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Stefano Carattini, Giseong Kim, Givi Melkadze, Aude Pommeret

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Abstract

Ambitious climate policy, coupled with financial frictions, has the potential to create macrofinancial stability risk. Such stability risk may expand beyond the economy implementing climate policy, potentially catching other countries off guard. International spillovers may occur because of trade and financial channels. Hence, we study the design and effects of climate policies in the world economy with international trade and financial flows. We develop a two-sector, two-country, dynamic general equilibrium model with financial frictions, climate policies, including carbon tariffs, and macroprudential policies. Using the calibrated model, we evaluate spillovers from unilateral domestic carbon pricing to foreign economies and back. We also examine more ambitious climate architectures involving carbon tariffs or a global carbon price. We find that accounting for cross-border financial flows and frictions in credit markets is crucial to understand the effects of climate policies and to guide the implementation of macroprudential policies at the global scale aimed at minimizing transition risk and paving the way for ambitious climate policy.

JEL-Codes: E440, E580, F380, F420, G180, Q580.

Keywords: financial frictions, carbon tax, carbon tariffs, open economy.

Stefano Carattini
Georgia State University, Atlanta / GA / USA
scarattini@gsu.edu

Giseong Kim
Georgia State University, Atlanta / GA / USA
gkim81@gsu.edu

Givi Melkadze
Georgia State University, Atlanta / GA / USA
gmelkadze@gsu.edu

Aude Pommeret
Université Savoie Mont Blanc
Chambéry / France
aude.pommeret@univ-smb.fr

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1 Introduction

Financial stability is one of the most important topics that economists can tackle as scholars and practitioners, as the recent experience with bank runs has reminded us. The literature on financial stability goes back several decades, including Nobel-worthy studies from the 1980s. The crucial role of financial stability has re-emerged over the last decade in the economics literature, following the Great Recession. Only more recently, though, the focus was extended to another concern for financial stability: transition risk.

Transition risk refers to the potential systemic risk that could follow from a necessary, yet abrupt transition to a more sustainable economy. Despite climate change being a major issue since the early 1990s, the private sector, including financial companies, is still misaligned with the goal of the Paris Agreement to maintain global temperature increases within 1.5°C above pre-industrial levels (e.g., ECB 2021). Stringent climate policy measures are therefore required at the global level. However, such policies may pose a threat to financial stability, especially if implemented abruptly, which may be necessary after decades of policy delays. Financial assets may become "stranded," leading to important losses for the financial institutions owning them. For instance, McGlade and Ekins (2015) stress that estimates of global fossil fuel reserves vastly exceed the amount of carbon that can still be emitted without exceeding the goals of the Paris Agreement, leading to one of two outcomes: either to more severe climate change or to such carbon staying in the ground and thus to a reevaluation of those assets. The same logic applies to carbon-intensive assets at large, beyond fossil fuels. To use the words of the former governor of the Bank of England Mark Carney (Carney 2015), "a wholesale reassessment of prospects, especially if it were to occur suddenly, could potentially destabilize markets, spark a pro-cyclical crystallization of losses and a persistent tightening of financial conditions. In other words, an abrupt resolution of the tragedy of horizons is in itself a financial stability risk".

Several recent papers analyze transition risk using quantitative macro models with climate externality and financial frictions in the banking sector, informing also the process of creating climate stress tests for enhanced financial surveillance. In particular, Carattini, Heutel, and Melkadze (2021) show how significant climate policy-driven financial stability risk is indeed possible: An abrupt implementation of ambitious climate policy can trigger asset losses in the banking sector that cause a tightening of credit supply and, as a result, an economy-wide recession. However, macroprudential financial regulation can mitigate transition risk. Diluiso et al. (2021) instead consider a gradual ramp-up approach to climate policy, which they show would not be conducive to transition risk, at the cost, however, of delaying climate action. These papers focus on closed economies in which domestic climate policies interact with domestic financial sector's stability.

In this paper we study international aspects of climate policies and the resulting cross-country spillovers through financial and trade linkages. Understanding cross-border implications of climate policies is important for several reasons. First, in the presence of cross-border financial and trade flows the effects of national climate policies are not limited only to the home countries. The realization of transition risk following the implementation of ambitious climate policy, even when originated only in one group of countries, can thus have implications for other economies in the world. Second, some climate policy measures that are being considered by policymakers, for instance in the European Union, directly target international trade flows with the stated goal of mitigating carbon leakage and ensuring a level playing field for domestic industries that are subject to climate policy at home. Carbon border adjustment mechanisms, in particular, would tax imports based on their carbon emissions in the same way that domestic production would be taxed. Third, gradualism may no longer be an option, if the government considering ambitious climate policy is that of a third country. Hence, it follows that countries may need to implement macroprudential policy in anticipation not only of their own policies, but also of other countries'. Therefore, appraising transition risk and designing the suitable policy response requires understanding the effects of climate policies within and across borders.

To explore these questions, we develop a two-country, two-sector, dynamic stochastic general equilibrium (DSGE) model that builds on the seminal papers by Backus, Kehoe, and Kydland

(1992) and Corsetti, Dedola, and Leduc (2008) on International Real Business Cycles (IRBC). We extend the IRBC model with polluting ("brown") and non-polluting ("green") sectors, climate policies, including carbon border adjustment mechanisms, global financial intermediaries, and macroprudential policies. We consider climate policies without damages being explicitly included in the model, consistent with a carbon budget objective as in van der Ploeg (2018) or Gollier (2021). In the model, the global financial intermediaries (or banks) lend to brown and green firms both domestically and abroad, and are subject to occasionally binding funding constraints à la Gertler and Kiyotaki (2010). The global nature of financial intermediation captures a well-established fact that financial markets across countries are integrated through large cross-border financial flows. A financial friction that limits banks' intermediation capacity takes the form of an agency problem between banks and their lenders as in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). The key implication of this friction is that global banks' ability to extend credit to the non-financial corporate sector depends on the strength of their balance sheets. When banks' net worth is sufficiently low, for example, in response to a negative shock to the economy, banks are forced to cut lending to non-financial firms, amplifying the effect of the initial shock through the standard "financial accelerator" mechanism. Since in our model banks operate globally, disruptions in bank credit supply have implications for global economic activity.

We calibrate the model to the European Union as the domestic country and the United States as the foreign country. Using the calibrated model, we simulate several climate policy scenarios that are relevant for policymakers around the world, and infer which policy packages achieve the transition from a high to a low carbon economy with the lowest transition cost, which in our novel framework accounts for the probability of financial contagion and possible policy-induced recessions, domestic or global. The objective is to identify potential sources of transition risk and provide policy recommendations to address them, so that if the opportunity for ambitious climate policy arises, transition risk would not be a reason not to go ahead with such ambitious plans.

In detail, we proceed as follows. First, we evaluate spillovers from domestic carbon taxes to foreign economies through cross-border financial linkages and international trade flows. An ambitious domestic carbon tax can affect the foreign economy through financial linkages because stringent climate regulations at home might tighten domestic banks' funding constraints, thereby forcing them to pull back their lending from foreign firms pushing foreign economic activity down. On the other hand, the negative impact of the ambitious carbon tax on the domestic carbon-intensive sectors may drive foreign production up, as global demand shifts toward cheaper foreign-produced goods, a mechanism known as carbon leakage. The model allows us to capture these financial and trade channels of international spillovers.

Second, we study a novel trade-off faced by a country when imposing a carbon border adjustment mechanism on goods imported from the foreign country, where the latter is assumed not to have any domestic carbon tax in place. The European Union, for instance, recently announced a plan to implement a carbon border adjustment mechanism on certain imports to the block. In our setting, we simulate the case where the jurisdiction's entire economy is covered by a carbon price and, in some of the scenarios, a carbon border adjustment mechanism also applies on top. While the carbon border adjustment mechanism may bring several key benefits - leveling the playing field to reduce carbon leakage - it may also trigger "asset stranding" in the carbon-intensive foreign economy. Asset stranding in the foreign economy, in turn, may have destabilizing effects on the domestic economy through cross-border exposure of the domestic financial sector to foreign assets. Our model allows us to quantify this unexplored trade-off and to assess the effectiveness of macroprudential policies, in the domestic as well as in the foreign country, in avoiding financial contagion and a potential policy-driven recession.

We find that financial frictions and cross-border financial linkages are very important for understanding the effects of ambitious climate policies. In particular, in our baseline model, the abrupt implementation of an ambitious carbon tax in the domestic economy generates a global recession. At the core of this result are leveraged global banks that fund domestic and foreign long-term assets subject to funding constraints. The domestic carbon tax lowers the realized return on domestic carbon-intensive capital that global banks are exposed to, thereby lowering banks' net worth. If the carbon tax is large enough, banks with depressed net worth are unable to raise external funds due to the financial friction, and thus, are forced to reduce lending to domestic green (and brown) firms, as in Carattini, Heutel, and Melkadze (2021), but also to firms in the foreign economy, in both the green and carbon-intensive sectors. When we shut down financial frictions, an ambitious domestic carbon tax results in an expansion of the green sectors both at home and abroad, and also an increase in foreign dirty production, i.e., some carbon leakage.

Next, we explore the scenario in which the domestic economy implements a more ambitious climate policy package: a domestic carbon tax plus carbon border adjustment mechanism, which we model as a tariff on carbon-intensive imports from the foreign country. In the baseline model with financial frictions, the carbon border adjustment mechanism does mitigate carbon leakage in the short to medium term. However, this benefit comes at the cost of further weakening banks' balance sheets leading to a more severe recession (compared to the case with only the domestic carbon tax). Hence, we identify a novel trade-off, in the absence of macroprudential policy, between transition risk and the mitigation of carbon leakage.

Finally, we consider the scenario wherein climate policy is implemented at the global stage, with both countries introducing a domestic carbon tax with the same level of stringency, thus leading to a global carbon price through harmonized carbon taxes. Such policy coordination successfully reduces global emissions, but results in stronger transition risk.

Importantly, we show that in all policy scenarios, macroprudential policy can address transition risk, making way for ambitious climate policy. Macroprudential policy in anticipation of a carbon tax penalizes banks' carbon exposures encouraging them to decarbonize their balance sheets. Notably, our findings indicate that macroprudential policy is necessary in both countries, regardless of whether they are both introducing climate policy. Indeed, we show that the use of macroprudential policy in one country shifts carbon-intensive exposures to the foreign banking sector, making the foreign economy more vulnerable to the subsequent implementation of climate policy in the domestic economy. Only by also implementing macroprudential policy, the foreign country can insulate itself from a climate policy shock coming from abroad.

Our findings support the efforts by the Network for the Greening of the Financial System, a network of 114 central banks and financial supervisors, to coordinate and expand climate stress tests across countries, which currently still rarely consider the realization of transition risk from domestic climate policy shocks, let alone from foreign shocks (see Acharya et al. 2023 for a review). Hence, global coordination on carbon pricing should be accompanied with global coordination on climate stress tests and macroprudential policy, which to be effective in turn require global coordination on mandatory disclosure of climate risks (Carattini et al. 2022). With global macroprudential policy, at the time of the abrupt implementation of globally coordinated climate policy, banks are more resilient to the risk of asset stranding and can withstand the climate policy shock without cutting back on green lending too much, facilitating a smooth transition to a low-carbon economy.

Related literature. Our paper is related to several strands of literature. First, it builds on an established literature examining the role of financial instability, its drivers, and the possible ways to minimize it, preemptively or in reaction to a financial crisis.[1] This strand of research also includes a growing body of work, which emerged largely in response to the Great Recession, on international financial flows, the cross-border transmission of shocks and the role of global banks in international spillovers (Devereux and Yetman 2010, Mendoza and Quadrini 2010, Milesi-Ferretti and Tille 2011, Dedola and Lombardo 2012, Cetorelli and Goldberg 2012, Ueda 2012, Dedola et al. 2013, De Haas and Van Horen 2013, Kalemli-Ozcan et al. 2013, Kollman 2013, Bruno and Shin 2015, Cerutti et al. 2015, Maggiori 2017, Hale et al. 2020, Gete and Melkadze 2020, Miranda-Agrippino and Rey 2020, Morelli et al. 2022), as well as the potential

[1] A non-comprehensive list includes Bernanke (1983), Diamond and Dybvig (1983), Bernanke and Gertler (1989), Kiyotaki and Moore (1997), Gertler and Kiyotaki (2010), Mendoza (2010), Meh and Moran (2010), Bianchi (2011), Gertler and Karadi (2011), Christiano and Ikeda (2013) Brunnermeier and Sannikov, (2014), and Gertler et al. (2021), among others.

of macroprudential policies in the international context, in particular through capital controls, to address such shocks and the related cross-border transmission (Ostry et al. 2010, Bianchi 2011, Costinot et al. 2014, Kara 2016, Korinek and Sandri 2016, Jean and Korinek 2020). We contribute to these strands of literature by studying the international spillovers of climate-policy driven transition risk through financial frictions and cross-border financial flows, and the role of macroprudential policies in managing such spillovers.

Second, we contribute to a strand of literature analyzing transition risk, in particular using DSGE models so far only in a closed economy, and assessing the role of macroprudential policies (Carattini, Heutel, and Melkadze 2021, Dilusio et al. 2021, Comerford and Spiganti 2022, Fried, Novan, and Peterman 2022). Related work also assesses the potential for and implications of asset stranding in various contexts (Rozenberg et al. 2018, Campiglio et al. 2020, van der Ploeg and Rezai 2020), the exposure of financial institutions to carbon-intensive assets, including as measured with the first generation of climate-stress tests (Battiston et al. 2018, Alogoskoufis et al. 2021), as well as the behavior of investors with respect to transition risk (Carattini and Sen 2019, Bolton and Kacperczyk 2021a,b, Ramelli et al. 2021, Bauer et al. 2023). The existing literature confirms that concerns about transition risks are justified as financial institutions are largely exposed to carbon-intensive assets and investors are not really aligned with long-term climate goals, even if they may increasingly demand a risk premium for holding carbon-intensive assets. By moving to an open economy, our study highlights the potential for a global downturn driven by transition risk, as well as the potential for macroprudential measures to mitigate it.

Third, we contribute to an important literature on trade and the environment (Grossman and Krueger 1991, Antweiler et al. 2001, Levinson 2009, Taylor 2011, Shapiro and Walker 2018, Shapiro 2021), which also includes a more recent stream examining the design and assessing the potential impact of carbon border adjustment mechanisms (Elliott et al. 2010, Fischer and Fox 2012, Kortum and Weisbach 2017, Larch and Wanner 2017, Lyubich et al. 2018, Bohringer et al. 2021, 2022, Farrokhi and Lashkaripour 2021, Weisbach et al. 2022, Fontagné and Schubert, 2023). The literature generally identifies competitiveness and terms-of-trade as the main channels that allow carbon border adjustment mechanisms to reduce leakage. The competitiveness channel involves adverse substitution and income effects on the brown product while unregulated countries also suffer from a deterioration of their terms-of-trade. However, the ability of carbon border adjustment mechanisms to reduce leakage is countered by other channels such as general equilibrium effects through the price of fossil fuels, a reshuffling effect that re-routs carbon-intensive output, and an adverse competitiveness effect on industries using carbon-intensive products as intermediate inputs. In this paper, we highlight a new channel, namely the interaction between carbon border adjustment and financial frictions, making macroprudential policy necessary, particularly in the foreign country.

Our paper also speaks to a related scholarship on the economics of global carbon pricing (Hoel 1992, Weitzman 2014, Nordhaus 2015, Cramton et al. 2017, Stiglitz et al. 2017, Weitzman 2017, Carattini et al. 2019, IMF 2019, Nordhaus 2019, Parry et al. 2021). In this respect, we show the importance of combining harmonized carbon taxes, leading to a global carbon price, with macroprudential policy, to ensure a smooth transition to a low-carbon economy.

Finally, we add to a body of work that uses DSGE models to tackle environmental issues, to which the literature generally refers to as E-DSGE models (see the original contributions of Fischer and Springborn 2011, and Heutel 2012, as well as Annicchiarico et al. 2021 for a review).[2] This literature has generally evolved in the context of a closed economy. Several recent studies do extend such a framework to open economies (Airaudo et al. 2023, Ernst et al. 2023, and Minesso and Pagliari 2023), but, unlike our paper, these studies do not consider climate-policy-related financial stability risks and international contagion of such risks through frictions in credit markets.

The remainder of the paper is organized as follows. Section 2 introduces our theoretical model. Section 3 describes the calibration. Section 4 provides our main results. Section 5

[2]Recent contributions have also used E-DSGE models to study the interactions between various central bank policies besides macroprudential regulation (such as green quantitative easing or green collateral policies) and environmental outcomes, such as Abiry et al. (2022), Ferrari and Nispi Landi (2023), Giovannardi et al. (2023), Papoutsi, Piazzesi, and Shneider (2022), among others.

concludes.

2 Model

We consider an open economy model with two countries, Home and Foreign. Both countries are assumed to be of similar size. Each country's economy consists of households, financial intermediaries, the government and two types of non-financial firms: capital producers and goods producers. Goods-producing firms operate in "brown" (polluting) and "green" (non-polluting) sectors.

We describe Home country's economy. Foreign country is similar. Foreign variables are denoted by asterisk (*).

2.1 Households

In each country there is a continuum of identical households of measure unity. There is a constant fraction of bankers and workers in each household. Bankers manage financial intermediaries (or banks) and pay dividends to their own household. Workers supply labor to non-financial firms in green and brown production sectors and return wage income to the household. There is perfect consumption insurance among the household members. The household consumes and saves in the form of domestic bank deposits. A representative household has standard preferences defined over consumption C_t and labor hours L_t,

$$U\left(C_t, L_t\right) = \frac{C_t^{1-\gamma}}{1-\gamma} - \varpi \frac{L_t^{1+\xi}}{1+\xi}, \tag{1}$$

where C_t is the nested constant elasticity of substitution (CES) aggregator of domestic consumption of brown ($C_{b,t}$) and green ($C_{g,t}$) goods,

$$C_t = \left[a_b^{1-\phi} C_{b,t}^{\phi} + (1-a_b)^{1-\phi} C_{g,t}^{\phi} \right]^{\frac{1}{\phi}}, \ \phi < 1, \tag{2}$$

with $C_{b,t}$ and $C_{g,t}$ denoting the CES composites of consumption on Home- and Foreign-produced brown and green goods, respectively:

$$C_{b,t} = \left[\theta_b^{1-\rho_b} (C_{b,t}^{h})^{\rho_b} + (1-\theta_b)^{1-\rho_b} (C_{b,t}^{f})^{\rho_b} \right]^{\frac{1}{\rho_b}}, \ \rho_b < 1, \tag{3}$$

$$C_{g,t} = \left[\theta_g^{1-\rho_g} (C_{g,t}^{h})^{\rho_g} + (1-\theta_g)^{1-\rho_g} (C_{g,t}^{f})^{\rho_g} \right]^{\frac{1}{\rho_g}}, \ \rho_g < 1. \tag{4}$$

Here a_b, θ_b and θ_g are shares of respective consumption, $\frac{1}{1-\phi}$ is the elasticity of substitution between brown and green goods. Similarly, $\frac{1}{1-\rho_j}$ is the elasticity of substitution between Home and Foreign goods produced in sector $j \in \{b, g\}$. L_t denotes aggregate labor hours supplied by the households to Home production sectors, $L_t \equiv \left[L_{b,t}^{\eta} + L_{g,t}^{\eta} \right]^{\frac{1}{\eta}}, \ \eta < 1$. The formulation of labor in the utility function allows for imperfect substitutability of labor across the two sectors with η governing the degree of substitutability. The parameter ξ controls the elasticity of aggregate labor hours with respect to wages, and ϖ is the labor disutility parameter.

The domestic household chooses state-contingent sequences $\{(C_{j,t}^{h}, C_{j,t}^{f}, L_{j,t})_{j \in \{b,g\}}, D_t\}$ to maximize the expected discounted lifetime utility,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t U\left(C_t, L_t\right) \right\}, \tag{5}$$

subject to the budget constraint,

$$\begin{aligned} &P_{b,t}^{h} C_{b,t}^{h} + P_{g,t}^{h} C_{g,t}^{h} + \left(P_{b,t}^{f} + \tau_{cba,t} \right) C_{b,t}^{f} + P_{g,t}^{f} C_{g,t}^{f} + D_t \\ &= W_{b,t} L_{b,t} + W_{g,t} L_{g,t} + R_{t-1} D_{t-1} + \Pi_t + div_t + \Xi_t, \end{aligned} \tag{6}$$

where $P^h_{b,t}$ and $P^f_{b,t}$ denote prices (in abstract units) of Home and Foreign goods produced in brown sectors. Similarly, $P^h_{g,t}$ and $P^f_{g,t}$ are prices of goods produced in green sectors. D_t denotes deposits and R_t is the gross interest rate on deposits. Imports of foreign brown goods $C^f_{b,t}$ can be subject to the carbon border adjustment mechanism (or carbon tariff) $\tau_{cba,t}$. Π_t and div_t denote lump-sum profits and (net) dividend payouts from Home firms and banks, respectively. Ξ_t is lump-sum transfers from the domestic government.

The household's consumption-savings decision problem implies that the household has to optimally decide on aggregate consumption C_t and the optimal allocation of expenditures over $(C^h_{j,t}, C^f_{j,t})_{j\in\{b,g\}}$ taking their prices as given. The solution to this problem leads to standard demand functions for each type of consumption and welfare-based price indices. Denoting by P_t the price (i.e., consumer price index, CPI) of domestic aggregate consumption basket (C_t) and by $P_{b,t}$ and $P_{g,t}$ the prices of brown and green consumption, the demand functions are given by:

$$C^h_{j,t} = \theta_j \left(\frac{P_{j,t}}{P^h_{j,t}}\right)^{\frac{1}{1-\rho_j}} C_{j,t} \quad \text{for } j \in \{b, g\}, \tag{7}$$

$$C^f_{j,t} = (1-\theta_j) \left(\frac{P_{j,t}}{P^f_{j,t} + \mathbb{1}_{\{j=b\}}\tau_{cba,t}}\right)^{\frac{1}{1-\rho_j}} C_{j,t} \quad \text{for } j \in \{b, g\}, \tag{8}$$

$$C_{b,t} = a_b \left(\frac{P_t}{P_{b,t}}\right)^{\frac{1}{1-\phi}} C_t, \quad C_{g,t} = (1-a_b) \left(\frac{P_t}{P_{g,t}}\right)^{\frac{1}{1-\phi}} C_t, \tag{9}$$

where the associated Home aggregate price index is given by

$$P_t = \left[a_b P_{b,t}^{\frac{\phi}{\phi-1}} + (1-a_b) P_{g,t}^{\frac{\phi}{\phi-1}}\right]^{\frac{\phi-1}{\phi}}, \tag{10}$$

and the price indices of Home dirty and green consumption baskets are,

$$P_{b,t} = \left[\theta_b (P^h_{b,t})^{\frac{\rho_b}{\rho_b-1}} + (1-\theta_b)\left(P^f_{b,t} + \tau_{cba,t}\right)^{\frac{\rho_b}{\rho_b-1}}\right]^{\frac{\rho_b-1}{\rho_b}}, \tag{11}$$

$$P_{g,t} = \left[\theta_g (P^h_{g,t})^{\frac{\rho_g}{\rho_g - 1}} + (1-\theta_g) \left(P^f_{g,t} \right)^{\frac{\rho_g}{\rho_g - 1}} \right]^{\frac{\rho_g - 1}{\rho_g}}. \tag{12}$$

We take the price P_t as the numeraire and normalize its value to 1 so that all prices are in terms of Home aggregate consumption composite.

The household's optimality conditions with respect to sector-specific labor hours imply

$$\varpi L_t^{1-\eta+\xi} L_{j,t}^{\eta-1} = \lambda_t W_{j,t}, \text{ for } j \in \{b, g\}. \tag{13}$$

The optimality condition with respect to deposits gives the standard Euler equation $E_t \left(M_{t,t+1} R_t \right) = 1$, where $M_{t,t+1}$ denotes the household's stochastic discount factor $M_{t,t+1} = \beta \frac{\lambda_{t+1}}{\lambda_t}$, with the Lagrange multiplier on the budget constraint given by $P_t \lambda_t = C_t^{-\gamma}$.

2.2 Bankers

An individual bank i combines its net worth $(N_{i,t})$ with deposits raised from domestic households $(D_{i,t})$ to fund loans $(S^h_{i,j,t}, S^f_{i,j,t}, j \in \{b, g\})$ to goods-producing firms in Home and Foreign economies. We assume that the government can levy macroprudential taxes (or subsidies) $(\tau^h_j, \tau^f_j, j \in \{b, g\})$ on banks' assets, which could be differentiated across types of assets. These macroprudential taxes essentially mimic the effect of differentiated capital requirements. An important assumption that we make here, and that the other studies in the reviewed E-DSGE literature considering differentiated macroprudential policy implicitly make as well, is that the government is able to observe banks' exposure to green and brown assets. We consider this assumption as very plausible in a context where mandated disclosure of climate risks and the use of climate stress tests are rapidly expanding.[3]

[3] See, for example, Carattini et al. (2022) for an extensive discussion on the importance of climate-related disclosures, including for financial stability.

The bank's flow-of-funds constraint in time period t is

$$\sum_{j\in\{b,g\}} \left[(1+\tau^h_{j,t})Q_{j,t}S^h_{i,j,t} + (1+\tau^f_{j,t})Q^*_{j,t}S^f_{i,j,t}\right] + \Psi_{i,t} = N_{i,t} + D_{i,t}, \tag{14}$$

where $Q_{j,t}$ ($Q^*_{j,t}$) denotes a unit price of loans to Home (Foreign) firms in sector $j \in \{b,g\}$. $\Psi_{i,t}$ denotes quadratic portfolio adjustment costs and their main purpose is to pin down banks' steady-state portfolio composition.[4] We provide the detailed description of these adjustment costs in Appendix A.

The law of motion of bank's net worth is given by

$$N_{i,t+1} = \sum_{j\in\{b,g\}} \left[R_{j,t+1}Q_{j,t}S^h_{i,j,t} + R^*_{j,t+1}Q^*_{j,t}S^f_{i,j,t}\right] - R_t D_{i,t}. \tag{15}$$

Following Gertler and Kiyotaki (2010) and Gertler and Karadi (2011), we assume that there is an agency problem between bankers and depositors that limits banks' ability to obtain external funds: After raising deposits and purchasing assets at time t, a banker managing the bank can divert funds for personal benefit. If the banker diverts funds, households force the bank into bankruptcy. We assume that upon the bank's bankruptcy, the households can only recover an exogenous fraction $(1-\kappa)$ of assets. A representative banker thus faces an incentive constraint which states that the depositors will lend to the bank only if the banker has no incentives to run away with depositors' money,

$$V_{i,t} \geq \kappa \sum_{j\in\{b,g\}} \left(Q_{j,t}S^h_{i,j,t} + Q^*_{j,t}S^f_{i,j,t}\right), \tag{16}$$

where $V_{i,t}$ is the bank's franchise (or continuation value) at the end of period t.

At the end of each period, a banker may be hit by an exogenous i.i.d. exit shock with

[4]Intuitively, we want to capture the idea that it might be costly for a bank to move financial assets across countries (e.g., due to transactions costs). We calibrate these adjustment costs to be small in magnitude so that quantitatively they do not affect model dynamics.

probability $(1-\pi)$. Upon exit, a banker transfers the retained earnings to her household in the form of dividends and becomes a worker.[5] The banker chooses the composition of asset portfolio and the amount of deposits to maximize the expected present discounted value of terminal equity (or dividend payouts). Since bankers are members of households, they discount future profits using the household's stochastic discount factor. The problem recursively is

$$V_{i,t} = \max_{D_{i,t},(S^h_{i,j,t},S^f_{i,j,t})_{j\in\{b,g\}}} \mathbb{E}_t \left\{ (1-\pi) M_{t,t+1} N_{i,t+1} + \pi M_{t,t+1} V_{i,t+1} \right\}, \tag{17}$$

subject to the balance sheet constraint (14), the net worth accumulation equation (15) and the incentive constraint (16). Appendix A also contains a detailed characterization of the bank's problem and associated optimality conditions. Here we discuss key equations.

We guess and verify that a bank's value function is linear in individual net worth,

$$V_{i,t} = \varphi_t N_{i,t}, \tag{18}$$

where $\varphi_t \geq 1$ is the time-varying shadow value of net worth, common across banks. Combining (18) with (16) and aggregating over the entire domestic banking sector yields

$$\sum_{j\in\{b,g\}} \left(Q_{j,t} S^h_{j,t} + Q^*_{j,t} S^f_{j,t} \right) \leq \frac{\varphi_t}{\kappa} N_t. \tag{19}$$

Equation (19) determines Home banks' credit supply that depends on the amount of their aggregate net worth. An analogous equation holds for Foreign banks. When banks' are financially constrained (i.e., the incentive constraint binds), the amount of assets intermediated is limited by the amount of the bank equity so that negative shocks to the economy get amplified through the standard financial accelerator mechanism. The amplification effect is potentially non-linear given an occasionally binding nature of the banks' financing constraint.

[5] The mass of bankers that become workers in every period is thus $(1-\pi)f$. We assume that in each period an equal number of workers randomly become bankers, keeping the size of each group constant over time.

Bankers who exit the business are replaced by an equal number of new bankers who receive small initial startup funds from the households, $\Lambda_t = \varsigma \sum_{j\in\{b,g\}} \left[Q_{j,t} S^h_{j,t} + Q^*_{j,t} S^f_{j,t} \right]$. The aggregate banking sector net worth thus evolves according to

$$N_{t+1} = \pi \left[\sum_{j\in\{b,g\}} \left(R_{j,t+1} Q_{j,t} S^h_{j,t} + R^*_{j,t+1} Q^*_{j,t} S^f_{j,t} \right) - R_t D_t \right] + \Lambda_t. \tag{20}$$

The aggregate net dividend payouts to households is given by

$$div_{t+1} = (1-\pi) \left[\sum_{j\in\{b,g\}} (R_{j,t+1} Q_{j,t} S^h_{j,t} + R^*_{j,t+1} Q^*_{j,t} S^f_{j,t}) - R_t D_t \right] - \Lambda_t. \tag{21}$$

We define the Home banking sector leverage as the ratio of the value of the Home banks' total assets to their aggregate net worth, $\frac{\sum_{j\in\{b,g\}} (Q_{j,t} S^h_{j,t} + Q^*_{j,t} S^f_{j,t})}{N_t}$, and credit spreads as the difference between expected return on risky assets and the risk-free rate, $\mathbb{E}_t(R_{j,t+1} - R_t)$ for $j \in \{b,g\}$.

2.3 Goods-producing firms

In each country there are two sectors – "brown" (polluting) and "green" (non-polluting). There is a continuum of identical firms operating in each sector. The production technologies in the two sectors are of the Cobb-Douglas form,

$$Y_{j,t} = A_{j,t} K^{\alpha_j}_{j,t-1} L^{1-\alpha_j}_{j,t}, \;\; j \in \{b,g\}, \tag{22}$$

where $K_{j,t}$ and $L_{j,t}$ denote capital and labor inputs, respectively, and $A_{j,t}$ is an exogenous sector-specific productivity that follows a standard AR(1) process,

$$\log A_{j,t} = \varrho_j \log A_{j,t-1} + \sigma_j \varepsilon_{j,t}, \;\; \varepsilon_{j,t} \sim \mathcal{N}(0,1).$$

Following much of the E-DSGE literature, we assume that emissions are a by-product of production. Firms can engage in costly abatement investment to reduce emissions as in Nordhaus (2018) or Shapiro and Walker (2018). Letting $\mu_{j,t}$ denote the fraction of emissions abated, emissions in sector j are given by

$$e_{j,t} = (1 - \mu_{j,t})\epsilon_j Y_{j,t}, \;\; j \in \{b, g\}, \tag{23}$$

where parameter $\epsilon_j \geq 0$ controls the sector-specific emissions intensity, absent abatement effort. Abating $\mu_{j,t}$ fraction of emissions costs

$$Z_{j,t} = \chi_1 \mu_{j,t}^{\chi_2} Y_{j,t}, \;\; \chi_1 > 0, \chi_2 > 1, \;\; j \in \{b, g\}. \tag{24}$$

Following Gertler and Karadi (2011) we assume that firms in each sector rely on banks to finance their purchases of capital to be used in next period's production. Specifically, at time t, a representative firm in sector j purchases capital $K_{j,t}$ from domestic capital producers at unit price $Q_{j,t}$. The firm finances these purchases by issuing claims to Home and Foreign banks such that $Q_{j,t}K_{j,t} = Q_{j,t}(S^h_{j,t} + S^{h*}_{j,t})$. Since there is no financial friction between firms and banks, the firm can promise a state-contingent payoff, equal to the return on capital $R_{j,t+1}$, on these claims. The firm hires labor on the spot market. After production takes place in time $t+1$, the firm sells the undepreciated capital back to the capital producers.

The firm's time t realized profit is thus given by

$$\Pi_{j,t} = P^h_{j,t}Y_{j,t} - W_{j,t}L_{j,t} - \tau_{e,t}e_{j,t} - P^h_{j,t}Z_{j,t} - R_{j,t}Q_{j,t-1}K_{j,t-1} + (1-\delta_j)\,Q_{j,t}K_{j,t-1}, \; j \in \{b, g\}, \tag{25}$$

where $\tau_{e,t}$ denotes the emissions tax. The firm's profit-maximizing condition for labor choice yields

$$W_{j,t} = (1-\alpha_j)\left[P^h_{j,t} - \tau_{e,t}(1-\mu_{j,t})\epsilon_j - P^h_{j,t}\chi_1\mu_{j,t}^{\chi_2}\right]\frac{Y_{j,t}}{L_{j,t}}, \;\; j \in \{b, g\}. \tag{26}$$

The firm's optimal emissions abatement satisfies,

$$\tau_{e,t}\epsilon_j = P^h_{j,t}\chi_1\chi_2\mu_{j,t}^{(\chi_2-1)}. \tag{27}$$

The state-contingent return on capital consistent with the firm's state-by-state zero profit condition is given by

$$R_{j,t} = \frac{\alpha_j\left[P^h_{j,t} - \tau_{e,t}(1-\mu_{j,t})\epsilon_j - P^h_{j,t}\chi_1\mu_{j,t}^{\chi_2}\right]\frac{Y_{j,t}}{K_{j,t-1}} + (1-\delta_j)\,Q_{j,t}}{Q_{j,t-1}}, \;\; j \in \{b,g\}. \tag{28}$$

2.4 Capital producers

Competitive capital-producing firms build sector-specific capital subject to standard quadratic investment adjustments costs, following Chari, Kehoe, and McGratten (2007). The sector-specific capital accumulates according to

$$K_{j,t} = (1-\delta_j)\,K_{j,t-1} + I_{j,t} - \frac{\psi_j}{2}\left(\frac{I_{j,t}}{K_{j,t-1}} - \delta_j\right)^2 K_{j,t-1}, \;\; j \in \{b,g\}\,, \tag{29}$$

where the parameter $\psi_j \geq 0$ controls the size of the adjustment cost.

Denote by $Q_{j,t}$ the price of new sector-specific capital in units of Home aggregate consumption. The capital producers maximize discounted lifetime profits,

$$\max_{\{I_{j,t}\}_{j\in\{b,g\}}} \mathbb{E}_0 \sum_{t=0}^{\infty} M_{0,t} \sum_{j\in\{b,g\}} \left[Q_{j,t}K_{j,t} - Q_{j,t}\,(1-\delta_j)\,K_{j,t-1} - P^h_{j,t}I_{j,t}\right] \tag{30}$$

subject to the capital accumulation equation (29). The first order optimality conditions for this problem imply

$$Q_{j,t} = P^h_{j,t}\left[1 - \psi_j\left(\frac{I_{j,t}}{K_{j,t-1}} - \delta_j\right)\right]^{-1}, \;\; \text{for } j \in \{b,g\}\,. \tag{31}$$

2.5 Government

The government implements climate and macroprudential policies. It can impose a carbon tax on the carbon-intensive sector, either unilaterally or in coordination with the Foreign country. In the latter case, coordination between the two countries leads to a uniform global carbon price, obtained through harmonized carbon taxes. When only the Home country imposes a carbon tax, the government in the Home country can decide to also levy a carbon tariff, or carbon border adjustment mechanism, on carbon-intensive imports from the Foreign country.

The government transfers the revenues from carbon and border adjustment taxes to the domestic households in a lump-sum manner,

$$\Xi_t = \tau_{e,t} e_{b,t} + \tau_{cba,t} C^f_{b,t} + \sum_{j\in\{b,g\}} \left[\tau^h_{j,t} Q_{j,t} S^h_{j,t} + \tau^f_{j,t} Q^*_{j,t} S^f_{j,t} \right]. \tag{32}$$

2.6 Market Clearing

Foreign country's economy has a symmetric structure to the Home country. Market clearing conditions for brown and green goods produced in Home and Foreign countries are given by:

$$Y_{b,t} = C^h_{b,t} + C^{h*}_{b,t} + I_{b,t} + Z_{b,t},\ \ Y^*_{b,t} = C^{f*}_{b,t} + C^f_{b,t} + I^*_{b,t} + Z^*_{b,t}, \tag{33}$$

$$Y_{g,t} = C^h_{g,t} + C^{h*}_{g,t} + I_{g,t} + +Z_{g,t} + \frac{\Psi_t}{P_{g,t}},\ \ Y^*_{g,t} = C^{f*}_{g,t} + C^f_{g,t} + I^*_{g,t} + Z^*_{g,t} + \frac{\Psi^*_t}{P^*_{g,t}}. \tag{34}$$

Financial market clearing conditions imply:

$$S^h_{b,t} + S^{h*}_{b,t} = K_{b,t},\ \ S^h_{g,t} + S^{h*}_{g,t} = K_{g,t}, \tag{35}$$

$$S^{f*}_{b,t} + S^f_{b,t} = K^*_{b,t},\ \ S^{f*}_{g,t} + S^f_{g,t} = K^*_{g,t}. \tag{36}$$

3 Calibration

The model is calibrated to the European Union (Home) and to the United States (Foreign) at quarterly frequency.[6] Table 1 summarizes the parameter values. We choose standard values for the subjective discount factor $\beta = 0.99$, the risk aversion parameter $\gamma = 2$, the labor supply elasticity parameter $\xi = 1$, the capital share $\alpha_j = 0.33$, the capital depreciation rate $\delta_j = 0.025$, for $j \in \{b, g\}$. The parameter controlling the elasticity of substitution of labor hours between two sectors, η, is set to 2 as in Carattini, Heutel, and Melkadze (2021). We set the labor disutility parameter ϖ to match the steady-state labor hours of 0.3.

To calibrate the emissions intensity parameters, we use data from the FIGARO database on gross value added and scope 1 carbon dioxide emissions to calculate sector-level emissions intensities. Table 2 contains the results. Using these results, first we classify sectors as "brown" or "'green" based on the individual sector-level emissions intensities, which gives us the following highly emissions-intensive sectors classified as brown: Agriculture, forestry, and fishing; mining and quarrying; manufacturing; electricity, gas, steam, and air conditioning supply; water supply, sewerage, waste management, and remediation activities; and transportation and storage. All other sectors are classified as green. We compute sectoral emissions intensity for each group of sectors $j = \{b, g\}$ in a given year as a total carbon emissions produced by sector j (in tons of CO_2) divided by the real gross value added (in thousands of 2015 USD) of sector j in the same year. We then set the emissions intensity parameters in the model equal to the average values of the sector-level emissions intensities over the period 2016-2019. This implies that for brown sectors we set $\epsilon_b = 0.41$, $\epsilon_b^* = 0.98$, while the green sectors' emissions intensity parameters, ϵ_g, ϵ_g^*, are set to zero. The latter are consistent with the very small emissions intensities of "green" sectors in the data (i.e., 0.02 for the EU and 0.04 for the US; see Table 2 for further details).[7]

[6] We include the United Kingdom as part of the European Union in our calibration.

[7] As an alternative parametrization of emissions intensity, we consider incorporating scope-2 emissions. Specifically, we allocate scope-1 emissions from sector D to all sectors, including sector D itself, in proportion to their share of electricity consumption in the country, which we classify as scope-2 emissions. The total emissions

Since according to our classification green sectors are dominated by services, we calibrate the elasticity of substitution between brown and green goods ($\frac{1}{1-\phi}$) to a relatively low value, 0.75. We set the elasticity of substitution ($\frac{1}{1-\rho_j}$) between domestic and foreign-produced goods at 0.85 following Corsetti et al. (2008). The value is in line with the open economy macro literature that suggest low trade elasticities (e.g., Lubik and Schorfheide 2005, Benigno and Thoenissen 2008). Sectoral consumption weight for brown goods $\theta_b = 0.70$ while the clean sector features stronger home bias, $\theta_g = 0.95$.[8]

The persistence and standard deviation of the TFP shocks are 0.95 and 0.007, standard values in the RBC literature. Similarly, we set the capital adjustment cost parameter $\psi_j = 20$ for both sectors, which implies an empirically reasonable value (i.e., 0.5) for the elasticity of the price of capital with respect to investment-capital ratio (Chari et al. 2007). These values also imply that aggregate investment is about 2.2 times more volatile than output in line with the data (e.g., Coenen et al. 2018).

For the carbon tax rate, we use \$80 per ton of CO_2, the central estimate in the cost-effectiveness study by Stiglitz et al. (2017), which identifies the range of carbon prices necessary to reach the temperature targets of the Paris Agreement.[9] Similar estimates are provided in IMF (2019). If anything, the carbon tax shock to which we subject the Home and Foreign economies is on the low end, making our approach rather conservative with respect to recent estimates of the social cost of carbon (see Rennert et al. 2022) or the scenarios considered by

from each sector are then assumed to be the sum of scope-1 and scope-2 emissions. For sector D, only scope-2 emissions are considered as the total emissions. This approach yields estimates similar to the baseline: $\epsilon_b = 0.34$, $\epsilon_b^* = 0.71$, $\epsilon_g = 0.03$, and $\epsilon_g^* = 0.04$ (refer to Table B2 and its notes for details). Our simulation results based on these estimates closely resemble the baseline results.

[8] In Appendix C we perform sensitivity analysis with respect to parameters including the elasticity of substitution between green and brown goods, the elasticity of substitution between home and foreign goods, and home bias in consumption.

[9] While \$80 per ton of CO_2 is the central estimate in Stiglitz et al. (2017), we note that their cost-effectiveness exercise also considers additional policies, making our approach rather conservative. More broadly, and in line with Stiglitz et al. (2017), we consider a carbon tax without damages being explicitly included in the model. This choice is justified by a cost-effectiveness approach consistent with a carbon budget objective, see van der Ploeg (2018) and Gollier (2021). Such an approach makes it possible to avoid the specification and calibration of damages, with its well-known issues, as well as the dynamics of the stock of greenhouse gases in the atmosphere, which should exhibit a unit root, as argued by Mattauch et al. (2020), a feature that is not compatible with a DSGE model.

the Network for Greening the Financial System. The parameter controlling the curvature of the abatement cost function is set at the same value as in Nordhaus (2018) Dynamic Integrated Climate-Economy (DICE) model, $\chi_2 = 2.6$. We calibrate χ_1 to target Home emissions reduction of 10% in response to a \$80 tax on CO_2, generally in line with the empirical estimates of Metcalf and Stock (2020) over a comparable horizon and assuming a standard distribution of marginal abatement costs.

We set the bank survival rate π to 0.974 as in Gertler and Karadi (2011), implying that, on average, bankers survive for about 9 years. We set the fraction of funds that can be diverted $\kappa = 0.20$ to match the financial intermediaries' steady-state leverage ratio of 5, the value in line with Gertler and Karadi (2011) and Morelli et al. (2022). The value of transfer parameter ζ is chosen such that in the steady-state the banks' leverage constraint does not bind and thus, credit spreads are zero. We set banks' steady state foreign exposure to 20%, a value in line with the empirical estimates of home bias in equities and bank assets (Coeurdacier and Rey 2013). The banks' portfolio adjustment cost parameters are set to a small value so that these costs do not affect the dynamics quantitatively.

Next we calibrate banks' cross-border and sectoral exposures using syndicated loan data from DealScan spanning the period 2008-2019. We focus on loans from the European banks to firms in the United States and from the United States banks to the European firms. Consistently with the rest of the paper, we treat the 27 European Union member states plus the United Kingdom as one country and define European banks and firms as banks and firms in those countries. To compute financial intermediaries' portfolio exposures to the brown sectors, we perform the following calculations: In a given period, we calculate the share of banks' outstanding loan amounts to firms in brown sectors, both domestically and abroad, to total outstanding loans.[10] The steady-state brown portfolio shares in the model are then matched to

[10]Following De Haas and Van Horen (2013) we define cross-border lending as loans where the location of the borrowing firm is different from that of the parent bank, and outstanding loan amounts in year t as those loans that are outstanding at the start of year t. Additionally, the DealScan data provides exact breakdown amount of loans for less than 30% of loans involving multiple banks. For the remaining loans, we distribute the loan amounts equally among the banks involved. Finally, we measure loan amounts in 2015 USD.

the average shares across the years 2017 to 2019.[11] Similarly, we compute cross-border brown asset exposures as a fraction of the intermediaries' outstanding loans to the firms in foreign country's brown sectors to total foreign lending. Appendix Table B1 reports aggregate results for all U.S. and European banks in our dataset, as well as for several globally systematically important banks.

According to our estimates, the European and U.S. financial intermediaries' overall syndicated-loan portfolio exposures to brown sectors are 54% and 49%, respectively. In terms of cross-border exposures, European ad U.S. banks hold about 56% and 57% of their foreign loan portfolios with firms in carbon-intensive industries. Consistent with these estimates we assume that in the steady-state of our model, global financial intermediaries hold about 52% of their loan portfolio in carbon-intensive firms[12] and about half of their foreign lending is to carbon-intensive sectors.

4 Transition risk and international spillovers

4.1 Domestic carbon tax in the Home country

In this section we use the calibrated model to study the international spillovers of transition risk that originates in Home country. Specifically, we consider a surprise introduction of a permanent carbon tax of $80 per ton of CO_2 in period 5 in the Home country, i.e. the European Union.[13]

[11] In our sample, the average duration of loans is approximately 5 years, and 90.9% mature in nine years. Thus, for precise measurement of banks' lending exposure in a given year, we need to utilize the data starting about nine years prior to that year.

[12] These estimates are in line with Battiston et al. (2017) and Alogoskoufis et al. (2021).

[13] While there is evidence suggesting that investors are increasingly asking for a risk premium to hold carbon intensive assets, also known as "carbon premium" following Bolton and Kacperczyk (2021a,b), complementary evidence also shows that investors, as well as banks, react to changes in the short-term probability of climate policy being implemented (Carattini and Sen 2019, Ramelli et al. 2021, Ivanov et al. 2022, Bauer et al. 2023), suggesting that they are not yet aligned with long-term climate goals (see also Acharya et al. 2023 for a discussion). Hence, our premise is that asset prices still largely underestimate such risks, although not totally. One can thus also interpret the magnitude of our carbon shock as an $80 per ton of CO_2 increase in the price of carbon above the level expected by private agents in the economy.

We focus on perfect-foresight simulations; that is, after period 5, the agents fully anticipate the future path of the Home carbon tax. Prior to the introduction of the carbon tax, both countries start in the baseline symmetric deterministic steady state without any policy in place. Figures 1 and 2 present transition dynamics in response to such climate policy shock. Since our interest is the possible realization of transition risk, we focus on short- to medium-term horizons displaying the simulation results for the first five years of transitional dynamics. Figure 1 displays the endogenous responses of emissions, output and capital, while Figure 2 focuses on the dynamics of financial variables.[14] To assess the role of financial frictions, we compare the baseline model presented in Section 2 to the model without credit market frictions.

Figure 1 illustrates the implications of financial frictions for the transmission of domestic carbon tax shock internationally and across sectors. Specifically, several results stand out: First, the Home carbon tax successfully lowers Home CO_2 emissions by giving proper abatement incentives to domestic polluting firms. Brown production in Home country falls as carbon tax increases the cost of polluting production. The emissions reduction and a fall in brown output are similar in magnitudes with or without financial frictions. Second, the presence of financial frictions implies that the domestic carbon tax has a negative effect on economic activity in domestic and foreign green sectors, while in the model with frictionless credit markets green sectors (i.e., green output and capital) expand both at home and abroad. Finally, in response to the domestic carbon tax, dirty production migrates to the Foreign country resulting in higher foreign emissions, that is, carbon leakage, which is stronger in the model without financial frictions. This leakage remains modest, which is generally in line with the existing empirical literature, as reviewed by Branger and Quirion (2014) and by Dechezleprêtre and Sato (2017). We note that some of the evidence in the literature comes precisely from the implementation of climate policy in the European Union, in particular with respect to the European Union Emissions Trading System (aus dem Moore et al. 2019, Koch and Basse Mama 2019, Naegele and Zaklan 2019, Borghesi et al. 2020, Garnadt et al. 2020, Dechezleprêtre et al. 2022, Colmer

[14] Appendix Figure B1 displays the dynamics of additional variables.

et al. 2023) and carbon taxes in member states (Metcalf and Stock 2020).

Figure 2 plots the behavior of banks' net worth and credit spreads to explain the key mechanisms behind the sectoral and international contagion of the domestic climate policy. A surprise introduction of an ambitious carbon tax lowers the realized return on domestic brown capital, imposing equity losses on domestic and foreign financial intermediaries. The net worth losses are large enough to make banks' financing constraints binding, forcing them to cut lending to domestic as well as foreign non-financial firms, both in brown and green sectors. This deleveraging by the global banks leads to an increase in credit spreads and a fall in asset prices which further amplify the fall in banks' net worth and credit supply. As a result, as shown in Figure 1, investment and production fall not only in the brown sector which is directly affected by the carbon tax, but also in the green sector. In addition, since banks hold cross-border financial claims, domestic transition risk transmits to the foreign economy. Instead, in the model without financial frictions, the international spillovers are driven by the trade channel: Home carbon tax increases the price of domestic polluting output causing global demand to shift towards Foreign-produced dirty goods. As foreign dirty production expands, so do foreign emissions, leading to carbon leakage. Such leakage is present in the model with financial frictions too, although it is more limited as global financial stress dampens an expansion of foreign polluting activities. Overall, an unanticipated implementation of the domestic carbon tax causes a global contraction in credit supply and economic slowdown.

The dynamics that we observe in our model are consistent with empirical regularities that the literature documents in presence of milder shocks. In particular, the empirical literature shows that following the implementation of carbon pricing, banks tend to reduce exposure to domestic carbon-intensive sectors and in turn increase their exposure to those sectors abroad, with overall exposure declining, as described in Laeven and Popov (2021). The findings in Laeven and Popov (2021) about banks' arbitraging are also consistent with evidence from Ivanov et al. (2022), who consider lending across sectors in the United States following possible or realized carbon pricing shocks, and Benincasa et al. (2021), who consider loan exposure across countries following an increase in a general index of climate policy stringency. Furthermore, our model allows us to document how, with a large shock, credit conditions tighten substantially, affecting the green sector as well and leading to a financial recession, in the absence of macroprudential policy.

The role of cross-border financial and trade linkages. Next, we assess the role of cross-country financial and trade linkages in driving the international spillovers documented above, by performing the following experiments. First, in order to evaluate the role of international financial integration we consider the scenario with complete financial autarky, that is, we assume that home and foreign banks can hold only domestic financial assets. In the second scenario we eliminate international trade in goods, i.e., we set home-bias parameters in both countries to 1, but we still allow for financial integration through cross-border bank flows. Figure 3 plots the transition dynamics for these two scenarios together with the dynamics in the baseline model with financial and trade linkages (and financial frictions).

The figure illustrates that financial linkages are responsible for the adverse spillovers of Home transition risk across borders. In the absence of cross-border financial flows (dashed lines), economic activity in Foreign country improves in response to Home carbon tax, while in the baseline model with financial integration, Home transition risk is inflicted onto the foreign economy via global credit tightening. Importantly, the lack of international financial integration makes Home's recession worse since Home banks are not diversified at all in their asset holdings, making them especially vulnerable to domestic shocks.

When we shut down international trade in goods, but still allow for cross-border financial flows, the negative spillovers become worse for the Foreign country, which now experiences a much deeper fall in banks' net worth and economic activity. This suggests that Foreign country benefits from trade spillovers in response to the introduction of carbon tax in the Home country. In addition, in the presence of financial frictions and financial market integration, the Home economy experiences a more severe recession under trade autarky, which shows that trade openness also benefits Home country when the latter enacts an ambitious carbon tax. The baseline transitional dynamics capture the interactions of all these channels.

Macroprudential policy. Next, we explore whether macroprudential policy can mitigate transition risk stemming from the implementation of necessary climate policy, studied in Figures 1 and 2. We start by considering a policy scenario in which the Home country implements an ex-ante macroprudential policy prior to the introduction of the carbon tax. Specifically, we assume that the domestic financial regulator imposes a constant tax on Home banks' brown loans and a constant subsidy on green loans as to reduce the banks' steady-state portfolio exposure to polluting industries from 52% (baseline) to 38%.[15] We then consider an unexpected introduction of the permanent Home carbon tax of $80 per ton of CO_2 as before. Figure 4 shows the results from this exercise, comparing the dynamics of transition to a low carbon economy with and without macroprudential policy. Home macroprudential policy lowers Home banks' exposure to dirty industries by about 16 percentage points, which means that the Home banks become more resilient to a carbon tax shock.[16]. As a result, the domestic banking sector incurs smaller equity losses, compared to the case without macroprudential policy, and a milder decline in green capital in response to the carbon tax shock.

The implications of Home macroprudential policy for Foreign country's financial stability is theoretically ambiguous. On the one hand, Home macroprudential policy could mitigate the spillovers of transition risk to the Foreign economy as Home banks, which are now more resilient to the transition risk, could keep providing credit to foreign non-financial firms. On the other hand, in the presence of Home macroprudential policy that penalizes Home banks' lending to polluting companies, Foreign banks would find it more profitable to increase their exposure to such lending as they are not subject, in the scenario that we analyze here, to macroprudential policy. This would make Foreign banks and, thus, Foreign economy more vulnerable to the

[15]The tax-subsidy scheme is such that it keeps Home banks' leverage at the initial level. This way of modeling climate-related factors in macroprudential regulation could be thought of as mimicking "brown penalizing" or "green supporting factors" in Basel-type capital requirements that would impose a higher risk weight on brown asset holdings in banks' portfolio.

[16]In a separate simulation, we confirm that macroprudential policy itself does not lead to financial stress in the banking sector, allaying the concerns raised by Coelho and Restroy (2023).

transition risk originating in the Home country, when domestic macroprudential policy is in place in the Home country. Figure 4 shows that in our calibrated model, the latter effect dominates and Foreign banks' net worth declines more in response to Home carbon tax shock with Home macroprudential policy than without it.

In sum, what we observe in Figure 4 is that while Home macroprudential policy can successfully protect the domestic banking sector from transition risk, it amplifies the adverse spillover effects to rest of the world. Hence, we ask next to what extent can Foreign economy isolate itself from the international spillovers of transition risk by implementing macroprudential policy as well.

Figure 5 shows the results from the scenario in which both Home and Foreign countries put ex-ante macroprudential policies in place. Since Foreign macroprudential policy reduces Foreign banks' exposure to Home brown assets, foreign banks' net worth does not fall as much as in the absence of Foreign country's macroprudential policy. The negative cross-country financial spillovers are thus more contained in this case. The exercise illustrates that foreign country is able to isolate itself from transition risk originating abroad.

4.2 Domestic carbon tax and carbon border adjustment mechanism in the Home country

This section considers the scenario in which the Home country simultaneously implements the domestic carbon tax and a carbon border adjustment mechanism (CBAM) as modelled in Section 2 (equation 6). The purpose of the carbon border adjustment mechanism is to level the playing field between Home and Foreign industries to mitigate carbon leakage. Figure 6 compares the transition dynamics in response to only a domestic carbon tax in the Home country to the dynamics with the Home carbon tax plus the carbon border adjustment mechanism in our baseline model with financial frictions. The carbon border adjustment mechanism has a negative effect on economic activity abroad: Foreign output falls by more both in the brown and green sectors compared to the case with only a domestic carbon tax in the Home country. The carbon border adjustment mechanism thus mitigates carbon leakage to some extent, as, for example, foreign production in the carbon-intensive sector, and thus, foreign emissions, temporarily fall more with the carbon border adjustment mechanism. But adding the carbon border adjustment mechanism on top of the domestic carbon tax also makes the recession in the domestic economy more severe, in presence of financial frictions and in the absence of macroprudential policy. The intuition behind this result is that the carbon border adjustment mechanism lowers the return on foreign brown capital and, thus, imposes equity losses on the exposed banks, which in turn cut the supply of credit to non-financial firms, including in the Home economy. Note that the carbon border adjustment mechanism has stronger negative effects on the Foreign economy and financial sector than on the domestic ones.

Figure 6 also shows that while the carbon border adjustment mechanism mitigates leakage in the short run, its effectiveness is limited in the medium to long term. That is, foreign emissions, after declining by more initially, pick up faster in the scenario with the border adjustment mechanism than without it. This happens because domestic consumers are captive due to the low elasticity of substitution between Home and Foreign brown goods while the redistribution of the proceeds of the carbon border adjustment mechanism generates a large wealth effect in the Home country. The long-run effectiveness of the carbon border adjustment to reduce leakage thus increases with the degree of substitutability between Home and Foreign goods.

Appendix Figures B3 and B4 illustrate the effects of unilateral and bilateral macroprudential policies in the scenario with the carbon border adjustment mechanism. As in the case of Home carbon tax, the unilateral macroprudential policy implemented by Home country makes Foreign country's banking system more negatively exposed to Home climate-policy-driven transition risk (Figure B3). Foreign country can thus benefit from also enacting ex-ante macroprudential policy that encourages foreign banks reduce their brown-asset exposures. Figure B4 illustrates such gains.

4.3 Uniform global carbon price

In this section we consider the scenario in which both Home and Foreign countries implement a carbon tax of the same magnitude (\$80 per ton of CO_2) in a coordinated effort to tackle climate change. Figure 7 shows the results. The global carbon price successfully reduces global emissions (by 15% relative to the initial state without climate policy). In the model without financial frictions, green capital and output expand globally. However, the presence of financial frictions implies that global climate policy has a negative unintended consequence for green sectors, with green capital and production declining in the medium term. This happens because banks make equity losses in response to the global carbon tax and are forced to cut lending as their funding constraints tighten. A decline in credit supply to non-financial firms in turn prevents a quick reallocation of capital towards green sectors.

As in the case of unilateral climate policy, we show that the recessionary forces brought about by financial frictions can be mitigated through macroprudential policy. We consider a scenario in which prior to the implementation of the global carbon price, financial regulators in both countries implement a symmetric macroprudential policy in the form of a tax on banks' brown and subsidy on green asset holdings to reduce banks' exposure to brown assets. Appendix Figure B5 illustrates that such macroprudential policy can mitigate the severity of transition risk. Hence, in this case countries not only coordinate on carbon pricing, but also coordinate on macroprudential policy.

5 Conclusions

Transition risk is currently one of the main issues for financial regulators. In this paper we argue that in a financially and trade integrated world, transition risk should not only be a concern for those countries planning to implement such policies, but for all others as well. The situation is even more acute when also considering the use of carbon border adjustment mechanisms in climate policy-making.

We develop a multi-sector, multi-country, dynamic stochastic general equilibrium model, with climate and macroprudential policies, and cross-border financial and trade flows. With it, we examine the impact of the following three policy experiments: the unilateral implementation of a carbon tax in either country, the unilateral implementation of a carbon tax and carbon border adjustment mechanism in either country, and the coordinated implementation of carbon taxes in both countries, leading to a global carbon price through harmonized carbon taxes.

We find that cross-border financial linkages can play a key role in the realization and contagion of transition risk, a result that carries important policy implications for financial regulators. In particular, our main policy experiment shows that the abrupt implementation of an ambitious carbon tax in the domestic economy generates a global recession. The global recession is driven by domestic and foreign banks suffering from asset losses in the carbon-intensive sector and adjusting lending downward to the clean sector as well. The economic slowdown is even more pronounced following the implementation of carbon border adjustment mechanisms, even if the latter contributes to reduce carbon leakage, as intended, or following the coordinated implementation of domestic carbon taxes, leading to a uniform global carbon price through harmonized carbon taxes. However, macroprudential policy can mitigate such recessionary forces, by addressing transition risk. Hence, macroprudential policy, especially when coordinated across countries, can pave the way to the most ambitious climate policy, including a global carbon price.

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Tables and Figures

Table 1: Calibration

Parameter	Value	Description
β	0.99	Discount factor
ϖ	10.47	Labor disutility
ξ	1	Labor elasticity
γ	2	Risk aversion
η	2	Intersectoral substitutability of labor
$\frac{1}{1-\phi}$	0.75	EoS between brown & green goods
$\frac{1}{1-\rho_j}$	0.85	EoS between Home & Foreign goods
a_b	0.55	Brown consumption share
θ_b	0.70	Share of domestic brown goods
θ_g	0.95	Share of domestic green goods
α_j	0.33	Capital share
ψ_j	20	Capital adjustment cost
ϵ_b, ϵ_b^*	0.41, 0.98	Emissions intensity of brown sector
ϵ_g, ϵ_g^*	0	Emissions intensity of green sector
χ_1	0.6	Abatement cost function param.
χ_2	2.6	Abatement cost function param.
δ_j	0.025	Capital depreciation rate
ϱ_j	0.95	Persistence of TFP
σ_j	0.007	Std. dev. of TFP innovations
κ	0.20	Fraction of divertable assets
π	0.974	Bankers' survival rate
ς	0.00324	Transfer to new bankers
ϕ_j	0.02	Portfolio adjustment cost

Table 2: Emissions intensity by sector

Sector (NACE rev. 2)	US	Europe
A. Agriculture; forestry and fishing	0.60	0.22
B. Mining and quarrying	0.60	0.34
C. Manufacturing	0.39	0.25
D. Electricity; gas, steam and air conditioning supply	7.28	1.56
E. Water supply; sewerage, waste management and remediation activities	0.29	0.17
F. Construction	0.11	0.06
G. Wholesale and retail trade; repair of motor vehicles and motorcycles	0.08	0.03
H. Transportation and storage	0.86	0.45
I. Accommodation and food service activities	0.04	0.02
J. Information and communication	0.02	0.01
K. Financial and insurance activities	0.01	0.01
L. Real estate activities	0.01	0.00
M. Professional, scientific and technical activities	0.03	0.01
N. Administrative and support service activities	0.06	0.02
O. Public administration and defence; compulsory social security	0.05	0.02
P. Education	0.02	0.01
Q. Human health and social work activities	0.03	0.01
R. Arts, entertainment and recreation	0.04	0.03
S Other service activities	0.09	0.03

Source: Authors' calculations based on inter-country input-output tables (industry by industry) and carbon footprints tables of "Full International and Global Accounts for Research in input-Output analysis" (FIGARO) database, compiled by Eurostat and the Joint Research Centre of the European Commission.
Notes: This table presents average emissions intensities of each sector for the period 2016-2019. Sectoral emissions intensity for each year is calculated by dividing scope-1 carbon dioxide emissions (in tons of CO_2) by the real gross value added of the sector (in thousands of 2015 USD) for that year. The reported values represent the averages over the years 2016 to 2019.

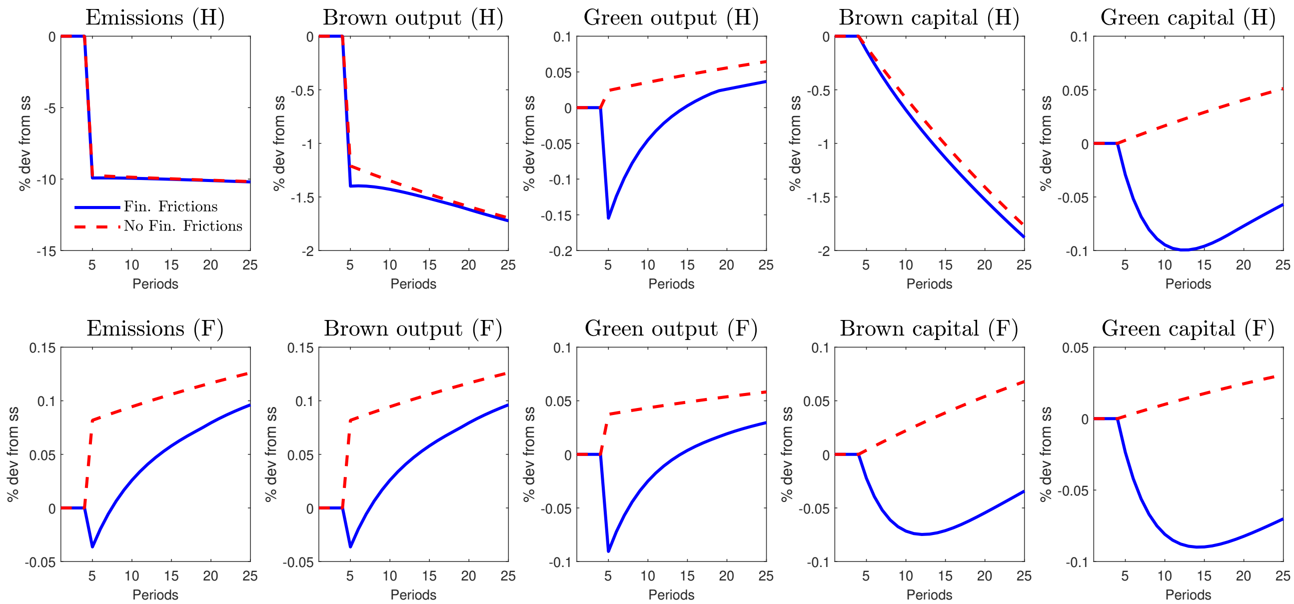

Figure 1: Transition dynamics in response to Home carbon tax: Emissions, output and capital. This figure plots the transition dynamics of selected variables in response to the introduction of Home carbon tax in the models with and without financial frictions.

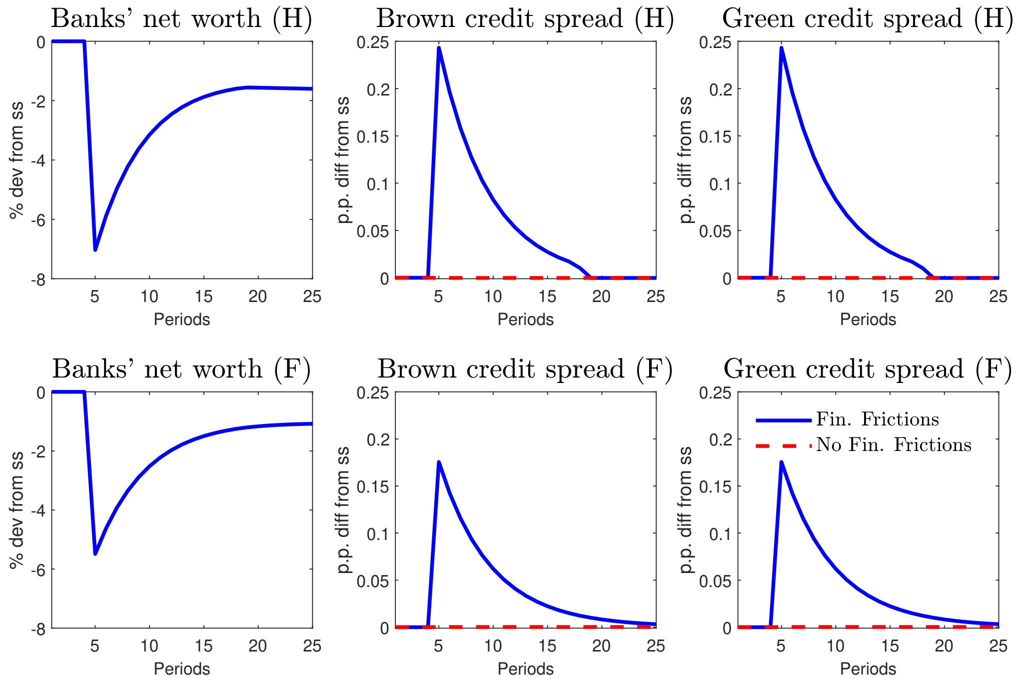

Figure 2: Transition dynamics in response to Home carbon tax: Banks' net worth and credit spreads. This figure plots the transition dynamics of financial variables in response to the introduction of Home carbon tax in the models with and without financial frictions.

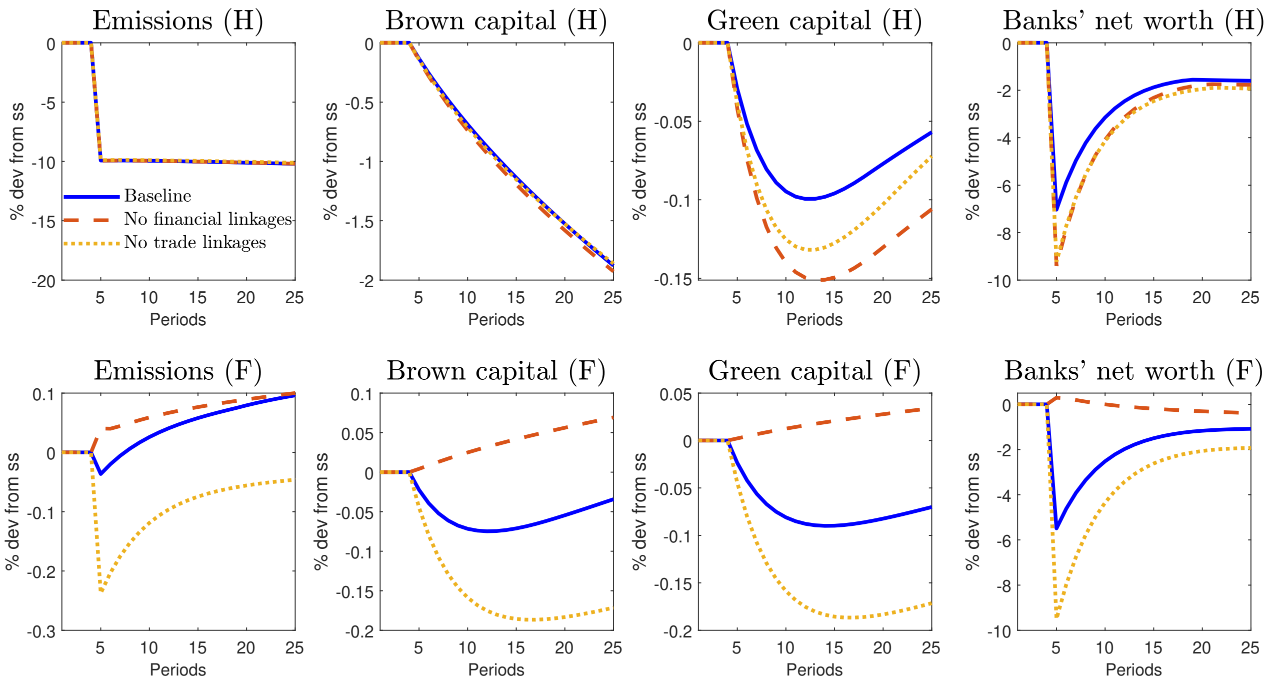

Figure 3: Transition dynamics in response to Home carbon tax. The role of financial and trade linkages. This figure compares the transition dynamics in response to the introduction of Home carbon tax in the baseline model with financial frictions to the case when (i) we shut down cross-country financial linkages; (ii) we shut down international trade.

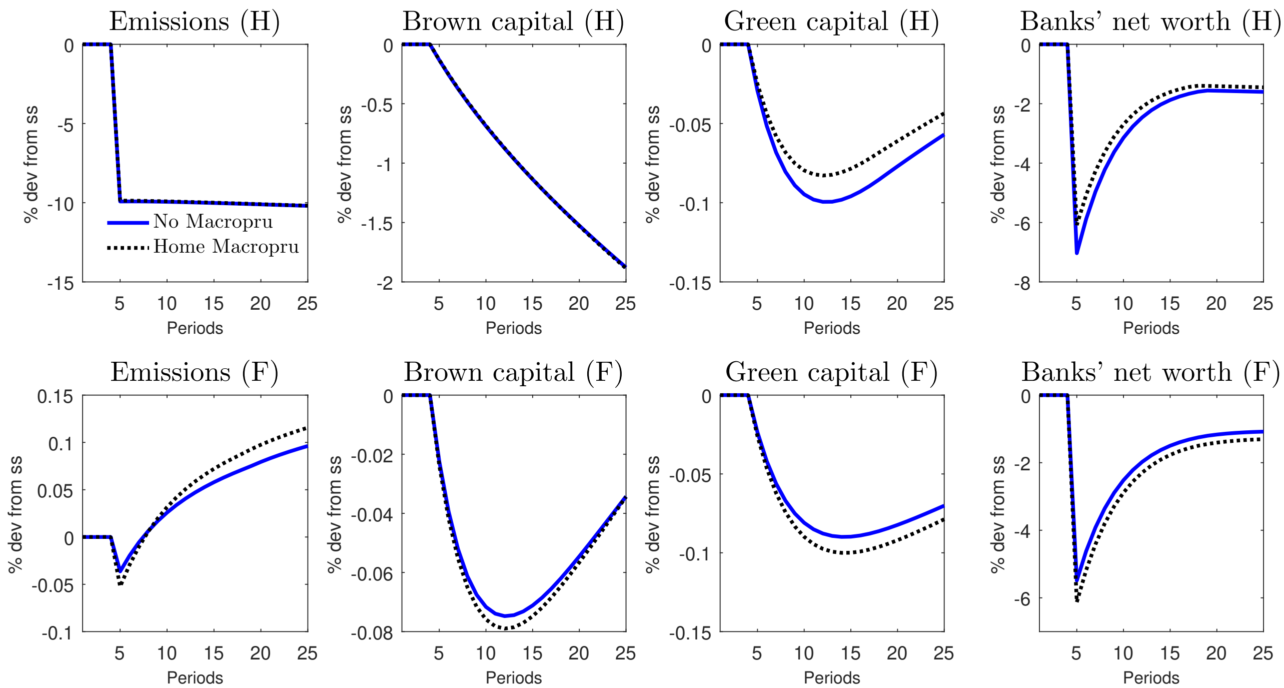

Figure 4: Transition dynamics in response to Home carbon tax with and without Home macroprudential policy. This figure compares the transition dynamics in response to the Home carbon tax shock in the model with financial frictions under two scenarios: (i) No macroprudential policy; (ii) only Home country implements macroprudential policy.

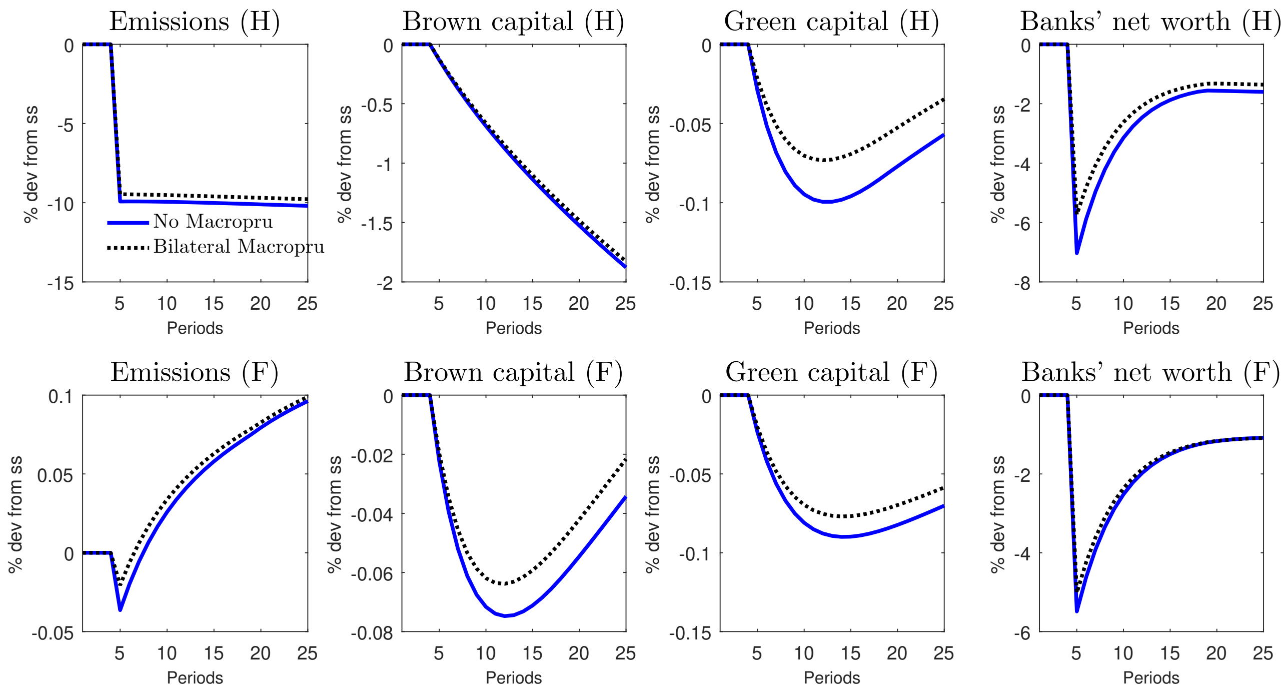

Figure 5: Transition dynamics in response to Home carbon tax with and without bilateral macroprudential policy. This figure compares the transition dynamics in response to the Home carbon tax shock in the model with financial frictions under two scenarios: (i) No macroprudential policy; (ii) both Home and Foreign countries implement macroprudential policies.

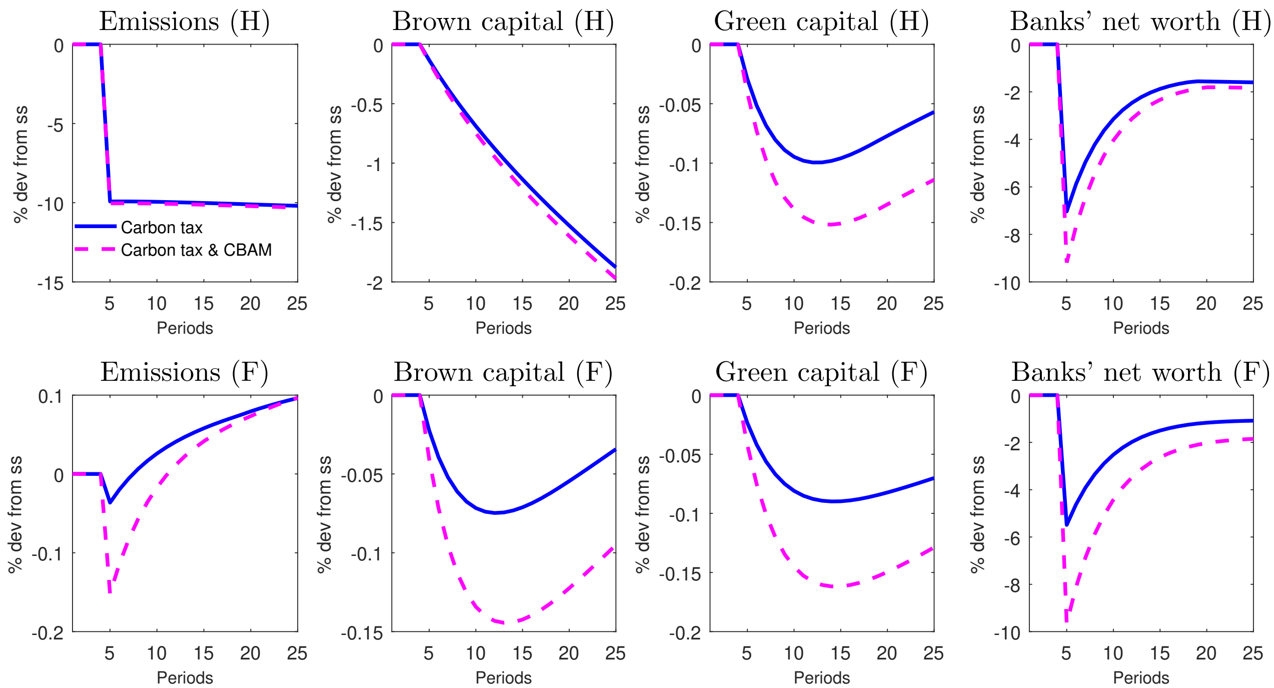

Figure 6: Transition dynamics in response to Home carbon tax and CBAM. This figure compares the transition dynamics in the model with financial frictions under two climate policy scenarios: (i) when the Home carbon tax is introduced; (ii) When the Home carbon tax is complemented by the Home carbon border adjustment mechanism (or CBAM).

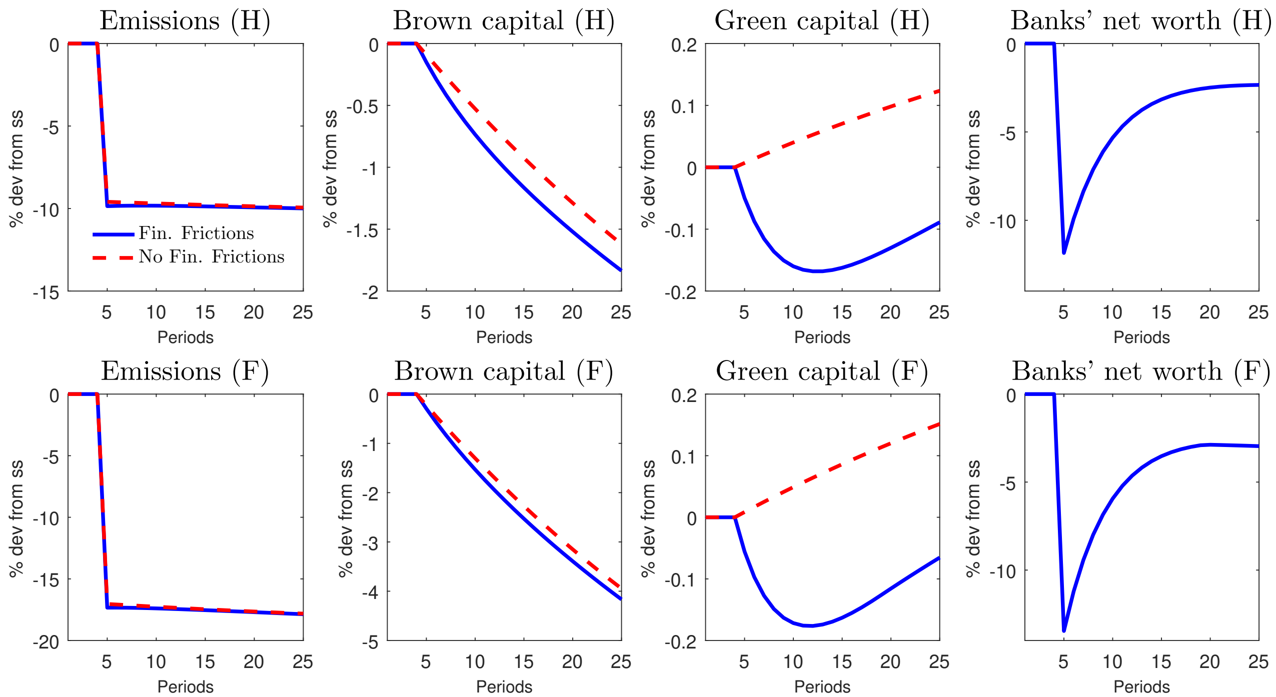

Figure 7: Transition dynamics in response to uniform global carbon tax. This figure plots the transition dynamics of selected variables in response to the introduction of uniform global carbon tax in the models with and without financial frictions.

Appendices

A Details on banks' optimization problem

Home bank i's flow-of-funds constraint in time period t is

$$\sum_{j\in\{b,g\}}\left[(1+\tau^h_{j,t})Q_{j,t}S^h_{i,j,t}+(1+\tau^f_{j,t})Q^*_{j,t}S^f_{i,j,t}\right]+\Psi_{i,t}=N_{i,t}+D_{i,t}. \tag{A1}$$

Here $\Psi_{i,t}$ denotes the quadratic portfolio adjustment costs,

$$\Psi_{i,t}=\left[\frac{\phi_b}{2}\left(\Upsilon^f_{b,t}-\overline{\Upsilon}^f_b\right)^2+\frac{\phi_g}{2}\left(\Upsilon^f_{g,t}-\overline{\Upsilon}^f_g\right)^2\right]\Gamma_{i,t}. \tag{A2}$$

where $\Gamma_{i,t}$ is the value of the bank's total asset portfolio,

$$\Gamma_{i,t}\equiv\sum_{j\in\{b,g\}}\left(Q_{j,t}S^h_{i,j,t}+Q^*_{j,t}S^f_{i,j,t}\right), \tag{A3}$$

and $\Upsilon^f_{b,t}$ and $\Upsilon^f_{g,t}$ denote the portfolio shares of Home bank's holdings of foreign brown and green assets, respectively:

$$\Upsilon^f_{b,t}\equiv\frac{Q^*_{b,t}S^f_{i,b,t}}{\Gamma_{i,t}},\quad \Upsilon^f_{g,t}\equiv\frac{Q^*_{g,t}S^f_{i,g,t}}{\Gamma_{i,t}}. \tag{A4}$$

Using the flow-of-funds constraint (eq. 14) and the definitions above, we can rewrite the law of motion of bank's net worth (eq. 15) as follows,

$$N_{i,t+1}=\left\{\begin{array}{c}\left[R_{b,t+1}-\left(1+\tau^h_{b,t}\right)R_t\right]\left(1-\Upsilon^h_{g,t}-\Upsilon^f_{b,t}-\Upsilon^f_{g,t}\right)+\left[R_{g,t+1}-\left(1+\tau^h_{g,t}\right)R_t\right]\Upsilon^h_{g,t}\\ +\left[R^*_{b,t+1}-\left(1+\tau^f_{b,t}\right)R_t\right]\Upsilon^f_{b,t}+\left[R^*_{g,t+1}-\left(1+\tau^f_{g,t}\right)R_t\right]\Upsilon^f_{g,t}-R_t ac_t\end{array}\right\}\Gamma_{i,t}+ \\ +R_tN_{i,t}, \tag{A5}$$

where $\Upsilon^h_{g,t}\equiv\frac{Q_{g,t}S^h_{i,g,t}}{\Gamma_{i,t}}$ and $ac_t\equiv\frac{\Psi_{i,t}}{\Gamma_{i,t}}=\frac{\phi_b}{2}\left(\Upsilon^f_{b,t}-\overline{\Upsilon}^f_b\right)^2+\frac{\phi_g}{2}\left(\Upsilon^f_{g,t}-\overline{\Upsilon}^f_g\right)^2$.

We guess and later verify that a bank's value function is linear in its individual net worth,

$$V_{i,t}=\varphi_tN_{i,t}, \tag{A6}$$

where φ_t is time-varying but common across banks. For convenience, we define the following variables:

$$x_{j,t}^h \equiv E_t\left[\Omega_{t+1}\left(R_{j,t+1} - \left(1+\tau_{j,t}^h\right)R_t\right)\right] \quad j \in \{b,g\}, \tag{A7}$$

$$x_{j,t}^f \equiv E_t\left[\Omega_{t+1}\left(R_{j,t+1}^* - \left(1+\tau_{j,t}^f\right)R_t\right)\right] \quad j \in \{b,g\}, \tag{A8}$$

$$\nu_t \equiv E_t\left[\Omega_{t+1}R_t\right], \tag{A9}$$

where $\Omega_{t+1} \equiv M_{t,t+1}\left(1-\pi+\pi\varphi_{t+1}\right)$ denotes the bank's stochastic discount factor.

The banker's optimization problem can then be rewritten as:

$$V_{i,t} = \max_{(\Gamma_{i,t},\Upsilon_{g,t}^h,\Upsilon_{b,t}^f,\Upsilon_{g,t}^f)} \left[\begin{array}{c} x_{b,t}^h\left(1-\Upsilon_{g,t}^h-\Upsilon_{b,t}^f-\Upsilon_{g,t}^f\right)+x_{g,t}^h\Upsilon_{g,t}^h \\ +x_{b,t}^f\Upsilon_{b,t}^f+x_{g,t}^f\Upsilon_{g,t}^f-\nu_t ac_t \end{array}\right]\Gamma_{i,t}+\nu_t N_{i,t}, \tag{A10}$$

subject to the incentive constraint,

$$\left[\begin{array}{c} x_{b,t}^h\left(1-\Upsilon_{g,t}^h-\Upsilon_{b,t}^f-\Upsilon_{g,t}^f\right)+x_{g,t}^h\Upsilon_{g,t}^h \\ +x_{b,t}^f\Upsilon_{b,t}^f+x_{g,t}^f\Upsilon_{g,t}^f-\nu_t ac_t \end{array}\right]\Gamma_{i,t}+\nu_t N_{i,t} \geq \kappa\Gamma_{i,t}. \tag{A11}$$

The Lagrangian for this problem is

$$\pounds_{i,t} = \left\{\left[\begin{array}{c} x_{b,t}^h\left(1-\Upsilon_{g,t}^h-\Upsilon_{b,t}^f-\Upsilon_{g,t}^f\right)+x_{g,t}^h\Upsilon_{g,t}^h \\ +x_{b,t}^f\Upsilon_{b,t}^f+x_{g,t}^f\Upsilon_{g,t}^f-\nu_t ac_t \end{array}\right]\Gamma_{i,t}+\nu_t N_{i,t}\right\}(1+\omega_t)-\omega_t\kappa\Gamma_{i,t}.$$

The first order optimality conditions with respect to $\Gamma_{i,t}$, $\Upsilon_{g,t}^h$, $\Upsilon_{b,t}^f$, $\Upsilon_{g,t}^f$, respectively, are:

$$\left[\begin{array}{c} x_{b,t}^h\left(1-\Upsilon_{g,t}^h-\Upsilon_{b,t}^f-\Upsilon_{g,t}^f\right)+x_{g,t}^h\Upsilon_{g,t}^h \\ +x_{b,t}^f\Upsilon_{b,t}^f+x_{g,t}^f\Upsilon_{g,t}^f-\nu_t ac_t \end{array}\right] = \frac{\omega_t}{1+\omega_t}\kappa, \tag{A12}$$

$$x_{b,t}^h = x_{g,t}^h \tag{A13}$$

$$(\Upsilon_{b,t}^f - \overline{\Upsilon}_b^f)\phi_b\nu_t = x_{b,t}^f - x_{b,t}^h, \tag{A14}$$

$$(\Upsilon_{g,t}^f - \overline{\Upsilon}_g^f)\phi_g\nu_t = x_{g,t}^f - x_{g,t}^h, \tag{A15}$$

When the incentive constraint (eq. 16) is not binding, the Lagrange multiplier $\omega_t = 0$, meaning credits spreads are also zero. When the constraint binds, credit spreads are positive and credit is undersupplied. In this case, banks' net worth determines the amount of credit intermediated in the economy.

Denote by $\aleph_t \equiv x^h_{b,t}\left(1 - \Upsilon^h_{g,t} - \Upsilon^f_{b,t} - \Upsilon^f_{g,t}\right) + x^h_{g,t}\Upsilon^h_{g,t} + x^f_{b,t}\Upsilon^f_{b,t} + x^f_{g,t}\Upsilon^f_{g,t} - \nu_t ac_t$. Using the optimality conditions and the incentive constraint, we have

$$\Gamma_{i,t} \leq \frac{\nu_t}{\kappa - \aleph_t} N_{i,t}. \tag{A16}$$

To verify the conjecture notice that the value function is linear in net worth, $V_{i,t} = \frac{\kappa \nu_t}{\kappa - \aleph_t} N_{i,t}$, which implies

$$\varphi_t = \frac{\kappa \nu_t}{\kappa - \aleph_t}. \tag{A17}$$

Whenever the banks are financially constrained, $\varphi_t > 1$, and the banks' stochastic discount factor differs from that of the household due to the financial friction.

B Additional Tables and Figures

Table B1: Banks' loan exposures to brown sectors

	Brown exposure	Domestic brown exposure	Foreign brown exposure
US banks	0.49	0.49	0.57
JP Morgan	0.53	0.53	0.44
BoA	0.48	0.46	0.41
Citi	0.56	0.55	0.39
Goldman	0.52	0.51	0.46
Mellon	0.49	0.48	0.36
M Stanley	0.58	0.58	0.39
Wells Fargo	0.49	0.49	0.58
European banks	0.55	0.54	0.56
HSBC	0.51	0.46	0.44
Barclays	0.52	0.50	0.47
BNP	0.59	0.57	0.38
Deutsche	0.52	0.59	0.51
Crédit Agricole	0.54	0.50	0.40
Santander	0.54	0.54	0.47
Société Générale	0.52	0.52	0.48

Notes: This table presents share of each loan type in total outstanding loan amount of all banks and selected Globally Systematically Important Banks (G-SIBs) in the United States and the European Union. Column 1 reports banks' loans to "brown" firms as a share of total outstanding loan amount. Column 2 reports domestic "brown" exposure as a share of loans to domestic firms. Similarly, Column 3 has foreign "brown" exposure as a share of foreign loans. Each share represents the average from 2017 to 2019.

Table B2: Emissions intensity by sector

Sector (NACE rev. 2)	US			Europe		
	Scope-1	Scope-2	Total	Scope-1	Scope-2	Total
A. Agriculture; forestry and fishing	0.60	0.02	0.62	0.22	0.03	0.25
B. Mining and quarrying	0.60	0.18	0.78	0.34	0.28	0.62
C. Manufacturing	0.39	0.23	0.62	0.25	0.09	0.33
D. Electricity; gas, steam and air conditioning supply	7.28	1.21	1.21	1.56	0.21	0.21
E. Water supply; sewerage, waste management and remediation activities	0.29	0.11	0.40	0.17	0.07	0.24
F. Construction	0.11	0.05	0.15	0.06	0.00	0.06
G. Wholesale and retail trade; repair of motor vehicles and motorcycles	0.08	0.01	0.09	0.03	0.02	0.05
H. Transportation and storage	0.86	0.01	0.87	0.45	0.02	0.47
I. Accommodation and food service activities	0.04	0.01	0.05	0.02	0.02	0.05
J. Information and communication	0.02	0.00	0.02	0.01	0.01	0.02
K. Financial and insurance activities	0.01	0.00	0.01	0.01	0.01	0.01
L. Real estate activities	0.01	0.02	0.02	0.00	0.01	0.01
M. Professional, scientific and technical activities	0.03	0.00	0.03	0.01	0.00	0.02
N. Administrative and support service activities	0.06	0.00	0.06	0.02	0.00	0.03
O. Public administration and defence; compulsory social security	0.05	0.01	0.06	0.02	0.01	0.03
P. Education	0.02	-	-	0.01	-	-
Q. Human health and social work activities	0.03	0.01	0.03	0.01	0.01	0.03
R, S. Arts, entertainment and recreation; Other services	0.07	0.01	0.08	0.03	0.02	0.05

Source: Authors' calculations based on inter-country input-output tables (industry by industry) and carbon footprints tables of "Full International and Global Accounts for Research in input-Output analysis" (FIGARO) database, compiled by Eurostat and the Joint Research Centre of the European Commission, and Environmental Accounts of World Input-Output Database (WIOD EA).

Notes: This table presents average emissions intensities of each sector for the period 2016-2019. Sectoral emissions intensity for each year is calculated by dividing tons of CO_2 emissions by real gross value added of the sector (in thousands of 2015 USD) for that year. Only scope-1 and scope-2 emissions count as numerators in columns labeled "Scope-1" and in columns labeled "Scope-2," respectively. To calculate scope-2 emissions, we allocate scope-1 emissions from sector D to all sectors, including sector D itself, in proportion to their share of electricity consumption in the country. For electricity consumption, we use 2012-2016 Gross Energy Accounts of WIOD EA. We calculate sectoral shares in national electricity consumption for each year and take the average for 2012-2016. Sector P, which would have minimal weight, is excluded due to anomalous trends observed in the 2012-2016 data. The reported values represent the averages over the years 2016 to 2019.

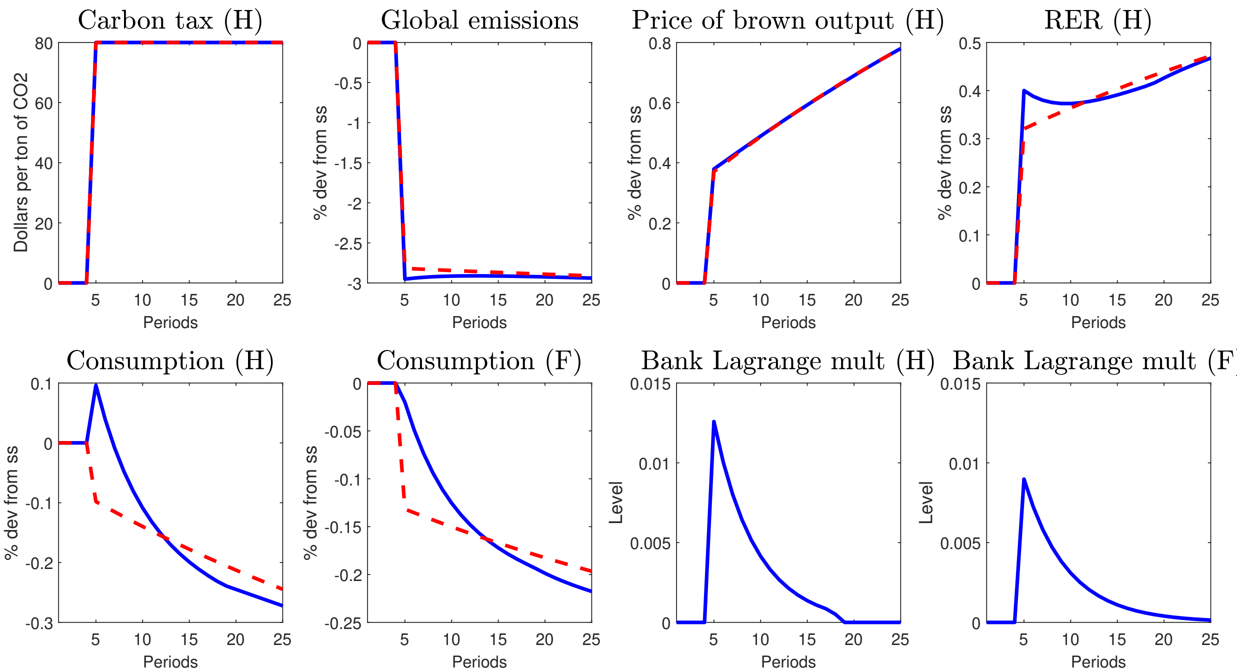

Figure B1: Transition dynamics in response to Home carbon tax: Additional variables. This figure plots the transition dynamics of additional variables in response to the introduction of Home carbon tax in the models with and without financial frictions.

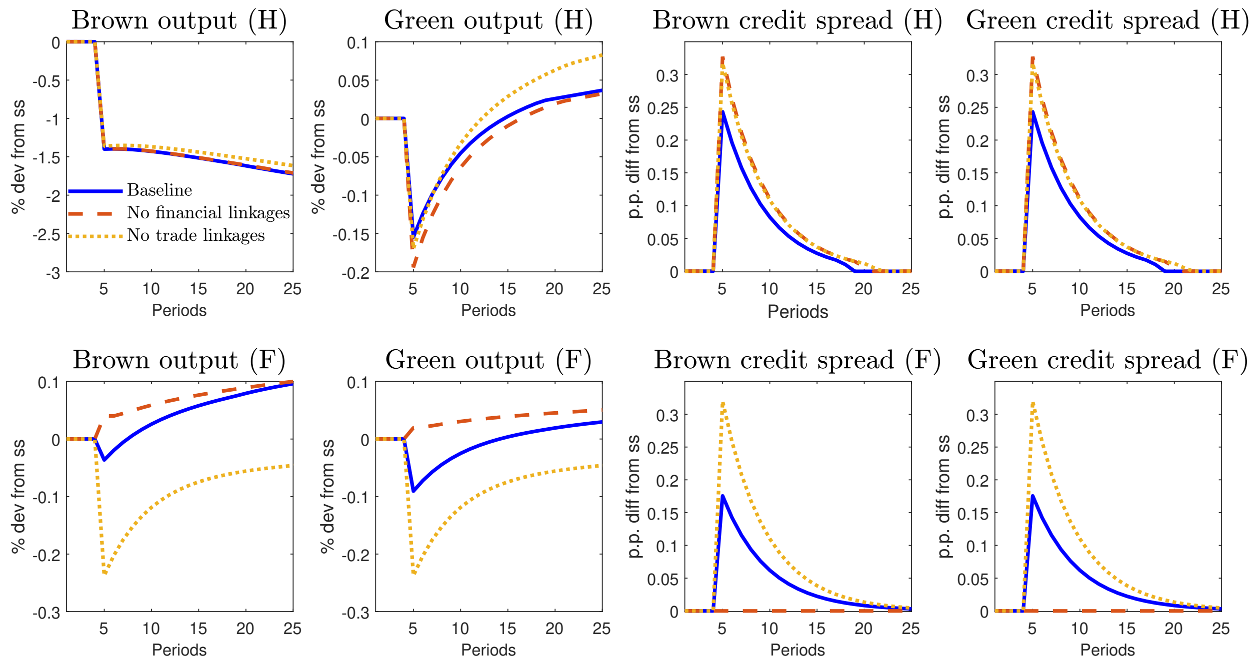

Figure B2: Transition dynamics in response to Home carbon tax. The role of financial and trade linkages: Additional variables. This figure compares the transition dynamics of additional variables in response to the introduction of Home carbon tax in the baseline model with financial frictions to the case when (i) we shut down cross-country financial linkages; (ii) we shut down international trade.

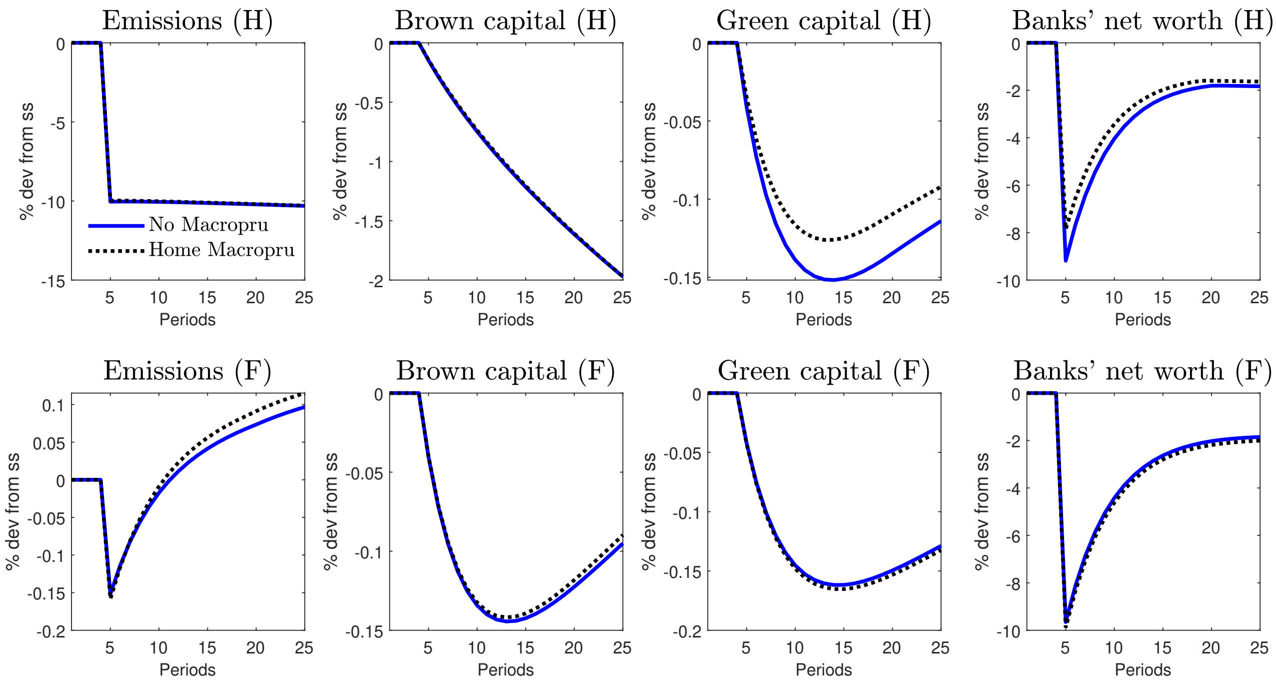

Figure B3: Transition dynamics in response to Home carbon tax & CBAM with and without Home macroprudential policy. This figure compares the transition dynamics in response to the introduction of Home carbon tax & CBAM in the model with financial frictions under two scenarios: (i) No macroprudential policy; (ii) only Home country implements macroprudential policy.

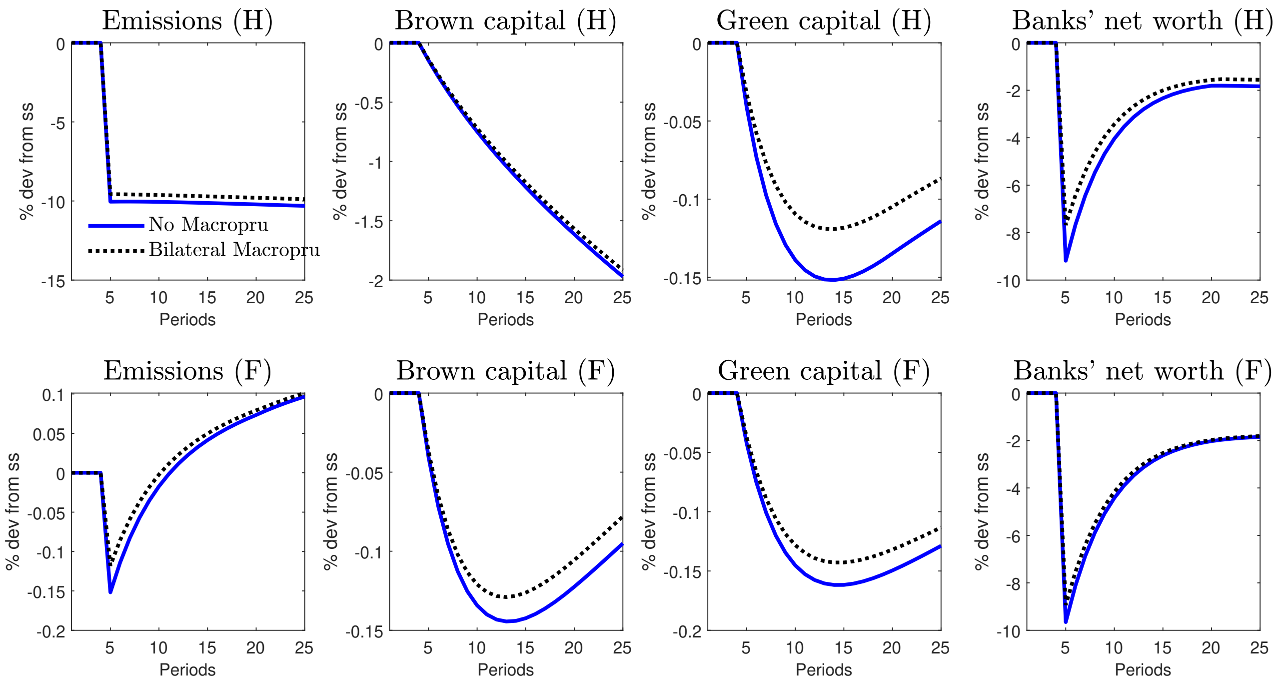

Figure B4: Transition dynamics in response to Home carbon tax & CBAM with and without bilateral macroprudential policy. This figure compares the transition dynamics in response to the introduction of Home carbon tax & CBAM in the model with financial frictions under two scenarios: (i) No macroprudential policy; (ii) both Home and Foreign countries implement macroprudential policies.

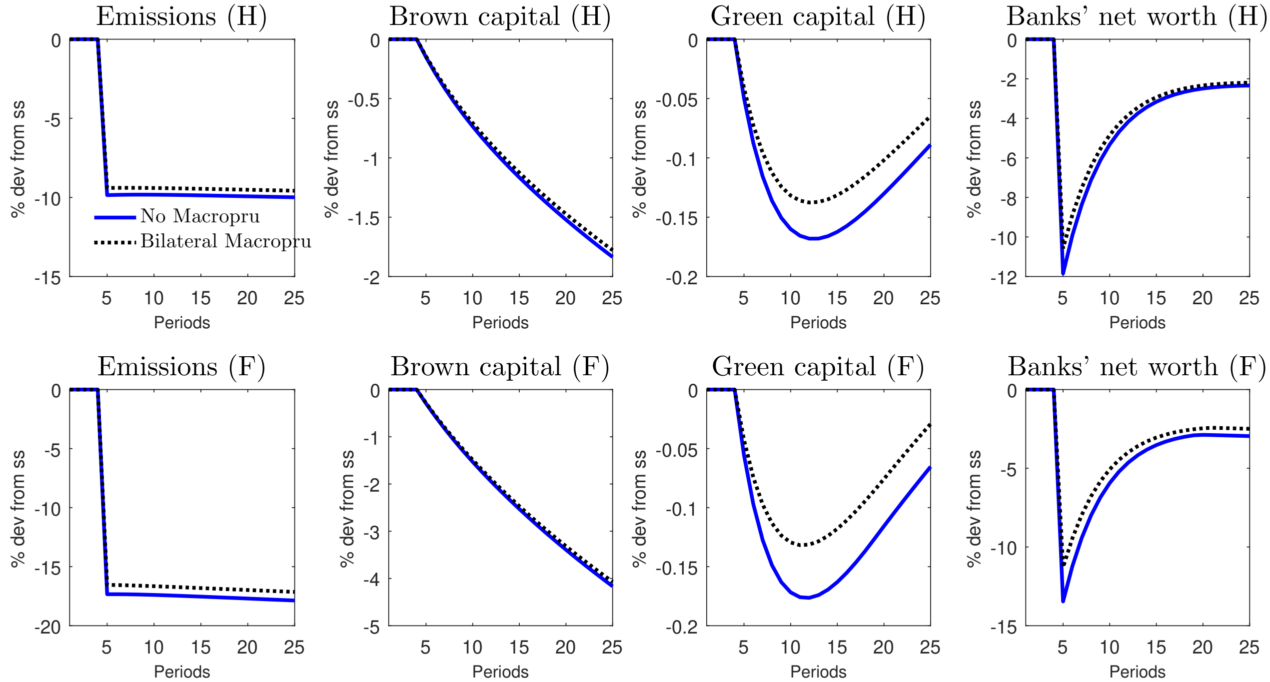

Figure B5: Transition dynamics in response to uniform global carbon tax with and without macroprudential policy. This figure compares the transition dynamics in response to the introduction of global carbon tax in the model with financial frictions under two scenarios: (i) No macroprudential policy; (ii) both Home and Foreign countries have macroprudential policies.

C Sensitivity analysis

This section considers sensitivity of our results to the model parameters that are potentially relevant for shaping sectoral and cross-border spillovers of the climate policies: (i) elasticity of substitution between home and foreign goods; (ii) elasticity of substitution between brown and green goods; (iii) home bias in consumption; (iv) the green sector's emissions intensity. We consider sensitivity of the results in the two domestic climate policy scenarios: (i) Home carbon tax; and (ii) Home carbon tax and CBAM. Appendix Figure C.1, Panels (a) and (b), report the sensitivity results for the two policy scenarios, respectively. We discuss the results in detail below.

Elasticity of substitution between brown and green goods. In our baseline calibration, we assume the elasticity of substitution between brown and green goods to be $1/(1-\phi) = 0.75$, suggesting that the two goods are imperfect complements in households consumption basket.[17] In the sensitivity exercise we consider a higher elasticity value ($1/(1-\phi) = 2$) while keeping all other parameters at their baseline values. The Home carbon tax induces then an easier substitution toward domestic and foreign green goods. Therefore, there is more substitution towards green goods that mitigates the negative effect on green domestic and foreign goods generated through financial frictions. As a result, green labor and capital fall by less with the higher elasticity of substitution. The stronger substitutability also implies that the negative spillovers to the foreign brown sector are amplified relative to the baseline as households aggressively substitute away from more expensive Home brown goods and towards green consumption. The implications of this parameter for the scenario when Home carbon tax is complemented by the carbon border adjustment mechanism are similar (Panel (b), Figure C.1). In both scenarios banks' net worth dynamics are quantitatively very similar across the two parameter values.

Elasticity of substitution between home and foreign goods. In the main parametrization of the model we set the elasticity of substitution to a value in line with open economy macro literature, $1/(1-\rho_j) = 0.85$. In Figure C.1 we simulate the domestic climate policy scenarios with the higher value of trade elasticity, $1/(1-\rho_j) = 1.5$. Higher trade elasticity mitigates the negative cross-border spillovers thanks to a stronger consumption expenditure switching effect towards foreign goods. Foreign banks' equity losses are thus dampened since the positive

[17] This is a reasonable assumption given our classification of sectors with the green sector comprising mostly low-emissions intensive services, while brown sector corresponds to manufacturing, agriculture, electricity generation, transportation, mining.

trade channel counteracts the negative financial spillovers. The dynamics of domestic banks' net worth is less affected by the trade elasticity. Overall, Foreign economy experiences milder recession in response to the implementation of ambitious climate policies in the Home country, both in the case of the Home carbon tax, and the Home carbon tax and CBAM. Leakage is reduced in the sense that foreign emissions are lower. However, in the short run, it is the effect of banks' net worth that prevails, resulting in an increase in foreign capital, both green and brown.

Home bias in brown consumption. Our baseline calibration assumes some degree of home bias in consumption of goods produced in the brown sector, e.g., $\theta_b = 0.70$. This choice is motivated by the fact that our definition of the brown sector includes multiple highly-tradable and high emissions-intensive sectors, such as mining or manufacturing. However, given that some high-emitting sectors in our classification are less traded across borders, such as for example, electricity generation, we consider the sensitivity of our results to the assumed degree of average home-bias in the brown sector. Specifically, we simulate the transition dynamics for $\theta_b = 0.95$ while keeping all other parameters at their baseline values. A higher home bias significantly amplifies the negative cross-border spillovers from the domestic carbon tax (Panel (a)). This amplification is driven by the fact that the trade spillovers benefit the Foreign country through competitiveness effects. With a stronger home bias, this channel is less operative and so the negative cross-border financial spillovers are in full force, as also seen in Section 4.1, Figure B2. In this case, Home banks also suffer more due to the severe recession in the Foreign economy to which they are exposed to.

When the domestic carbon tax is complemented with the CBAM, the recessionary effect of the CBAM is dampened relative to what we observe with the baseline value of home bias. The reason is that the trade margin that the CBAM targets is much smaller now, so the spillovers of CBAM policy are themselves muted with the stronger home bias in brown consumption.

Dirtier green sector. In our baseline model parametrization, we assume emissions intensity parameters of the green sector to be zero, i.e., $\epsilon_g = \epsilon_g^* = 0$. Under this assumption, the domestic carbon tax does not apply to the domestic green sector, and therefore, it has no direct impact on this sector. As a sensitivity test, we consider a higher emissions intensity in the green sector ($\epsilon_g = 0.02$ and $\epsilon_g^* = 0.04$), based on the actual estimates from the data. Under this calibration, domestic green capital contracts more than in the baseline, as the green sector is not only affected by financial frictions but also directly by the emissions tax. The outcomes for banks' net worth and brown capital in both the Home and Foreign countries are almost the same as those of the baseline. This result can be attributed to the very low emissions intensity in the domestic green sector, resulting in a minimal carbon tax payment and, thus, a minor financial contagion from this sector.

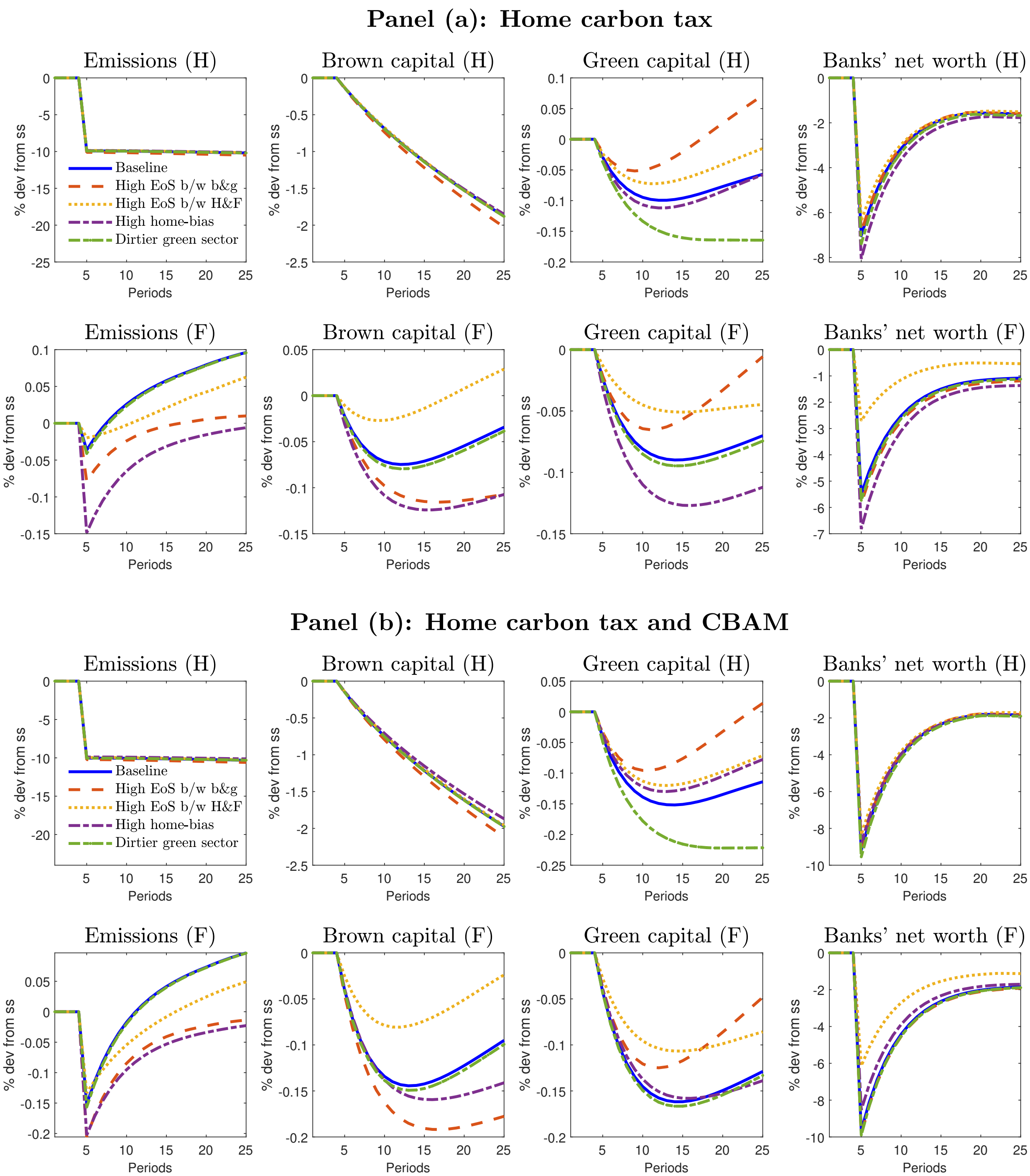

Figure C.1: Sensitivity to parameters. This figure displays the sensitivity results in the model with financial frictions for two climate policy scenarios: (i) Home carbon tax - Panel (a), and (ii) Home carbon tax and CBAM - Panel (b). Blue solid lines plot the transition dynamics under the baseline calibration; Orange dashed lines correspond to the case with high elasticity of substitution between brown and green consumption, $(1/(1-\phi)=2)$. Yellow dotted lines are for the high elasticity of substitution between home and foreign-produced goods, $(1/(1-\rho_j)=1.5)$. Purple dash-dotted lines are for high home-bias in brown consumption, $(\theta_b = 0.95)$. Green dash-dotted lines are for the green sector being dirtier ($\epsilon_g = 0.02$ and $\epsilon_g^* = 0.04$). Section C contains further details.