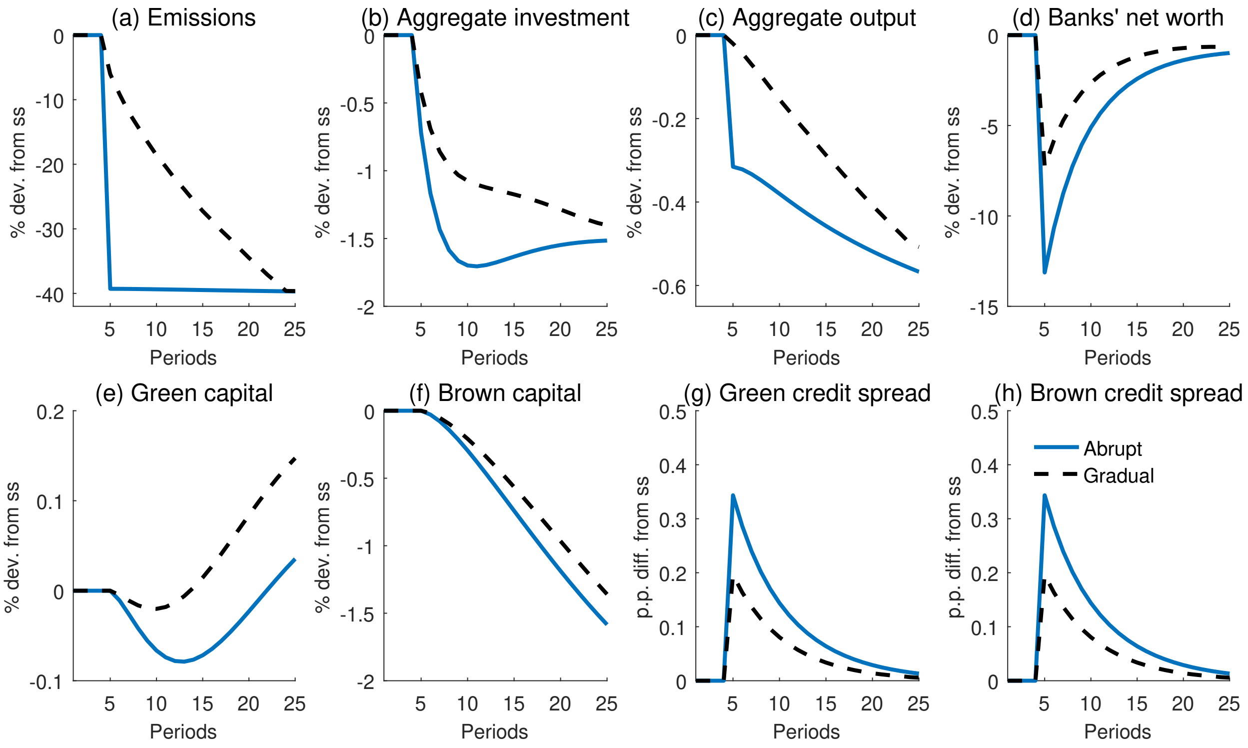
Note: This figure plots the transition dynamics of additional variables in response to the same path of the emissions tax as in Figure 1. Each simulation begins at the no-policy steady state under the given model.

Figure A2: Transition to a low carbon economy with macroprudential policy: Additional variables



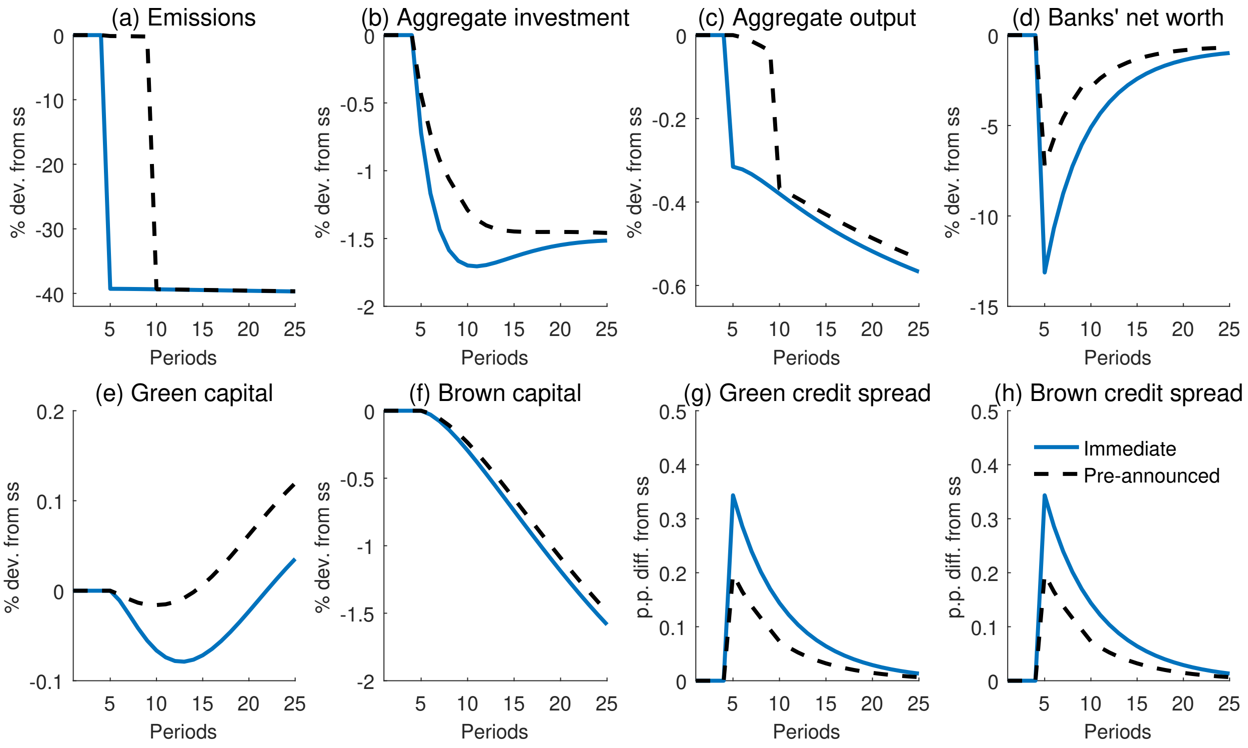
Note: This figure plots the transition dynamics of additional variables in response to the emissions tax introduction in the economies with and without macroprudential policy. Each simulation begins at the steady state with no emissions policy under the given model.

Figure A3: Transition dynamics: Abrupt versus gradual "ramp-up" approach



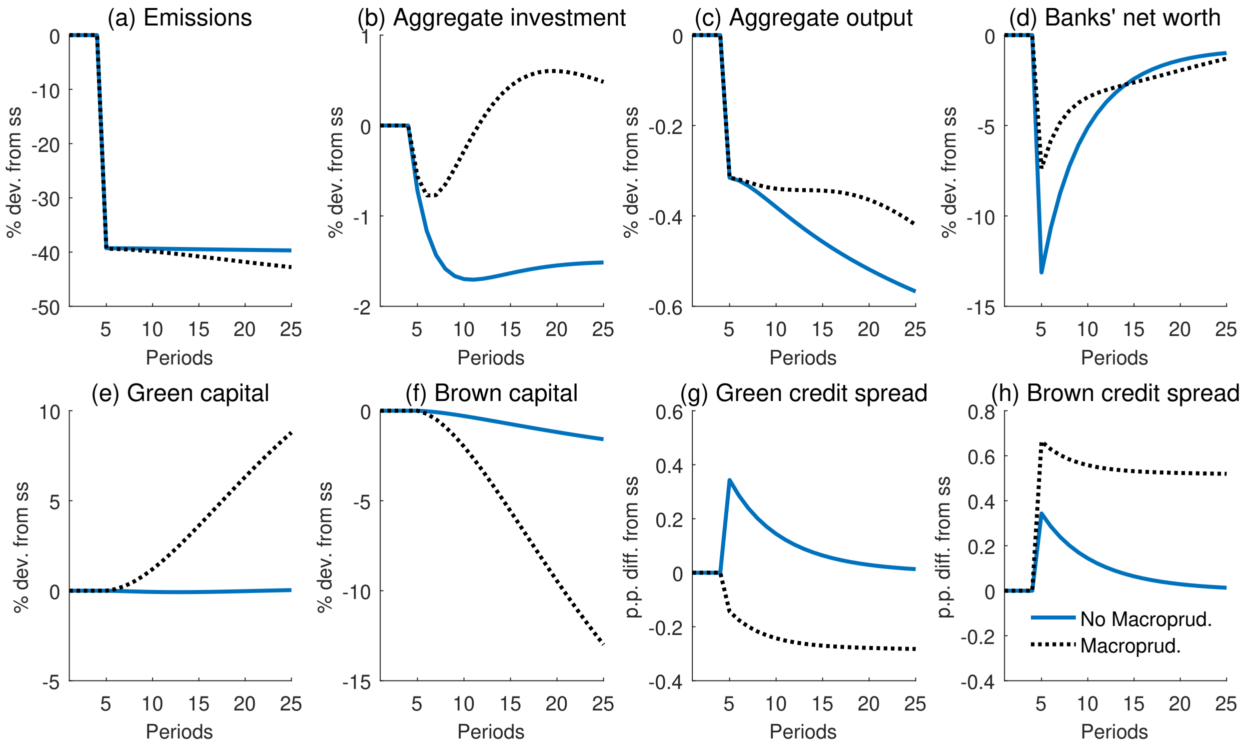
Note: This figure plots the transition dynamics in response to an unanticipated introduction of the permanent emissions tax of about 17 dollars per ton of CO_2, gradually introduced over 20 periods, in the economy with financial frictions. Each simulation begins at the identical no-policy steady state.

Figure A4: Transition dynamics: Immediate versus pre-announced implementation



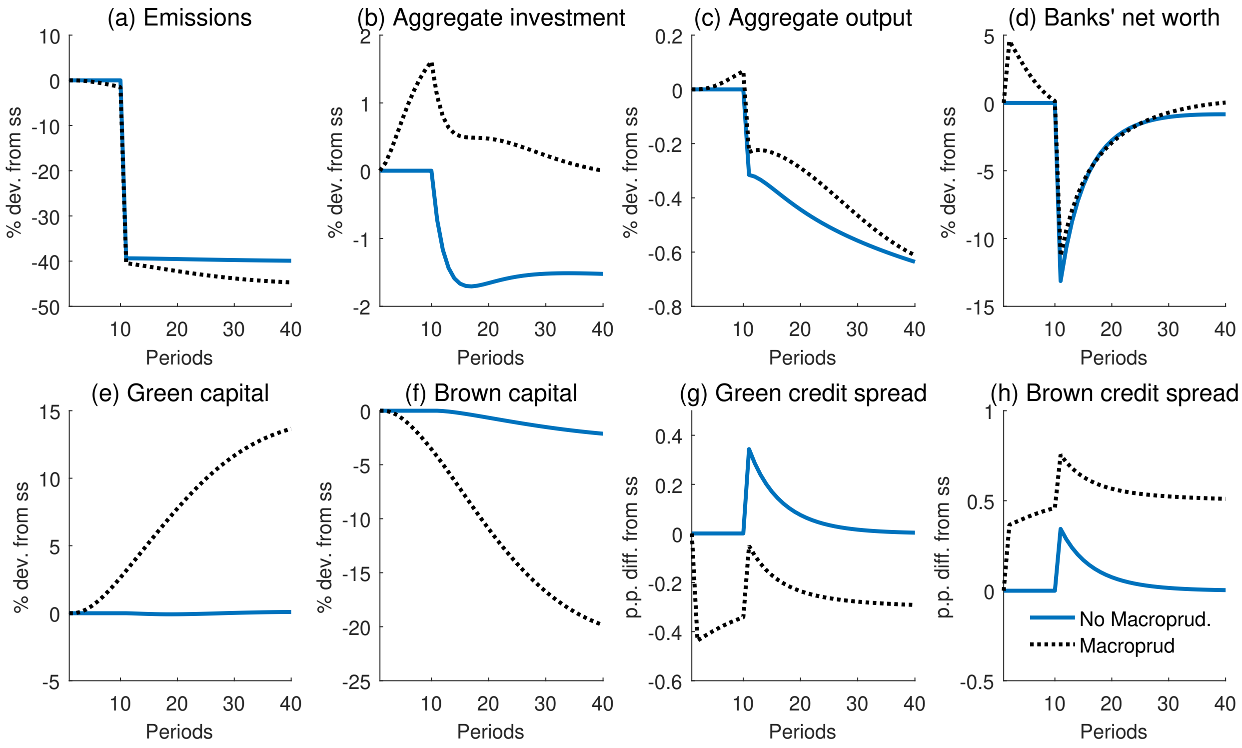
Note: This figure shows the transition dynamics in response to an introduction of a permanent emissions tax of about 17 dollars per ton of CO_2, which is announced in period 5 but does not go into effect until period 10, in the economy with financial frictions. Each simulation begins at the identical no-policy steady state.

Figure A5: Transition dynamics: Simultaneous macroprudential policies



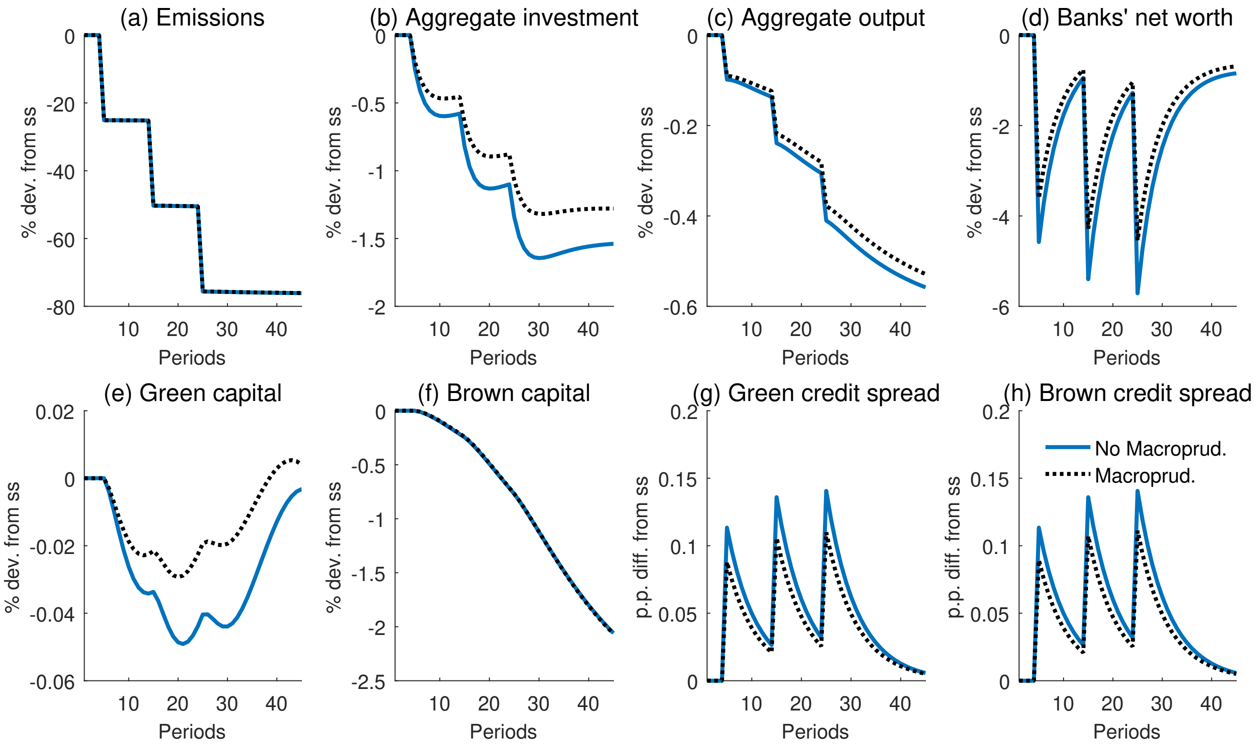
Note: This figure plots transition dynamics in response to an unanticipated introduction of the permanent emissions tax of about 17 dollars per ton of CO_2, along with a simultaneous introduction of macroprudential policies of the same magnitude as those presented in Figure 2. Each simulation begins at the steady state with no emissions policy under the given model.

Figure A6: Transition dynamics: Sequential implementation of policies



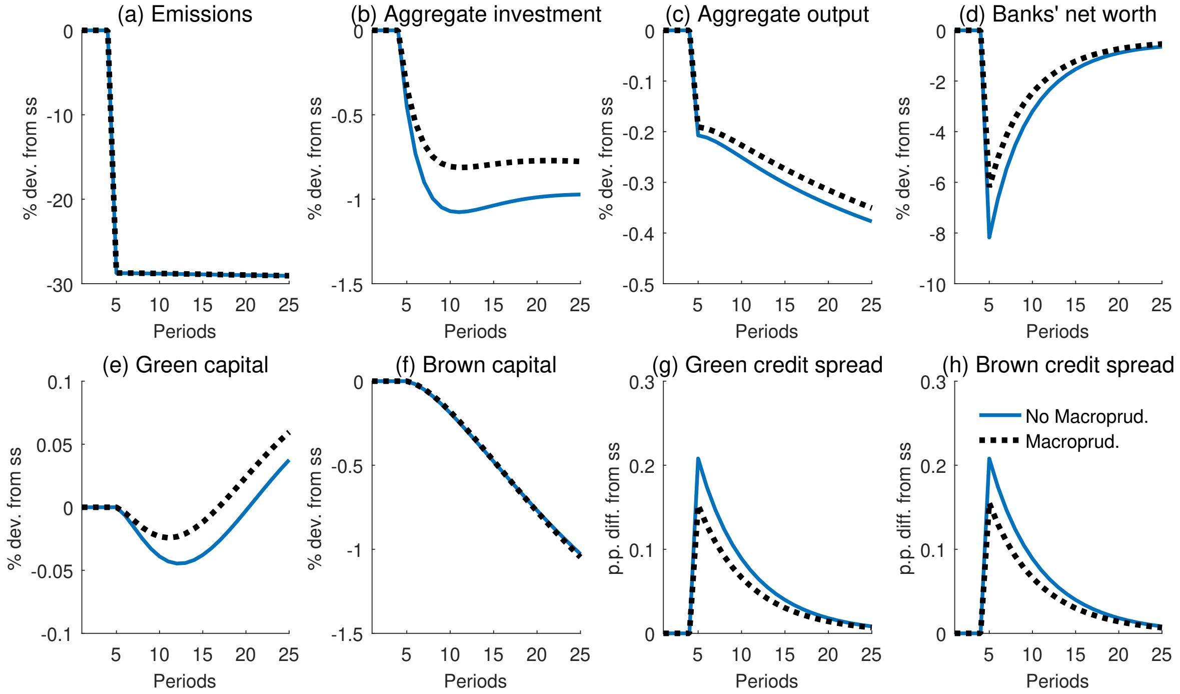
Note: This figure plots transition dynamics in response to an unanticipated introduction of the permanent macroprudential policies in period 2 and the permanent emissions tax in period 11. The magnitudes of the policies are the same as in Figure 2. Blue solid lines depict the case when only the emissions tax is introduced in period 11, but no macroprudential policy is enacted beforehand. Each simulation begins at the identical no-policy steady state.

Figure A7: Stochastic emissions tax



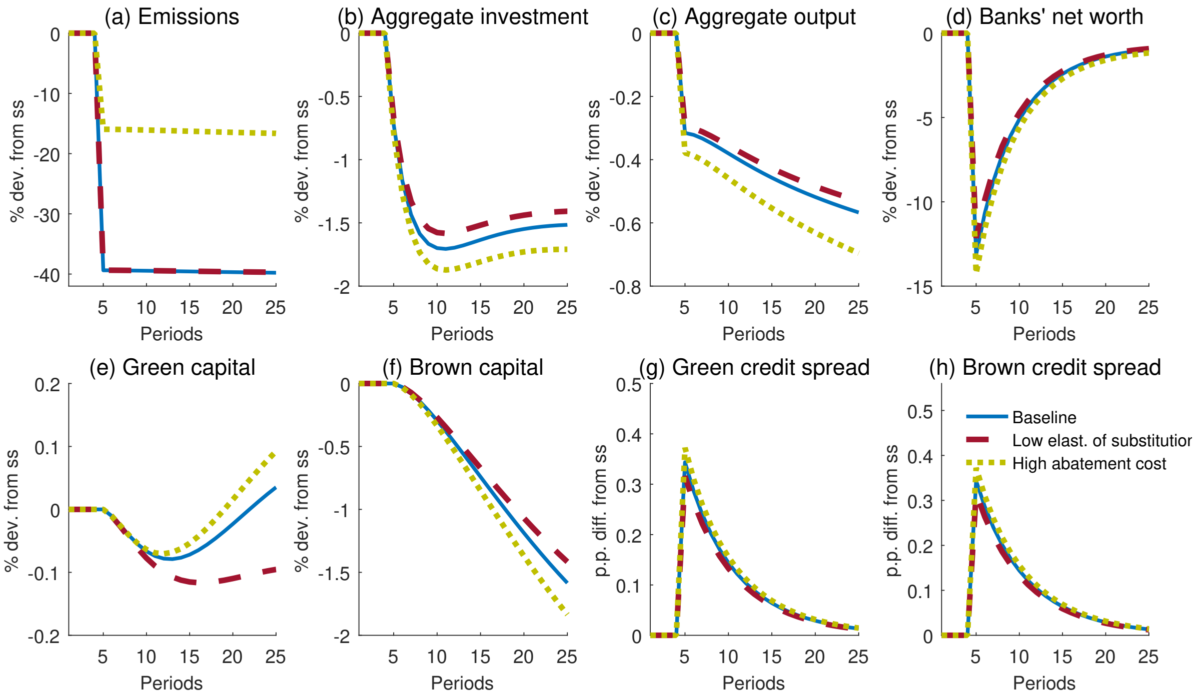
Notes: This figure plots the stochastic simulations when the economy is hit by a sequence of emissions tax shocks (in periods 5, 15, and 25). In these simulations emissions tax τ_t^e is assumed to follow the following stochastic AR(1) process: $\tau_t^e = (1 - \rho_\tau)\,\tau_{ss}^e + \rho_\tau \tau_{t-1}^e + \sigma_\varepsilon \varepsilon_t, \quad \varepsilon_t \sim \mathcal{N}(0, 1)$ with $\rho_\tau = 0.9999$ and $\sigma_\varepsilon = 0.01$. Each simulation begins at the steady state under the given model.

Figure A8. Transition dynamics to a low carbon economy: Low steady-state pollution stock



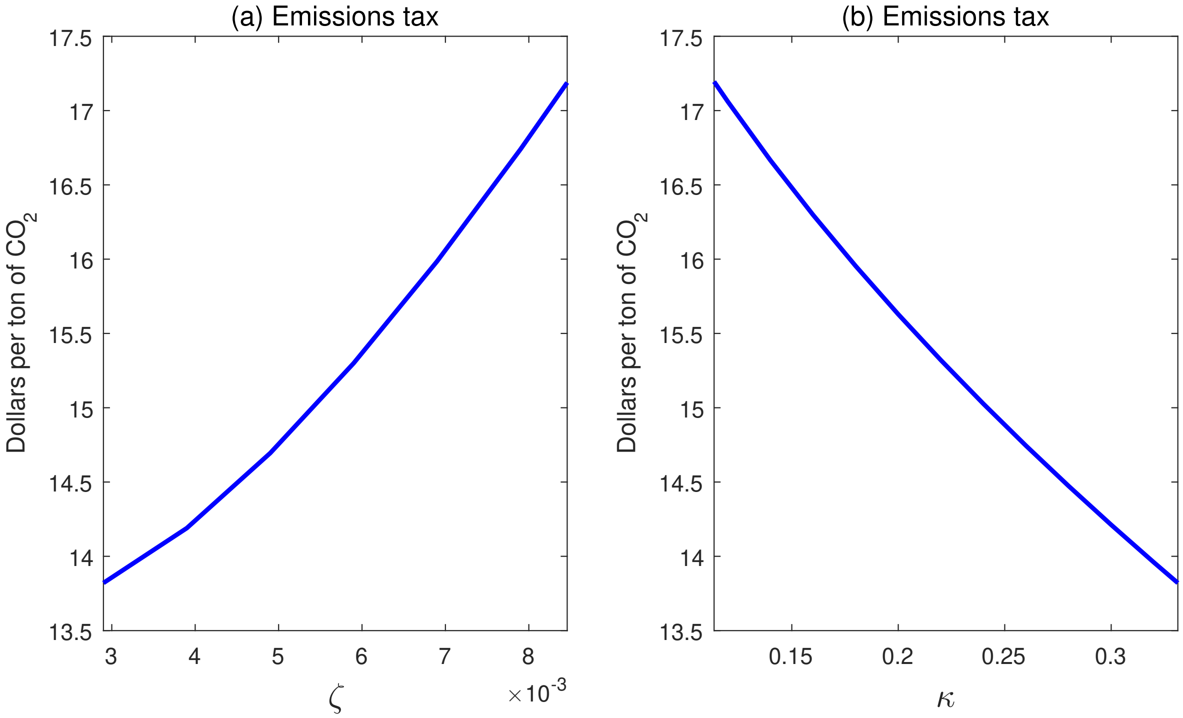
Note: This figure plots transition dynamics to a low carbon economy in the model with financial frictions with and without macroprudential policies, when we calibrate the steady state of the model to the current atmospheric carbon stock. In the low carbon stock calibration, we assume that the steady state pollution stock in the model corresponds to 851 GtC. The first best efficient tax in this case is 0.0116 (or about 10 dollars per ton of CO_2). The effects of the climate policy shock are qualitatively similar to the baseline calibration. Quantitatively the effects are smaller because of the lower carbon tax. Each simulation begins at the steady state with no emissions policy under the given model.

Figure A9: Transition dynamics to a low carbon economy: Sensitivity to parameters



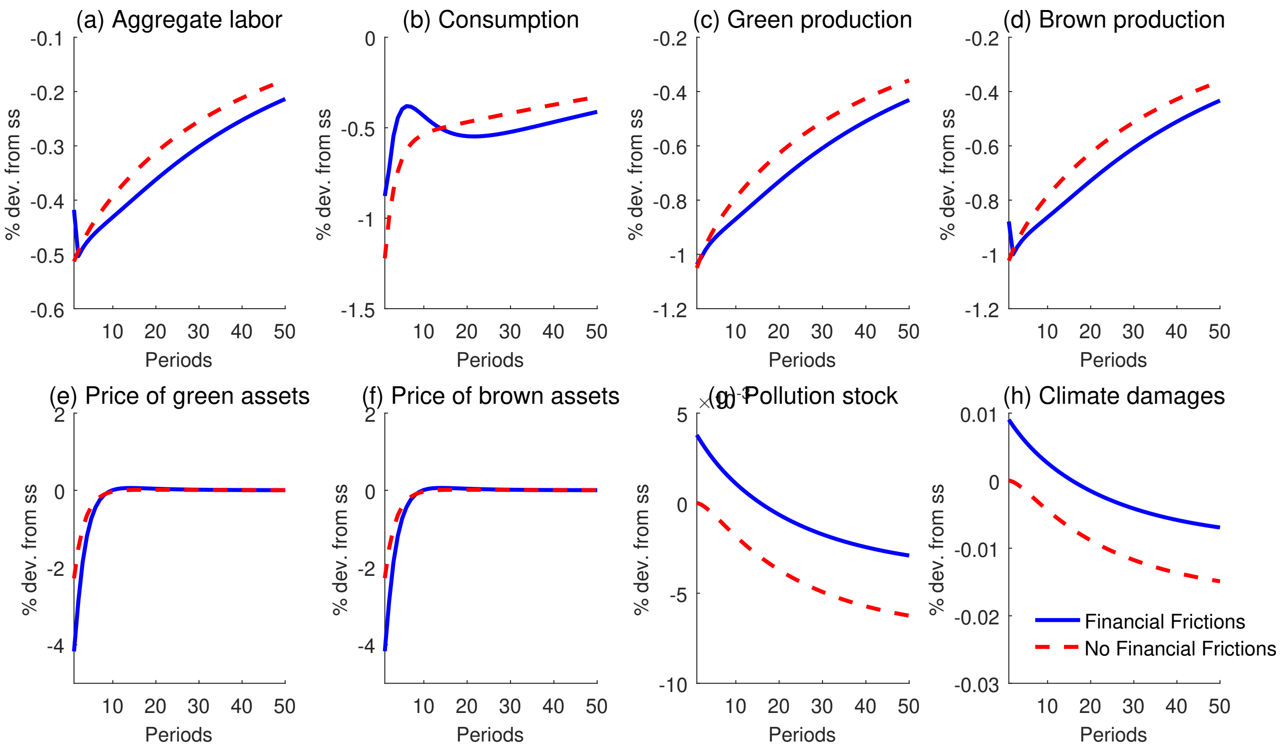
Note: This figure compares the baseline transition dynamics in the model with financial frictions (i.e., Figure 1, solid lines) to the case with the low elasticity of substitution between green and brown inputs ($\rho_L = 1.2$), and high abatement cost ($\theta_1 = 0.15$). The path of the emissions tax in all the scenarios is the same as in Figure 1. Each simulation begins at the steady state with no emissions policy under the given model.

**Figure A10: Second-best steady-state emissions tax:
Sensitivity to parameters controlling financial frictions**



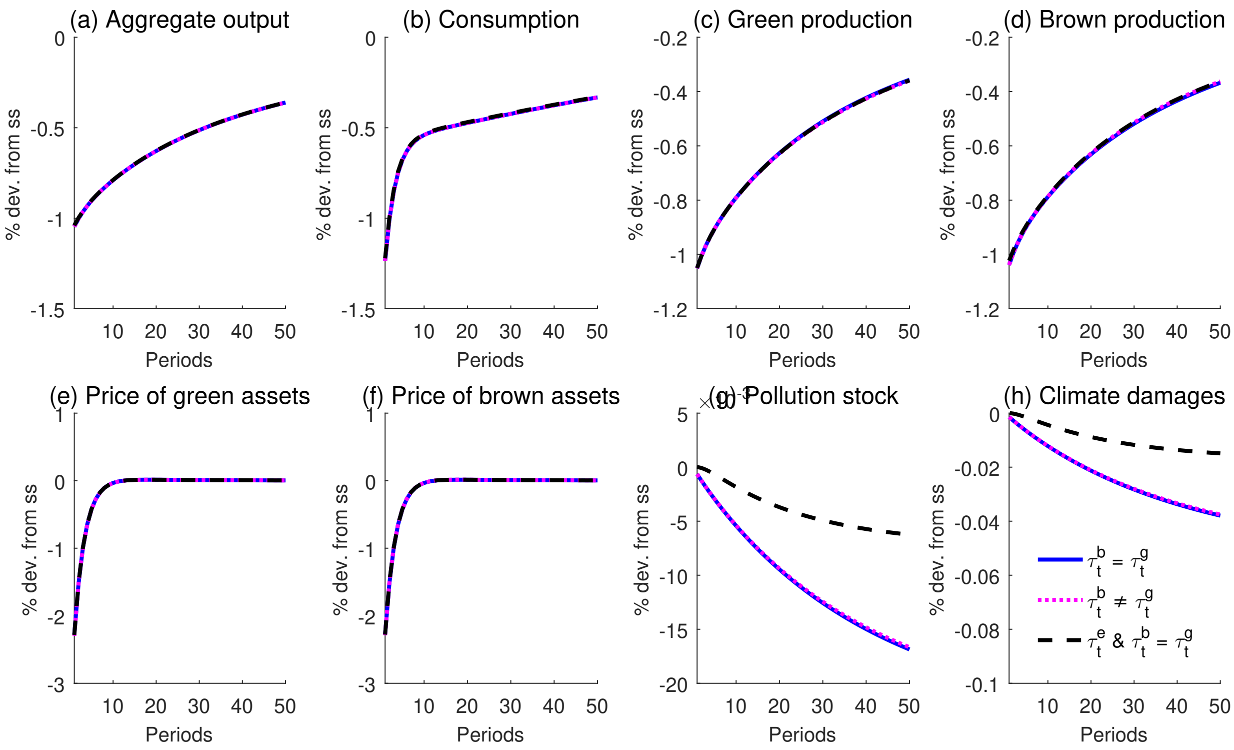
Note: This figure plots the second-best steady-state value of the emissions tax when varying either the banks' transfer parameter (ζ) or the agency problem parameter (κ) from their base-case values of 0.0029 and 0.3313, respectively.

Figure A11: The Ramsey-efficient dynamic emissions tax:
Additional variables



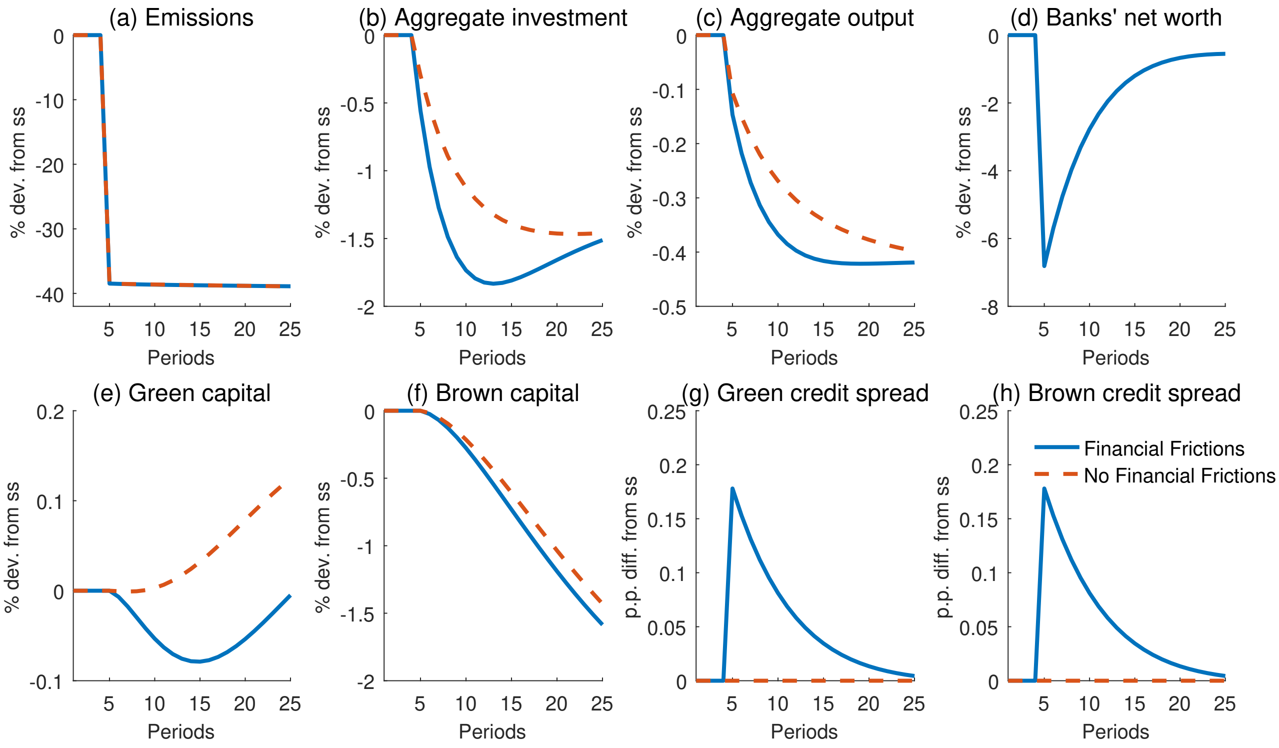
Note: This figure plots the impulse responses of additional variables to the same TFP shock as in Figure 3 under the Ramsey-efficient emissions tax policy in the economies (i) with financial frictions (solid lines) and (ii) without financial frictions (dashed lines). Each simulation begins at the steady state that includes the Ramsey-efficient emissions tax under the given model.

Figure A12: Ramsey-efficient dynamic policies under different sets of instruments: Additional variables



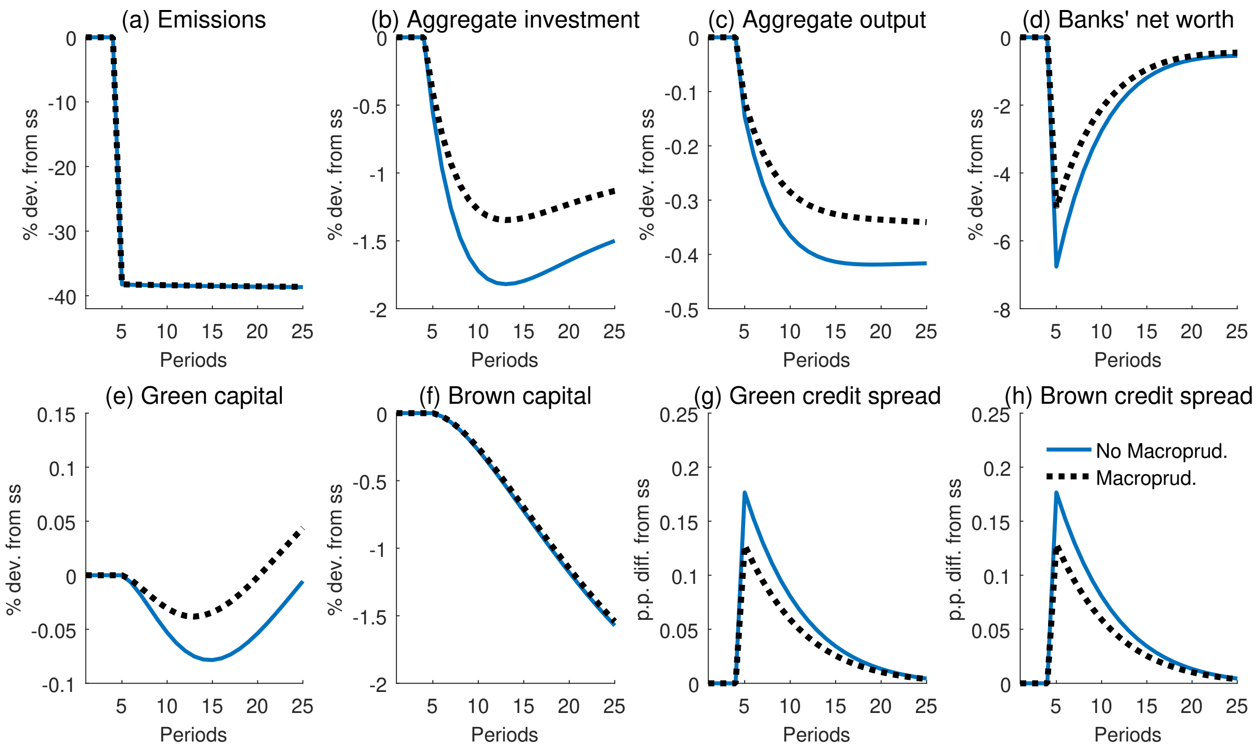
Note: This figure plots the impulse responses of additional variables to the same TFP shock as in Figure 4 under Ramsey-efficient policies with different sets of available instruments. Each simulation begins at the steady state that includes the specified policy combination.

Figure A13: Transition dynamics to a low carbon economy: Separable preferences



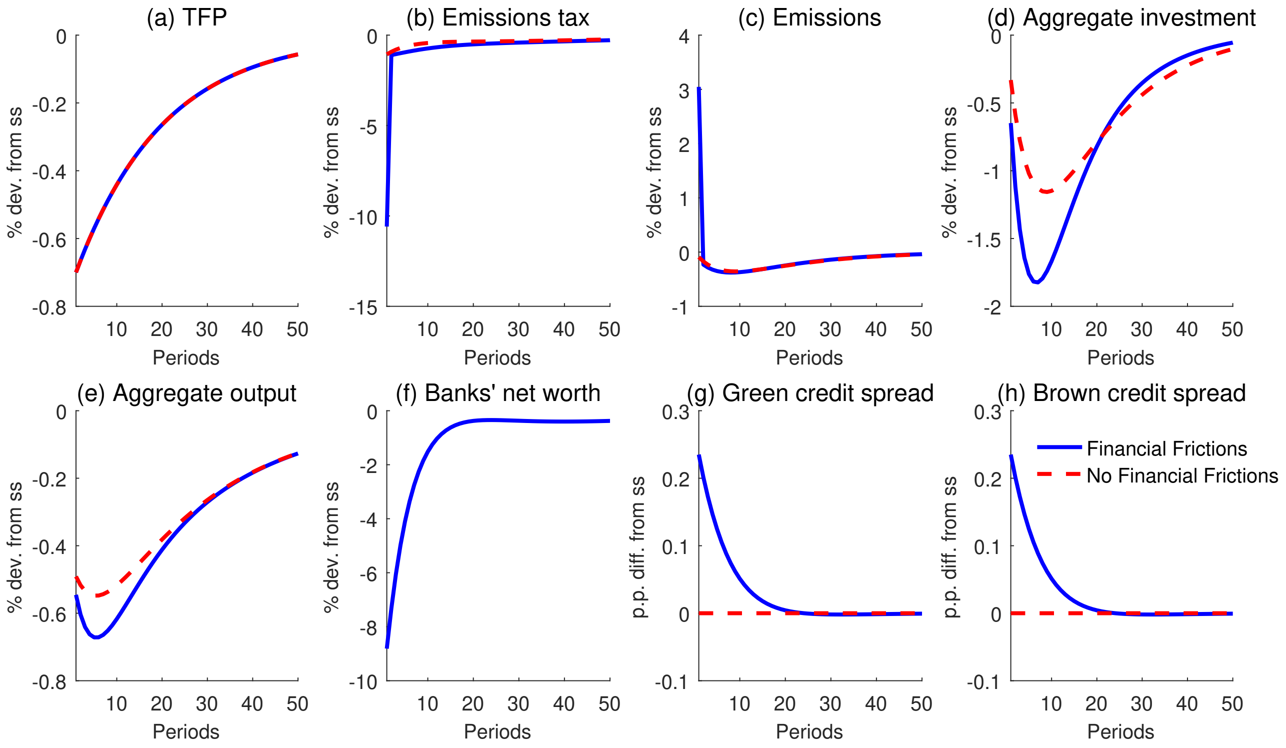
Note: This figure shows the transition dynamics to a low carbon economy in the models with and without financial frictions when the households' preferences are given by equation (F1). Each simulation begins at the steady state with no emissions policy under the given model.

Figure A14: Transition to a low carbon economy with macroprudential policy: Separable preferences



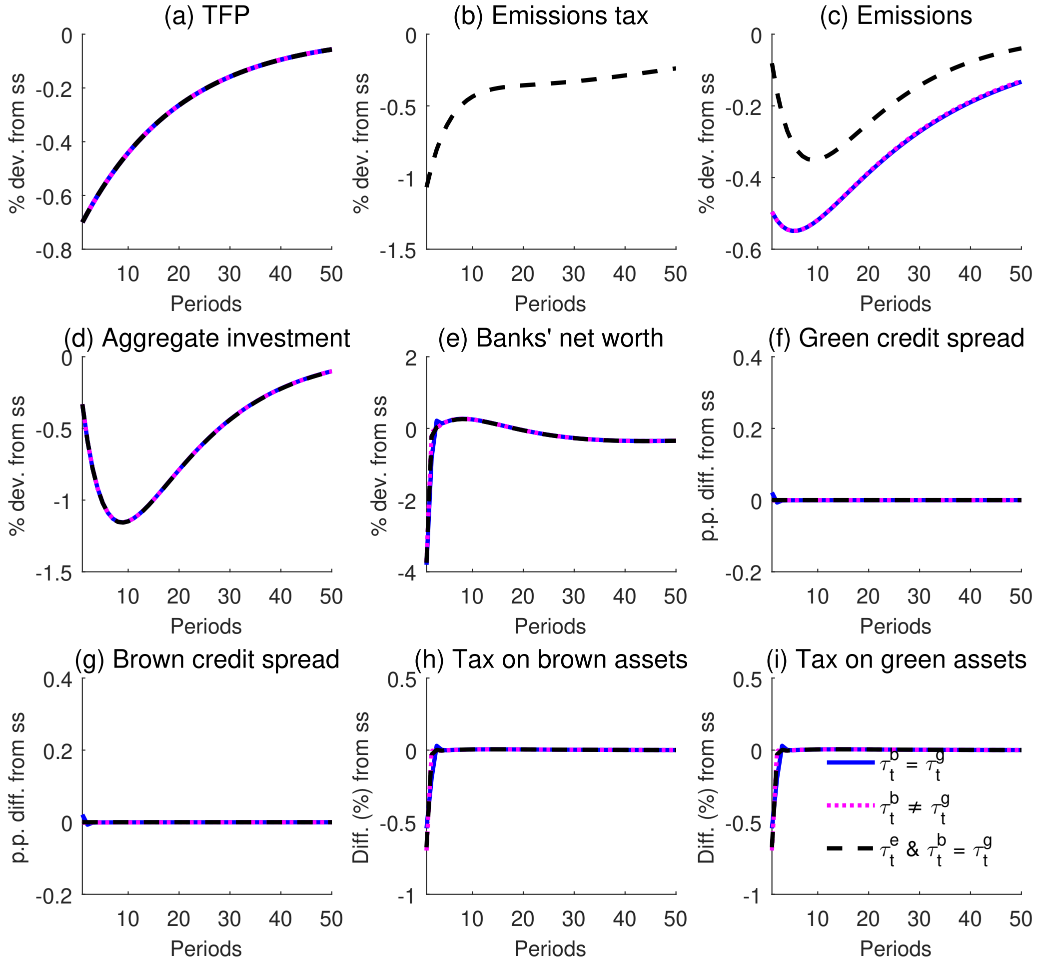
Note: This figure plots the transition dynamics in the model with financial frictions to the same emissions tax shock as in Figure A11 under two scenarios: (i) No macroprudential policy (solid lines); (ii) with macroprudential policy (dashed lines). Deviations are calculated relative to the respective initial steady states. The households' preferences are given by equation (F1). Each simulation begins at the steady state with no emissions policy under the given model.

Figure A15: The Ramsey-efficient dynamic emissions tax: Separable preferences



Note: This figure plots the impulse responses to a one-standard-deviation negative TFP shock under the Ramsey-efficient emissions tax policy in the economies (i) with financial frictions (solid lines) and (ii) without financial frictions (dashed lines). The households' preferences are given by equation (F1). Each simulation begins at the steady state that includes the Ramsey-efficient emissions tax under the given model.

A16: Ramsey-efficient dynamic policies under different sets of instruments: Separable preferences



Note: This figure plots the impulse responses to a one-standard-deviation negative TFP shock in the model with financial frictions under the Ramsey-efficient policies when (i) only uniform tax on banks' assets ($\tau_t^b{=}\tau_t^g$) is available (solid lines); (ii) only differentiated taxes on banks' brown (τ_t^b) and green (τ_t^g) assets are available (dotted lines); (iii) emissions tax (τ_t^e) and a uniform tax on banks' assets ($\tau_t^b{=}\tau_t^g$) are available (dashed lines). The households' preferences are given by equation (F1). Each simulation begins at the steady state that includes the specified policy combination.