Climate Policy and Sovereign Default Risk*

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Abstract

This paper examines climate policy in an economy with endogenous sovereign default risk. Empirical evidence demonstrates that an increase in carbon price leads to higher sovereign spreads and lower economic activity in the short run, with the effects magnified for highly indebted countries. Building on these findings, we develop a small open economy model with strategic sovereign default and pollution externalities to quantify the role of default risk in shaping the macroeconomic effects of climate policy. Consistent with the data, the calibrated model predicts that sovereign risk increases following a carbon price shock, especially when sovereign debt is high. We find that endogenous sovereign default risk can significantly amplify the short-run economic costs of the green transition. Our results suggest a role for international official lending to alleviate transition risk in fiscally constrained economies, preventing financial distress from derailing climate goals.

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1 Introduction

Achieving the 2°C goal of the Paris agreement requires governments to implement ambitious climate policies. While such measures are essential to limit severe physical damages from climate change, they may entail short- to medium-term economic costs. In particular, stringent carbon pricing can raise production costs of energy-intensive firms, reducing productivity and output (e.g., Känzig 2025). Abrupt or steep increases in carbon taxes may also strand carbon-intensive assets and create financial stability risks – so-called 'transition risk' – a concern that has received increasing attention from central banks and financial regulators given the financial sector's sizable exposure to high-emitting industries (Carney 2015, ECB 2021, Rudebusch 2021, Carattini, Heutel, and Melkadze 2023).

At the same time, sovereign risk has re-emerged as a central policy concern, especially in the aftermath of the COVID pandemic, which left many governments with historically elevated debt levels (IMF 2024). In such an environment, ambitious climate policies may have direct implications for sovereign risk by affecting economic activity and fiscal revenues, thereby influencing governments' ability to service their debt. Despite the growing policy relevance of both climate transition risk and sovereign debt sustainability, their interaction remains largely unexplored in the literature. Our paper aims to fill this gap by asking two related questions: Does climate policy affect sovereign default risk? And, if so, how does endogenous sovereign risk shape the transition to a low-carbon economy?

We begin by providing empirical evidence on the impact of climate policy on sovereign spreads, a common measure of sovereign risk, and real economic activity in a panel of European countries covered by the European Union's Emissions Trading System (EU-ETS). Using the carbon policy shocks of Känzig (2025) in a panel local projection framework, we document that an exogenous tightening of climate policy (i.e., an increase in carbon price) raises sovereign spreads and reduces industrial production. The effects are economically meaningful: a one standard deviation carbon policy shock leads to a 0.14 percentage point increase in sovereign

spread (roughly 9% of its sample mean) and a 0.77% decline in industrial production. These effects are also heterogeneous across countries depending on their government debt levels. In particular, countries with higher sovereign debt-to-GDP ratios experience larger increases in sovereign spreads and more pronounced declines in real activity. Our empirical findings thus suggest that fiscal capacity and sovereign default risk influence how carbon policy is transmitted to the real economy.

To quantify the role of the sovereign risk channel in the transmission of carbon policy shocks, we develop a small open economy model with pollution externalities, working capital constraints, and strategic sovereign default. We model pollution externalities following the Nordhaus (1994) Dynamic Integrated Climate-Economy (DICE) model. Production of output entails pollution, which negatively affects aggregate productivity in the economy through physical damages, not internalized by individual firms. This creates the rationale for climate policy in the model. A novel feature of our model, relative to the previous macro-climate literature, is that a government, who borrows from international lenders to finance consumption and abatement spending, cannot commit to repay its debt as in the work of Arellano (2008) and Mendoza and Yue (2012).

In the model, climate policy affects sovereign borrowing costs and default incentives through two main channels. On the one hand, carbon price improves aggregate productivity in the economy by reducing physical damages from climate change. This channel lowers sovereign's default incentives, and in turn, reduces sovereign spreads. On the other hand, emissions abatement is costly and diverts resources away from consumption, which increases government's incentives to default. The relative strengths of these channels vary depending on the time horizon. In the short to medium run–that is, during the transition to a low pollution steady state–the costs of emissions abatement outweigh the benefits, since it takes many years for the stock of pollution and the associated damages to decline. Hence, sovereign spreads increase in response to tighter carbon policy in the short run, consistent with our empirical evidence. Sovereign default risk, in turn, propagates to the economy through its impact on firms' borrowing costs. When sovereign

risk rises, firms face higher interest rates on working capital loans, constraining their ability to hire and spend on emissions abatement.

We calibrate the model to the EU economy. The model successfully reproduces standard macro dynamics observed around sovereign default episodes in the data. The model also does a fairly good job at matching the key features of the empirical impulse responses to a carbon policy shock, along with other targeted and non-targeted moments in the data. Consistent with the empirical evidence, the model predicts stronger sovereign spread responses to a carbon policy shock when government debt-to-GDP ratios are high, suggesting that climate transition risk is amplified by the pre-existing government debt burdens.

We use the model to quantify the role of endogenous sovereign default risk in shaping the economy's response to carbon price shocks. To this end, we consider a counterfactual economy in which sovereign default risk is shut down and the government always borrows at the risk-free rate. Our results suggest that sovereign risk substantially amplifies the short-run economic costs of climate policy. In the absence of default risk, the government can borrow at lower cost and smooth the adverse impact of carbon pricing on output. We also find that sovereign risk impairs the effectiveness of climate policy in reducing CO_2 emissions reduction. This happens because an increase in sovereign spreads raises interest rates on firm's working capital loans, effectively making abatement more costly.

The model can also be used to explore whether international official lending linked to climate mitigation efforts can alleviate transition risk and strengthen governments' incentives to price carbon.

Related Literature. We contribute to several strands of the literature. First, our paper relates to the empirical literature exploring the macroeconomic effects of carbon policy (Metcalf and Stock 2020, Konradt and Weder di Mauro 2023, Berthold et al. 2023, Känzig 2025, Kapfhammer 2025). We extend this work by documenting novel empirical facts on the impact of carbon policy shocks on sovereign debt markets, and by quantifying the role of sovereign risk

in the green transition.

Second, our paper contributes to the rapidly growing literature that studies the effects of climate change and mitigation policies using quantitative macroeconomic models (Nordhaus 1994, Heutel 2012, Golosov et al. 2014, Barrage 2020, Hassler, Krusell, and Olovsson 2021, Fried, Novan, and Peterman 2022, Cruz and Rossi-Hansberg 2024, Gilchrist, Martinez, and Rickard 2024, Bilal and Känzig 2025, Fornaro, Guerrieri, and Reichlin 2025, Hambel and Van Der Ploeg 2025, among others). While this literature emphasizes significant welfare gains from ambitious climate policies, it also highlights the short-run economic costs associated with the transition to a low-carbon economy. Recent studies in this strand focus in particular on the role of financial frictions in shaping the economic effects of climate-related risks – both physical and transition risks (Mallucci 2022, Hong, Wang, and Yang 2023, Carattini, Heutel, and Melkadze 2023, Kaldorf and Rottner 2024, Phan and Schwartzman 2024, Bakkensen, Phan, and Wong 2025). For example, Carattini, Heutel, and Melkadze (2023) find that, in the presence of frictional credit markets, an abrupt implementation of ambitious climate policy can disrupt financial intermediation by stranding carbon-intensive assets on banks' balance sheets, thereby amplifying the short-run economic costs of the green transition. We identify a new source of potential financial risks from ambitious climate policy: the sovereign default risk.

Our modeling of sovereign default risk builds on the well-established literature on sovereign default (e.g. Arellano 2008, Mendoza and Yue 2012, Chatterjee and Eyigungor 2012, among others) which accounts for the sovereign risk premium and debt dynamics in models with income risk or productivity shock. Some recent studies (Mallucci 2022, Phan and Schwartzman 2024, and Duffy 2025) examine physical risks of climate change (e.g. natural disasters) in small open economy models with endogenous sovereign default risk. They find that endogenous default risk significantly amplifies and propagates the adverse effects of natural disasters. By contrast, our focus is on understanding how endogenous sovereign risk interacts with climate transition risk. In particular, we examine how default incentives may interact with pollution externalities and climate policy.

The remainder of the paper is organized as follows. We present our data and empirical results in Section 2. Section 3 presents the baseline macro-climate model with endogenous default risk. Section 4 evaluates the quantitative implications of the model, specifically exploring how endogenous default risk shapes the macroeconomic response to a carbon price shock. Section 5 extends the baseline framework to incorporate working capital constraints. Section 6 concludes.

2 Empirical evidence

In this section, we use monthly panel data from a sample of European countries to document that a tightening of climate policy–that is, an increase in the carbon price–leads to higher sovereign spreads and lower industrial production. We further show that these effects are stronger for countries with higher sovereign debt-to-GDP ratios.

2.1 Data

Our panel comprises of 26 EU member countries for which government bond yield data is available, plus the United Kingdom, over the period 2005M1-2019M12.[1] To estimate the causal effect of carbon policy on sovereign spreads and economic activity, we use the carbon policy shocks constructed by Känzig (2025) in the context of the EU Emissions Trading System (EU ETS). The EU ETS is Europe's flagship climate policy, covering roughly 40% of EU greenhouse gas (GHG) emissions and making up the largest carbon market in the world. The system operates under a cap-and-trade policy that sets limits on greenhouse gas emissions from key sectors. Under this system, companies must obtain enough allowances to fully account for their annual emissions, if not they are subject to steep fines. Emission allowances are traded in

1. Specifically, our sample includes the following 27 countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and United Kingdom. Our data covers the period from 2005, when the EU-ETS was launched, to December 2019, before the Covid pandemic. Appendix A provides more details on the sample and data sources.

auctions and can be traded among firms to promote cost-effective emission reductions. The cap is tightened over time to meet the EU's long-term climate goals.[2]

Känzig (2025) identifies carbon policy shocks using high-frequency surprise movements in EU emissions allowance prices around regulatory announcements as an external instrument in a structural VAR, following the high-frequency identification approach of Mertens and Ravn (2013), Gertler and Karadi (2015), Ramey (2016). We use these identified shocks in our analysis. Appendix Figure A.1 displays the identified carbon policy shocks alongside with the EU carbon prices.

Our analysis focuses on two monthly outcome variables: (i) sovereign spreads, measured as the difference between yields on 10-year domestic government bonds and German bonds of comparable maturity, and (ii) industrial production. The following section discusses the methodology in detail.

2.2 Panel local projections

We estimate the dynamic impulse responses of our variables of interest to a carbon policy shock using Jordà (2005)-style panel local projections,

$$y_{i,t+h} = \alpha_{i,h} + \beta_h CPShock_t + \sum_{l=1}^{L} B_{h,l} X_{i,t-l} + \eta_h t + \varepsilon_{i,t+h}, \tag{1}$$

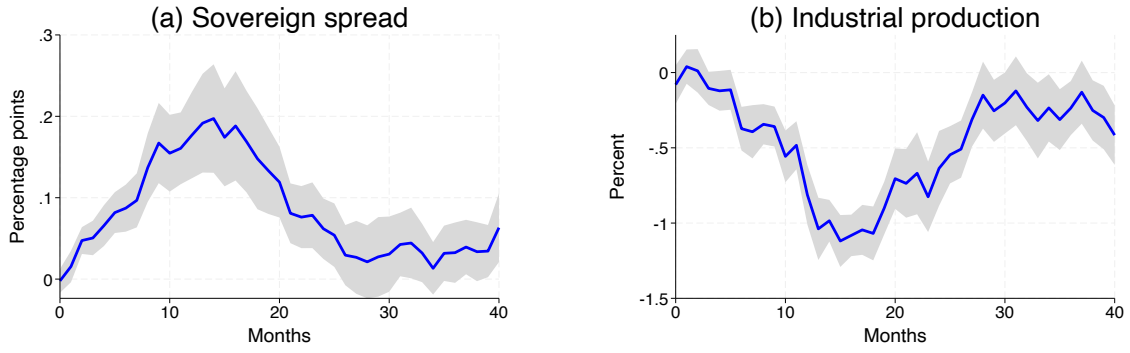
where $y_{i,t+h}$ denotes the outcome variable of interest – either sovereign spreads or (log) industrial production) – for country i at horizon $t+h$, with $h = 0, 1, ..., H$. The variable $CPShock_t$ represents Känzig's monthly carbon policy shock. The coefficient β_h captures the dynamic response of the outcome variable at horizon h to a carbon policy shock. Country fixed effects are denoted by $\alpha_{i,h}$. The vector $X_{i,t}$ contains control variables which include the country-level consumer price index (HICP), the euro area monetary policy rate (EONIA) and the

2. For more details, see https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.

(log) nominal exchange rate, their respective lags, as well as the lags of $CPShock_t$ and of the dependent variables. The matrix $B_{h,l}$ collects the corresponding regression coefficients. We also include a linear time trend in the regression. In the baseline specification, we set the number of lags $L = 8$ months, and later assess robustness to alternative lag lengths.

Figure 1 shows the impulse responses to a restrictive, unit carbon policy shock estimated using the local projections specification (1). The solid lines depict point estimates, while the shaded areas represent 90% confidence bands. A carbon policy shock that raises the carbon price leads to a statistically significant increase in sovereign spreads (Panel (a)) and a decline in industrial production (Panel (b)). The peak responses of sovereign spreads and industrial production–occurring roughly at the 15-month horizon–are 0.2 percentage points (p.p.) and 1.1%, respectively. These magnitudes are economically meaningful. For example, the peak response of sovereign spread to a one-standard-deviation carbon policy shock is about 0.14 p.p., or roughly 9% of its sample mean. Similarly, the peak decline in industrial production to a one-standard-deviation shock is sizable, amounting to about 0.77%. The negative impact of carbon policy shocks on industrial production has also been documented by Känzig (2025), whose analysis uses aggregate time-series data at the euro area level. Our panel data evidence for European countries aligns with his findings both qualitatively and in terms of magnitudes.

Figure 1: Dynamic Responses to a Carbon Policy Shock: Average Effects



Notes: The figure plots the impulse responses of sovereign spreads and industrial production to a restrictive, unit carbon policy shock. Shaded areas report 90% confidence bands. Robust standard errors are clustered at the country level.

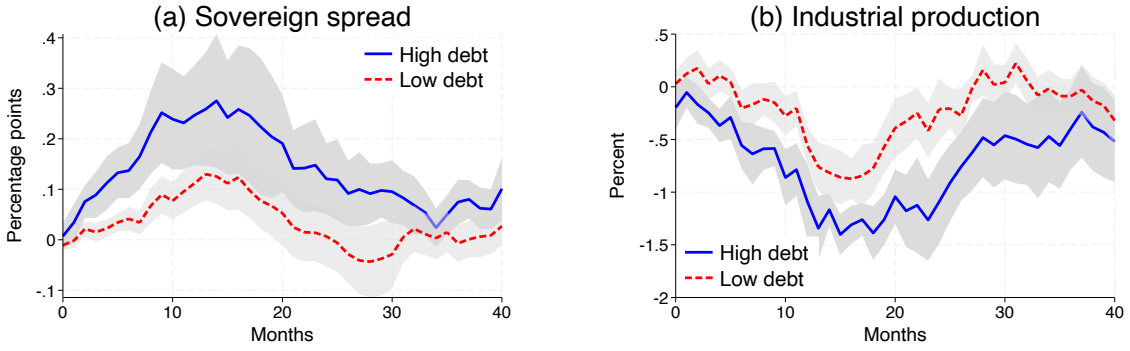
Next, we explore how the above responses vary across countries with different levels of government debt. To this end, we estimate the following panel local projections model,

$$y_{i,t+h} = \alpha_{i,h} + \beta_h CPShock_t + \gamma_h High\text{-}Debt_i \times CPShock_t + \sum_{l=1}^{L} B_{h,l} X_{i,t-l} + \eta_h t + \varepsilon_{i,t+h}, \quad (2)$$

where $High\text{-}Debt_i$ is a dummy variable equal to one if a country's average sovereign debt-to-GDP ratio is above the sample median.[3] Figure 2 shows that both sovereign spread and industrial production respond more strongly to a carbon policy shock in high-debt countries. In particular, the peak responses of sovereign spreads and output are about 0.13 and 0.4 percentage points larger, respectively, in high-debt countries than in low-debt countries.

Overall, our empirical results suggest that tighter carbon pricing raises governments' borrowing costs–particularly in countries with limited fiscal space–potentially amplifying its negative short-run impact on real activity. Our goal in the subsequent sections is to develop a macro-climate model that enables us to precisely quantify the contribution of the sovereign spread channel in shaping the economy's responses to climate policy shocks.

Figure 2: Dynamic Responses to a Carbon Policy Shock: High- vs Low-Debt Countries



Notes: The figure compares the impulse responses of sovereign spreads and industrial production to a restrictive, unit carbon policy shock in high- and low-debt countries. High-debt countries are defined as those with average sovereign debt-to-GDP ratios above the sample median. Shaded areas report 90% confidence bands. Robust standard errors are clustered at the country level.

3. In the next subsection, we show that the results are robust to alternative definitions of high-debt countries.

2.3 Robustness

This subsection summarizes the results from a series of robustness exercises.

Controlling for emissions intensity. An alternative explanation for the heterogeneous responses documented above can be that the countries whose governments are highly indebted, may also be the ones that are more polluting. If so, then the differential responses to the common carbon policy shock could reflect differences in emissions intensity rather than differences in sovereign debt per se. To account for this competing channel, we augment the regression specification in (2) by including an interaction between the shock and a country's emissions intensity, $High\text{-}Emissions_i \times CPShock_t$, where $High\text{-}Emissions_i$ denotes a dummy equal to one for countries with average emissions intensity above the sample median.[4] Appendix Figure A.2 shows that, even after controlling for the emissions intensity, countries with larger sovereign debt levels continue to respond differentially more to the carbon policy shock, emphasizing the relevance of the sovereign-risk channel.

Controlling for time fixed effects. Next we show that our results on the differential responses of high-debt countries to a carbon policy shock are robust to including time fixed effects in the regression equation (2). When time fixed effects are included, we can no longer estimate the base effects of a carbon policy shock on high- and low-debt countries, since the shock is common across all countries. The advantage of adding time fixed effects, however, is that they absorb any EU-wide time-varying aggregate factors that may be correlated with the carbon policy shock and could bias the estimated differential effects (γ_h). Figure A.3 plots the baseline differential responses of sovereign spreads and industrial production alongside the estimates obtained when time fixed effects are included. The responses are extremely similar, further supporting the exogeneity of Känzig's carbon policy shocks.

Alternative definitions of high-debt countries. In our baseline analysis, we classify countries as high- or low-debt using the sample median. Our results are robust to alternative

4. As is standard in the literature, we measure emissions intensity as total GHG emissions divided by GDP.

definitions of the high-debt group. For example, Appendix Figure A.4 shows that when we use the 75th percentile as the threshold the results remain qualitatively unchanged. As expected, the responses of the high-debt countries become even stronger under this stricter definition of the high-debt group, compared to the baseline median split.

Finally, Figure A.5 reports the results when we replace the high-debt dummy with a continuous measure of the government debt-to-GDP ratio interacted with the carbon policy shock. The corresponding coefficient on the interaction term, shown in Figure A.5, illustrates that the impact of the carbon policy shock increases monotonically with the level of government debt.

Number of lags. Our results are robust to including fewer or larger number of lags than the baseline 8 lags. Appendix Figure A.6 presents the results from this robustness exercise.

3 Model

We consider a small open economy model with a negative pollution externality, working capital constraints, and sovereign default risk. The model has four types of agents: domestic households, firms, government, and international lenders residing in the rest of the world.

3.1 Households

Households choose consumption and labor supply to maximize the expected present discounted value of lifetime utility,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\gamma} \left[C_t - \varphi \frac{L_t^{1+\xi}}{1+\xi} \right]^{1-\gamma} \right\}, \tag{3}$$

subject to the budget constraint,

$$C_t = W_t L_t + \Pi_t + T_t, \tag{4}$$

where C_t and L_t denote consumption and labor hours, respectively. $\beta \in (0,1)$ is a discount factor, $\gamma > 0$ is the curvature parameter. The parameter ξ controls the Frisch elasticity of labor supply and $\varphi > 0$ is the labor disutility parameter. When making decisions, the households take wages W_t, profits from the domestic firms Π_t and government transfers T_t as given. As in Mendoza and Yue (2012), we assume that households do not borrow directly from abroad, but the government borrows, pays transfers, and makes default decisions internalizing their utility.

3.2 Firms

Perfectly competitive firms produce the final good using the following production technology,

$$Y_t = \left[1 - d\left(X_t\right)\right] \tilde{A}_t K^{\alpha} L_t^{1-\alpha}, \tag{5}$$

where K denotes fixed stock of capital, and L_t is labor hours. $\tilde{A}_t$ denotes productivity whose value depends on the exogenous TFP A_t and the sovereign's default status, to be specified below. X_t denotes the pollution stock in the atmosphere, and $d\left(X_t\right) \in (0,1)$ is an increasing quadratic damage function. That is, higher pollution stock in the atmosphere imposes output (productivity) losses on the economy as in Nordhaus (1994) DICE model.

Following the environmental-macro literature, we assume that production of goods entails emissions of carbon dioxide (CO_2). The pollution stock X_t in the atmosphere evolves according to

$$X_{t+1} = \delta_X X_t + E_t + E_t^{row}, \tag{6}$$

where E_t denotes current-period domestic CO_2 emissions and E_t^{row} are (exogenous) emissions imposed from the rest of the world. Domestic emissions in turn depend on the amount of production, Y_t, and the fraction of emissions abated, μ_t,

$$E_t = \left(1 - \mu_t\right) Y_t. \tag{7}$$

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

$$Z_t = \theta_1 \mu_t^{\theta_2} Y_t, \tag{8}$$

where $\theta_1 > 0, \theta_2 > 1$ are parameters controlling the shape of the cost function. The specification of emissions and the abatement cost function follows Nordhaus (2008) and Heutel (2012).

We assume that firms face working capital constraint as is standard in the small open economy literature (Uribe and Yue 2006, Neumeyer and Perri 2005) That is, firms need to borrow intratemporally to finance an exogenous fraction χ of their wage bill and abatement spending. The interest rate on these working capital loans $\tilde{r}_t$ is linked to the sovereign borrowing rate, capturing the well-established positive relationship between corporate borrowing costs and sovereign spreads (see e.g. Bocola 2016, Baskaya et al. 2024). In addition, when the sovereign defaults, we assume that alternative yet more costly source of financing is available to provide the working capital loan at interest rate $\bar{r}$ so that $\tilde{r}_t = \min\{r_t, \bar{r}\}$ where r_t denotes sovereign's borrowing rate, defined as $r_t = \kappa/q_t - (1-\delta)$, with q_t being the price of a long-term bond, to be determined later.[5]

The firm chooses labor input and abatement spending to maximize static profits,

$$\max_{\{L_t, \mu_t\}} Y_t - (1 + \tilde{r}_t \chi)(W_t L + Z_t) - \tau_{e,t} E_t, \tag{9}$$

subject to (5), (7), and (8). In this setup, an environmental externality arises because the individual firms do not internalize how their production affects the net output through the pollution stock X_t and associated damages $d(X_t)$. The negative environmental externality creates the rationale for a carbon tax.

The optimality conditions with respect to labor demand and abatement effort, respectively,

5. An alternative assumption is to introduce imperfect domestic substitute for the country to continue its production in default as in Mendoza and Yue (2012).

are:

$$W_t(1+r_t\chi) = (1-\alpha)\frac{Y_t}{L_t}\left[1-(1+\tilde{r}_t\chi)\theta_1\mu_t^{\theta_2}-\tau_{e,t}(1-\mu_t)\right], \tag{10}$$

$$\tau_{e,t} = (1+\tilde{r}_t\chi)\theta_1\theta_2\mu_t^{\theta_2-1}. \tag{11}$$

Equation (11) states that at the optimum, the firm equates the marginal benefit of abatement (i.e., marginal increase in profits from not paying the carbon tax $\tau_{e,t}$) to the marginal cost of abatement. In the absence of carbon tax, i.e., when $\tau_{e,t} = 0$, the firms do not have any incentives to engage in costly abatement ($\mu_t = 0$).

3.3 Government

The description of the government sector closely follows Mendoza and Yue (2012) and Arellano and Ramanarayanan (2012). The government issues long-term debt in the form of a perpetuity contract with coupon payments that decay geometrically at rate δ. The sovereign issues new bonds ℓ_t and receives $q_t\ell_t$ units of goods each period. In return, the borrower promises to pay, conditional on not defaulting, $\kappa\delta^{n-1}\ell_t$ units of goods in every future period $t+n$. Denote by B_t the outstanding debt level in period t. The assumed payment structure implies that $B_{t+1} = \delta B_t + \ell_t$. Also, debt service payments are proportional to the stock of outstanding debt, κB_t. Thus, the budget constraint of the sovereign can be expressed as:

$$C_t - q_t(B_{t+1}, X_t, A_t, \tau_{e,t})\ell_t + \kappa B_t + \theta_1\mu_t^{\theta_2}Y_t = Y_t. \tag{12}$$

The endogenous market price reflects the possibility of sovereign default.

The sovereign cannot commit to future debt payments and may decide to default on its debt optimally. If the borrower defaults, the country faces exclusion from international financial markets, and all outstanding debt becomes nil. Thus, consumption equalizes output net of

abatement costs. Upon default, the government can regain market access next period with an exogenous probability π. Moreover, default entails asymmetric productivity costs $\lambda(A_t)$ of the form:

$$\lambda(A_t) = \max\left\{0, a_0 + a_1 A_t + a_2 A_t^2\right\}. \tag{13}$$

This assumption captures the asymmetric losses used in Arellano (2008), Chatterjee and Eyigungor (2012), and others. Default is more costly if it occurs when productivity is higher. As a result, the productivity for the economy is

$$\tilde{A}_t = \begin{cases} A_t \text{ if not default,} \\ A_t - \lambda(A_t) \text{ if default.} \end{cases}$$

3.4 Private foreign lenders

International lenders are perfectly competitive and risk-neutral. They can invest funds in a risk-free asset which offers the rate r and the risky bonds issued by the domestic sovereign. The lenders' problem is to choose bonds a every period to maximize expected profits

$$\begin{aligned} &q(B_{t+1}, X_t, A_t, \tau_{e,t})a + \\ &- \frac{1}{1+r}\mathbb{E}\left[(1 - \mathcal{D}(B_{t+1}, X_{t+1}, A_{t+1}, \tau_{e,t})\left(1 + \delta q(\mathcal{B}\left(B_{t+1}, X_{t+1}, A_{t+1}\right), X_{t+1}, A_{t+1}, \tau_{e,t+1}\right)|A_t, \tau_{e,t}\right] a, \end{aligned}$$

where $\mathcal{D}$ and $\mathcal{B}$ represent default and debt policies, respectively. The optimality condition with respect to a gives

$$\begin{aligned} q(B_{t+1}, X_t, A_t, \tau_{e,t}) = \frac{1}{1+r}\mathbb{E}\Big[&(1 - \mathcal{D}(B_{t+1}, X_{t+1}, A_{t+1}, \tau_{e,t+1})) \\ &(\kappa + \delta q\left(\mathcal{B}(B_{t+1}, X_{t+1}, A_{t+1}, \tau_{e,t+1}), X_{t+1}, A_{t+1}, \tau_{e,t+1}\right)) \Big| A_t, \tau_{e,t}\Big]. \end{aligned} \tag{14}$$

If the government does not default, each unit of bond makes service payment κ and a share δ remains outstanding, with market value $\delta q\left(\mathcal{B}\left(B_{t+1}, X_{t+1}, A_{t+1}\right), X_{t+1}, A_{t+1}\right)$. In expectations,

lenders break even in every bond contract offered. The risk-free level of bond price is $\frac{\kappa}{1+r-\delta}$, while the Macaulay duration of bond is $\frac{1+r}{1+r-\delta}$. Thus, we define sovereign spreads as $\frac{\kappa}{q(B_{t+1},X_t,A_t,\tau_{e,t})} - (1+r-\delta)$.

3.5 Recursive equilibrium

In the quantitative analysis, we assume the carbon tax to be exogenous. Firms take the carbon tax $\tau_{e,t}$ as given and optimally choose abatement. The two exogenous state variables are TFP A_t and the carbon tax $\tau_{e,t}$. The endogenous state variables are the outstanding debt level B_t and the aggregate pollution stock X_t. As standard in the sovereign debt models, the benevolent sovereign solves the following optimization problem:

$$V(B_t, X_t, A_t, \tau_{e,t}) = \max_{d\in\{0,1\}} \left\{(1-d)v^{nd}(B_t, X_t, A_t, \tau_{e,t}) + dv^{d}(X_t, A_t, \tau_{e,t})\right\} \tag{15}$$

where $v^{nd}(B_t, X_t, A_t, \tau_{e,t})$ is the value of repaying debt and $v^{d}(X_t, A_t, \tau_{e,t})$ is the value of default. The policy function $\mathcal{D}(B_t, X_t, A_t, \tau_{e.t}) \in \{0, 1\}$ encompasses the government's default decision.

The value of continuing to service external debt is

$$v^{nd}(B_t, X_t, A_t, \tau_{e,t}) = \max_{C_t, L_t, B_{t+1}, \mu_t} \{u(C_t, L_t) + \beta \mathbb{E}\left[V(B_{t+1}, X_{t+1}, A_{t+1}, \tau_{e,t+1}\right]\} \tag{16}$$

$$\text{subject to} \qquad C_t - q_t(B_{t+1}, X_t, A_t, \tau_{e,t})\ell_t + \kappa B_t + \theta_1 \mu_t^{\theta_2} Y_t = Y_t, \tag{17}$$

$$Y_t = \left[1 - d\left(X_t\right)\right] A_t K^{\alpha} L_t^{1-\alpha}, \tag{18}$$

$$B_{t+1} = \delta B_t + \ell_t, \tag{19}$$

$$\tilde{r}_t = \min\{r_t, \bar{r}\}, \ r_t = \frac{\kappa}{q_t(B_{t+1}, X_t, A_t, \tau_{e,t})} - (1 - \delta), \tag{20}$$

$$L_t^{\alpha+\xi} = \frac{(1-\alpha)[1 - \tau_{e,t}(1-\mu_t) - (1+\tilde{r}_t\chi)\theta_1 \mu_t^{\theta_2}]}{\varphi(1+\tilde{r}_t\chi)}[1 - d(X_t)]A_t K^{\alpha}, \tag{21}$$

$$\mu_t = \left(\frac{\tau_{e,t}}{(1+\tilde{r}_t\chi)\theta_1\theta_2}\right)^{1/(\theta_2 - 1)}, \tag{22}$$

$$X_{t+1} = \delta_X X_t + \left(1 - \mu_t\right) Y_t + E_t^{row}. \tag{23}$$

The resource constraint (17) states that when the government does not default, the current output and new borrowings are used to finance debt repayments, households' consumption, and abatement spending.

The value of defaulting is

$$v^d(X_t, A_t, \tau_{e,t}) = \max_{C_t, L_t, \mu_t} \left\{u(C_t, L_t) + \beta(1-\pi)\mathbb{E}v^d(X_{t+1}, A_{t+1}, \tau_{e,t+1}) + \beta\pi\mathbb{E}V(0, X_{t+1}, A_{t+1}, \tau_{e,t+1})\right\} \tag{24}$$

subject to the autarky resource constraint $C_t + \theta_1 \mu^{\theta_2} Y_t = Y_t$, equations (21) (22), (23), with $r_t = \bar{r}$, the production function given by $Y_t = \left[1 - d\left(X_t\right)\right](A_t - \lambda(A_t))K^{\alpha} L_t^{1-\alpha}$ due to the default cost.

Definition of the decentralized recursive equilibrium. A decentralized recursive equilibrium encodes value functions $V(B_t, X_t, A_t, \tau_{e,t}),\ v^{nd}(B_t, X_t, A_t, \tau_{e,t}),\ v^d(X_t, A_t, \tau_{e,t})$; default, bond holdings, consumption, and labor supply policies $\mathcal{D}(B_t, X_t, A_t, \tau_{e,t}), \mathcal{B}(B_t, X_t, A_t, \tau_{e,t}), \mathcal{C}(B_t, X_t, A_t, \tau_{e,t}), \mathcal{L}(B_t, X_t, A_t, \tau_{e,t})$; together with a bond price schedule $q(B_{t+1}, X_t, A_t, \tau_{e,t})$ such that:

(i) The policy functions solve the maximization problems in (16) and (24).

(ii) The value functions V, v^d, and v^{nd} are consistent with (15), (16), and (24).

(iii) Given the sovereign's policies, the bond price schedule $q(B_{t+1}, X_t, A_t, \tau_{e,t})$ is consistent with the arbitrage condition of foreign lenders (14).

4 Quantitative analysis

In this section, we examine the quantitative implications of the baseline model. Using the calibrated framework, we analyze the economy's response to a carbon price shock.

4.1 Calibration

We calibrate the model at a quarterly frequency as reported in Table 1. To this end, we split the parameters into two groups. The first group adopts standard values commonly used in the literature. We calibrate the second group–comprising parameters that control environmental dynamics as well as default cost and duration–to match relevant empirical targets. The discount factor is chosen to match the default frequency. The duration of the long term debt is 40 quarters. The productivity loss parameters are calibrated to match the average debt-to-GDP ratio. Finally, the reentry probability is set to imply an average exclusion period of 3.5 years following default.

The damage function $d(X_t)$ is assumed to be quadratic,

$$d(X_t) = \omega_0 + \omega_1 X_t + \omega_2 X_t^2, \tag{25}$$

In Nordhaus's original DICE model, climate damages are modeled as a quadratic function of temperature, which itself depends on atmospheric CO_2 concentration. Here we make the

Table 1: Calibration

Parameter	Value	Source/Target
γ: Risk aversion	2.00	Standard value
r: Risk-free interest rate	0.01	Standard value
ξ: Labor elasticity of substitution	1/3	Standard value
φ: Labor disutility	1/3	Standard value
α: Capital share in production	0.33	Standard value
ρ, σ: TFP persistence and volatility	0.95, 0.01	Standard values
ρ_{τ_e}, σ_{τ_e}: Carbon tax persistence and volatility	0.872, 0.139	Empirical carbon price dynamics
β: Discount factor	0.981	Default frequency of 2.8%
δ: Decay rate of perpetuity contract	0.98475	Macaulay duration of 40 quarters
a_1, a_2, a_3: Productivity loss	0.0, -0.48, 0.525	Debt/GDP ratio
θ: Reentry probability	0.083	Exclusion of 3.5 years
ω_0, ω_1, ω_2: Damage function parameters	-0.026, 3.661e-5, 1.481e-8	Carattini-Heutel-Melkadze (SS damages=2%)
δ_X: Pollution stock persistence	0.986	IPCC reported CO_2 half-life (50 years)
E_{row}: Emissions from ROW	12.0617	Domestic emissions = 6% of global emissions
θ_1, θ_2: Abatement cost, scale and exponent	0.05607, 2.8	Nordhaus DICE, Heutel (2012)

climate damages depend directly on the stock of atmospheric CO_2 following, for example, Heutel (2012). This approach is more tractable, avoiding modeling the detailed complex dynamics of the climate system. We assign the values $\theta_1 = 0.05607, \theta_2 = 2.8$ for the abatement cost function, based on Nordhaus DICE model.

Our model features two exogenous processes, A_t and $\tau_{e,t}$, each specified as a first-order autoregressive (AR(1)) process,

$$\ln A_t = \rho \ln A_{t-1} + \sigma\varepsilon_t, \quad \varepsilon_t \overset{\text{i.i.d.}}{\sim} \mathcal{N}(0,1),$$
$$\ln \tau_{e,t} = \tau_e + \rho_{\tau_e} \ln \tau_{e,t-1} + \sigma_{\tau_e}\eta_t, \quad \eta_t \overset{\text{i.i.d.}}{\sim} \mathcal{N}(0,1)$$

The parameters ρ and σ are set to standard values from the literature. We estimate an AR(1) for the carbon tax using non-linear least squares to minimize, choosing parameters to minimize the distance between the model-implied path of $\tau_{e,t}$ and the observed carbon price dynamics following a one-standard-deviation shock. The resulting values for ρ_{τ_e} and σ_{τ_e} are 0.872 and 0.139, respectively.

We discretize the shock processes using 15 equally spaced points in logarithms using Tauchen (1986)'s procedure. We approximate the equilibrium dynamics of the model by implementing a value function iteration (VFI) algorithm over a discretized state space. The stock of debt

outstanding (B_t) and pollution stock (X_t) are endogenous states. We use 100 equally spaced points between 0.0 and 1.5 to build the debt grid. To discretize X_t, we use 30 evenly spaced points between 950 and 1000.[6] Following Mihalache (2025), we incorporate extreme value taste shocks in the VFI algorithm, which ensures convergence of both the value function and bond price schedule.[7]

Table 2: Simulated moments

Moment	Value
Defaults per century	2.83
Avg. sovereign spreads	3.91
Avg. debt/GDP	8.33
Sd. sovereign spreads	3.26
Sd. consumption / sd. GDP	0.97
Corr. consumption, GDP	0.99
Corr. spreads, GDP	-0.57

Note. Model-implied moments computed conditional on good financial standing. Average sovereign spreads are expressed in percentage points. Average debt/GDP is expressed as a percentage. Both variables are annualized.

Table 2 reports the simulated moments from the baseline model. The model replicates well the standard macro and sovereign debt dynamics in the data. The average sovereign spreads is 3.9%. The sovereign spreads are countercyclical. The consumption is about as volatile as the GDP.

4.2 Carbon tax, the bond price schedule, and abatement effort

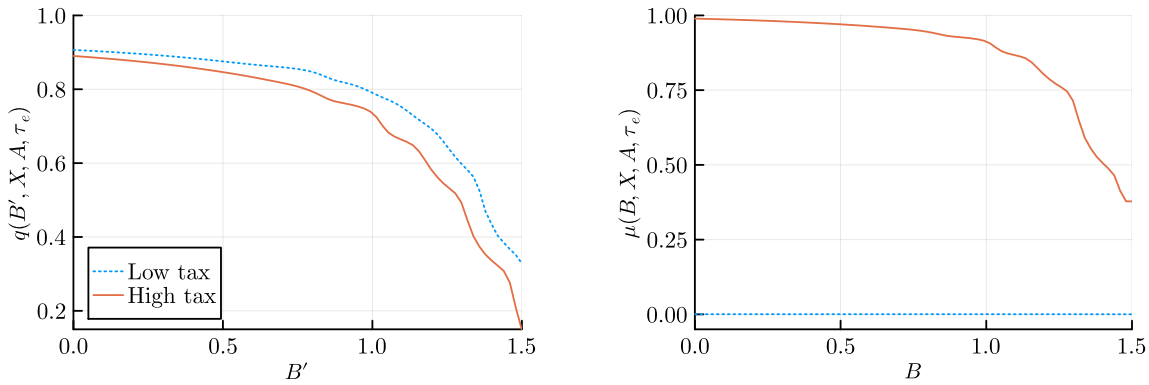
To understand how climate policy affects sovereign risk, we first analyze the equilibrium bond price schedule. The left panel of Figure 3 displays the bond price schedule $q(B', X, A, \tau_e)$ as a function of next period's debt B' for two realizations of the carbon tax: a low level ($\tau_e = 0.32\%$,

6. The intervals ensure to cover the ergodic distribution of debt and pollution stock.

7. Nonconvex budget sets and nonconcavities in the value function are known to pose a challenge for the computation of default risk models with long-term debt, with the bond price function often lacking convergence (Chatterjee and Eyigungor 2012). A detailed description of the computational approach is presented in Appendix B.

or equivalently, 10.08 euros per ton of CO_2) and a high tax level ($\tau_e = 3.12\%$, or equivalently, 98.35 euros per ton of CO_2). The figure illustrates a negative relationship between the stringency of climate policy and the price of debt. The bond price schedule for the high-tax economy (solid orange line) lies strictly below the schedule for the low-tax economy (dashed blue line). This implies that, for any given level of debt issuance, international lenders demand a higher risk premium when the carbon tax is high. This result is consistent with our empirical findings.

Figure 3: Bond Price and Abatement Effort Schedules across Tax Regimes



Note. This plot displays the bond price schedule and expected abatement fraction as functions of debt for low and high levels of carbon tax in the decentralized economy with a stochastic carbon tax and working capital constraint. TFP and pollution stock are fixed at their ergodic means.

The mechanism driving this result is the fiscal tightening induced by the carbon tax. A higher tax forces firms to increase costly abatement efforts. This increase in abatement is illustrated by the right panel of Figure 3. In turn, abatement costs go up, which reduces the resources available for consumption and debt repayment. Consequently, the sovereign's incentive to default increases, leading lenders to price in a higher probability of default.

Importantly, due to the working capital constraint, abatement activity is sensitive to the sovereign's financial position. As Figure 3 illustrates, while abatement is stable at low levels of indebtedness, it begins to decline as debt approaches its highest levels. This downward slope reflects the financial distortion whereby rising interest rates increase the effective cost of abatement. Consequently, when credit conditions deteriorate, firms are forced to scale back green investment to protect their working capital and production levels, suggesting that financial

instability can actively undermine the effectiveness of environmental policy. This mechanism is muted under lower carbon prices, illustrated by the relatively flat abatement profile in the low-tax regime.

4.3 Dynamics around default events

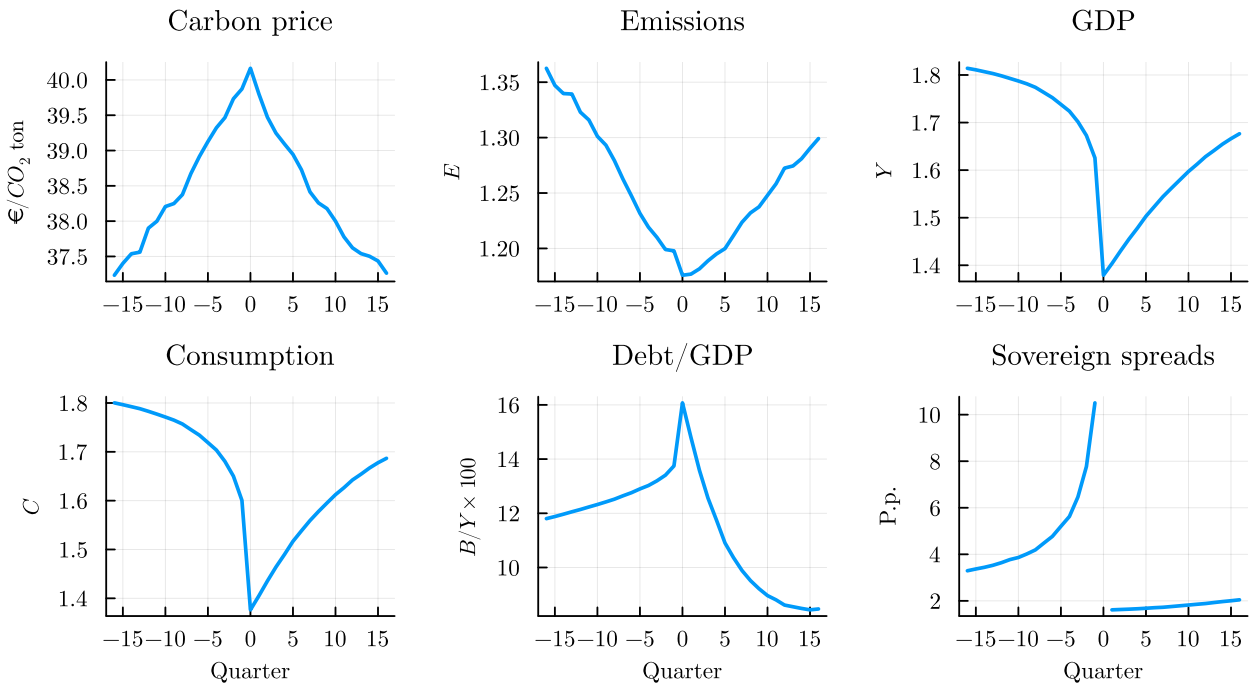
Next, we evaluate the ability of the model to replicate default dynamics. We simulate both the social planner and decentralized equilibria for 1,000,000 quarters and construct a typical default episode. We average the path of each variable over a window spanning 16 quarters before and after a default event. The results for the decentralized economy are displayed in Figure 4. The model successfully reproduces the standard features of sovereign default episodes documented in the literature. In the periods leading up to the default ($t = 0$), the economy experiences sharp contractions in GDP and consumption, as well as a spike in sovereign spreads. The debt-to-GDP ratio rises before the event, driven by both the accumulation of debt and the contraction in output.

Figure 4 also shows the dynamics of environmental variables around the default episodes. During defaults, emissions decline primarily as a result of reduced production. In the model, default episodes tend to coincide with high realizations of the carbon tax; however, the carbon tax itself plays only a minor role in triggering defaults, which are instead largely driven by consecutive negative productivity shocks.

4.4 Dynamics responses to a carbon price shock

We now explore the effects of a positive carbon price shock in the decentralized model with a stochastic carbon tax. To construct the impulse response functions (IRFs), we simulate $1,000,000$ paths over 120 quarters. We initialize each path with values from the ergodic distributions of debt and pollution stock. In period 50, a transitory one-standard-deviation increase

Figure 4: Event Study



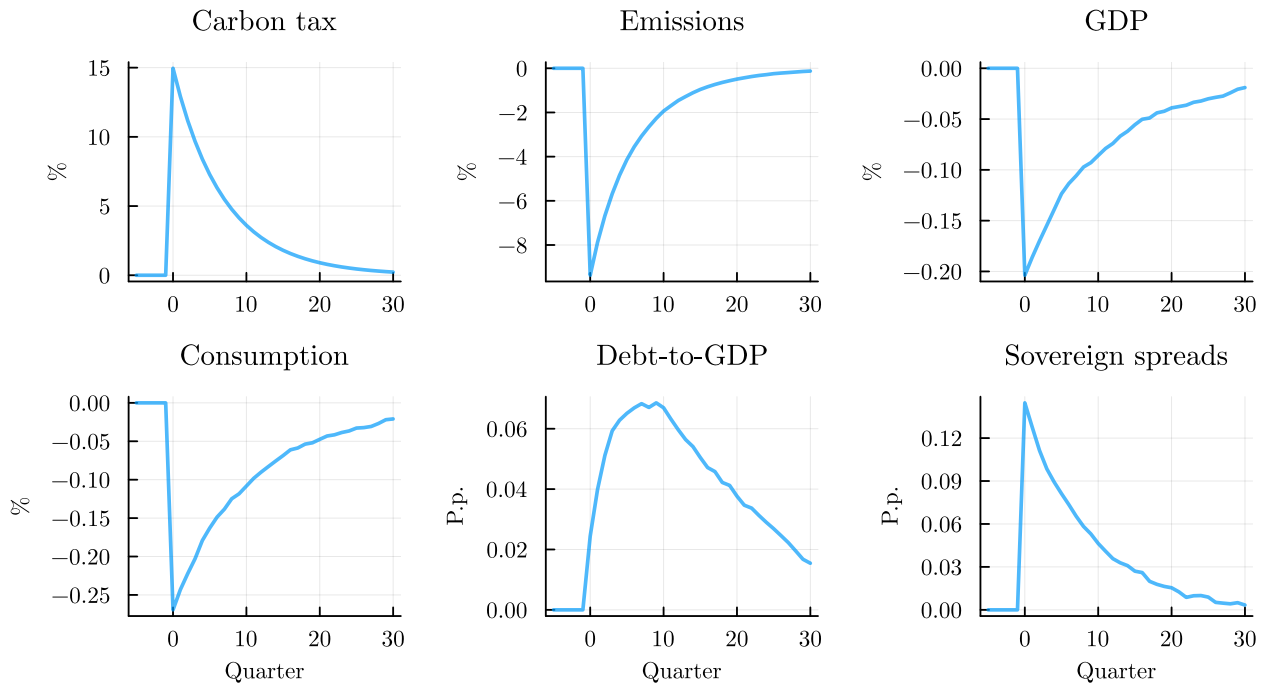
Note. This plot shows the typical behavior of fundamentals around a default in the decentralized economy under a stochastic carbon tax. For each quarter relative to default, we compute the mean across all identified default events. We annualize sovereign spreads and the debt-to-GDP ratio. We report all variables in levels unless noted otherwise.

in carbon tax occurs in all simulations. We report the average across all paths around the occurrence of the shock.

Figure 5 shows the average dynamic response of the economy to a carbon tax shock. The higher carbon tax encourages firms to increase their abatement efforts. As a result, domestic emissions fall, making the policy environmentally effective. However, this reduction in emissions comes at an economic cost. Higher carbon taxes increase production costs, slowing hiring, as the marginal product of labor falls, and reducing overall output as a result. Consumption falls both because of lower production and because resources are diverted toward abatement.

Importantly, the carbon tax shock also affects sovereign debt markets. Sovereign spreads increase by approximately 13 basis points (0.13 p.p.) on impact. In an attempt to smooth consumption in the face of transition risk, the government issues more debt. However, the

Figure 5: Dynamic Responses to a Carbon Tax Increase: Average Effects



Note. This figure plots the average responses to a one-standard-deviation increase in the carbon tax. Units are percent deviations for GDP, consumption, emissions, and the tax itself; and percentage point deviations for ratios (abatement, debt, trade balance) and spreads.

increase in borrowing is limited due to the increase in borrowing costs. Notably, the model successfully matches the peak response of sovereign spreads observed in the empirical impulse responses.

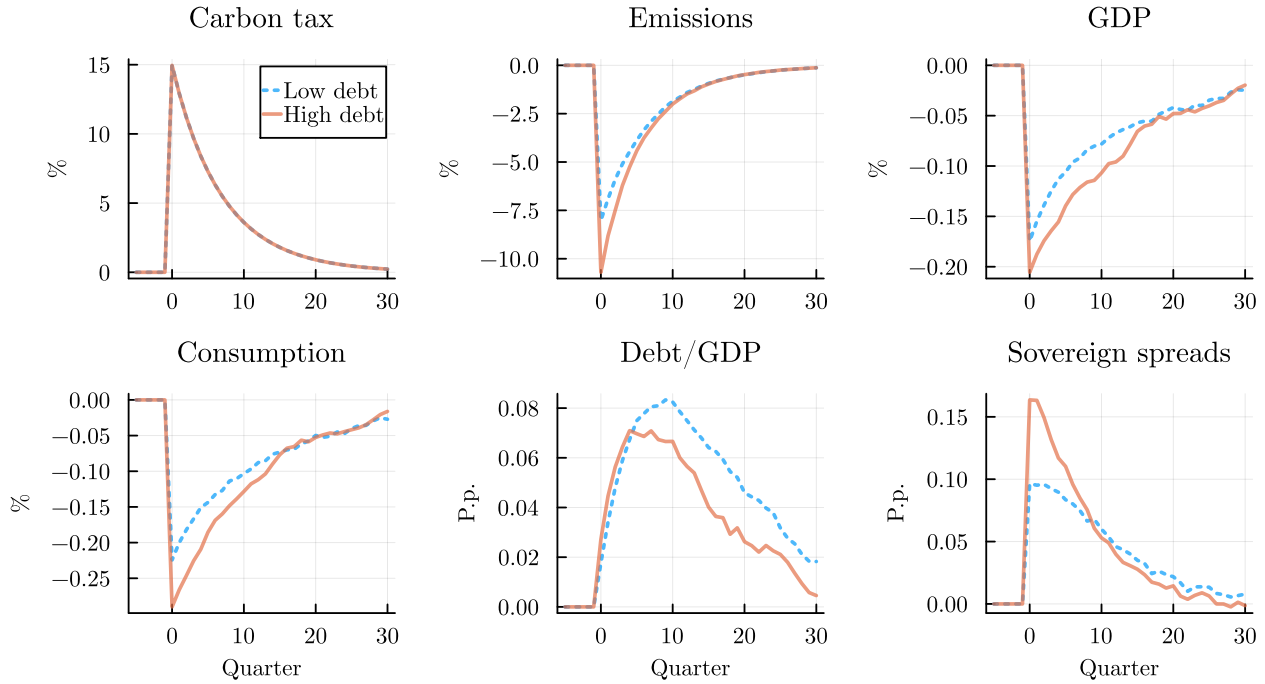
As we show below, higher sovereign spreads propagate to the real economy by raising private borrowing costs on working capital loans, thereby amplifying the initial impact of the shock. Quantifying this mechanism is a central objective of our analysis.

4.4.1 The role of debt

How does the level of debt shape the impact of climate policy on the economy? To answer this question, we examine conditional impulse responses based on the debt-to-GDP ratio in the quarter before the carbon tax shock hits. We split the simulations into two groups: those with

debt-to-GDP above the median (high debt), and those below the median (low debt)–as in our empirical approach.

Figure 6: Dynamic Responses to a Carbon Tax Increase: High and Low Debt Levels



Note. This figure plots the responses to a one-standard-deviation increase in the carbon tax in high- and low-debt simulations. Units are percent deviations for GDP, consumption, emissions, and the tax itself; and percentage point deviations for ratios (abatement, debt, trade balance) and spreads. High (low)-debt simulations are those with debt-to-GDP ratio above (below) the median one period before the carbon tax shock.

Figure 6 presents the results. The orange solid lines represent the responses in the high-debt scenario, while the blue dotted lines correspond to the low-debt scenario. The comparison reveals a substantial amplification effect driven by default risk. On average, the economy experiences a significantly sharper increase in sovereign spreads when its debt-to-GDP ratio is high prior to the shock. This non-linearity arises from the properties of the bond price schedule discussed in the previous section. At high debt levels, the bond price is more sensitive to shocks. As a result, the same climate policy shock pushes high-debt economies closer to default, leading to a sharper increase in borrowing costs. Importantly, the increased default risk also limits the environmental effectiveness of climate policy. Higher sovereign spreads transmit to private

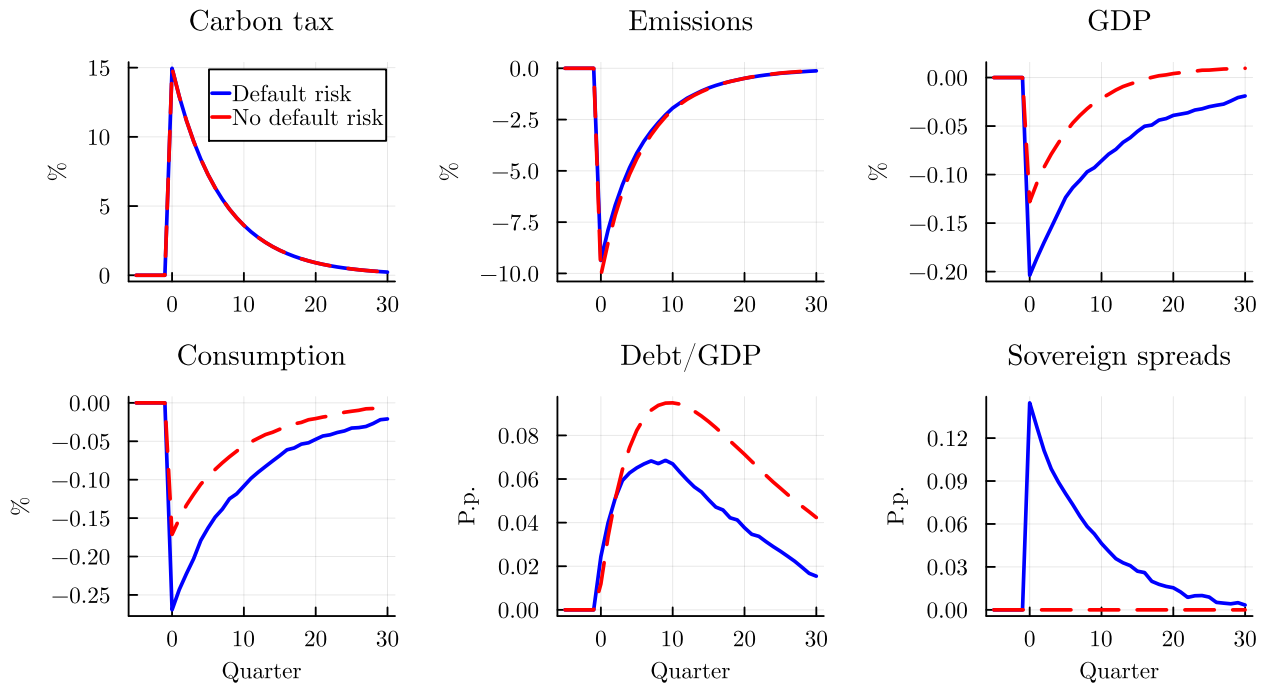
borrowing costs on working capital loans, making it more expensive for firms to abate.

4.4.2 The role of sovereign risk

Finally, we evaluate how the sovereign risk channel exacerbates the macroeconomic impact of a carbon price shock when operating in conjunction with working capital frictions. Figure 7 illustrates the conditional impulse responses to a one-standard-deviation increase in the carbon tax. The solid blue line depicts the economy with both endogenous sovereign risk and working capital constraints, while the dashed red line represents the economy subject to working capital frictions but devoid of default risk. The carbon price shock precipitates a contraction in GDP and consumption, while simultaneously driving an increase in the abatement fraction. However, the presence of endogenous sovereign risk introduces a significant amplification effect. In the model with endogenous sovereign default risk, the increase in sovereign debt is markedly higher as the government attempts to navigate the added financing requirements imposed by the working capital constraint. The rise in sovereign spreads triggered by the carbon price shock further depresses consumption relative to the risk-free benchmark. These dynamics demonstrate that the short-term economic costs of the green transition are substantially magnified by the interaction between financial frictions and sovereign default risk.

Figure 7 demonstrates the role of sovereign risk by comparing the baseline economy to a counterfactual model where sovereign default risk is absent. Crucially, the figure emphasizes that the drop in GDP is significantly smaller in the no-default model (dashed red line) than in the baseline economy (solid blue line). While both scenarios achieve nearly identical reductions in domestic emissions and similar abatement efforts, the economy without default risk avoids the sharp spike in sovereign spreads. This access to risk-free borrowing allows the government to smooth the transition more effectively, thereby cushioning the decline in output. The responses of consumption are similar in the two cases because of the different response in debt upon the carbon tax increase.

Figure 7: Dynamic Responses to a Carbon Tax Increase: The Role of Default Risk



Note. This figure plots the average responses to a one-standard-deviation increase in the carbon tax in two models: (i) the baseline model with endogenous sovereign risk, (i) a small open economy model subject to a working capital constraint and portfolio adjustment cost without default risk. Units are percent deviations for GDP, consumption, emissions, and the tax itself; and percentage point deviations for ratios (abatement, debt, trade balance) and spreads.

5 Conclusions

This paper studies the impact of climate policy shock through the sovereign-risk channel. Empirical evidence from the European Union's Emissions Trading System (EU-ETS) shows that a tightening of climate policy increases sovereign spreads and reduces industrial production, with these effects being significantly more pronounced in countries with high initial debt-to-GDP ratios. We reconcile these findings through a quantitative model illustrating that while carbon pricing provides long-run productivity gains by mitigating climate damage, the immediate costs of emissions abatement divert resources away from consumption and debt service. In the short run, this economic cost increases the government's incentive to default, driving up risk premiums and creating a "transition risk" that is amplified by pre-existing debt burdens.

The quantitative analysis further reveals that endogenous sovereign risk can amplify the impact of climate transition risk, as the lack of access to risk-free borrowing prevents governments from effectively smoothing the transition. Our extension to working capital constraints demonstrates a detrimental feedback loop: as sovereign borrowing costs rise, the effective cost of abatement increases, potentially forcing firms to scale back abatement efforts to maintain production levels. These results suggest that financial risk can actively undermine the effectiveness of environmental policy. To prevent financial distress from derailing climate goals, our findings underscore the importance of incorporating sovereign risk into climate frameworks and suggest a role for international official lending to alleviate transition risk in fiscally constrained economies.

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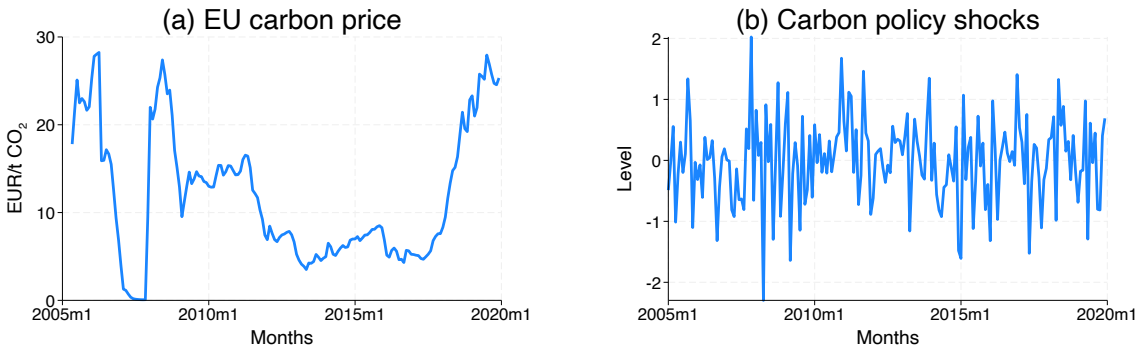
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Additional Figures and Tables

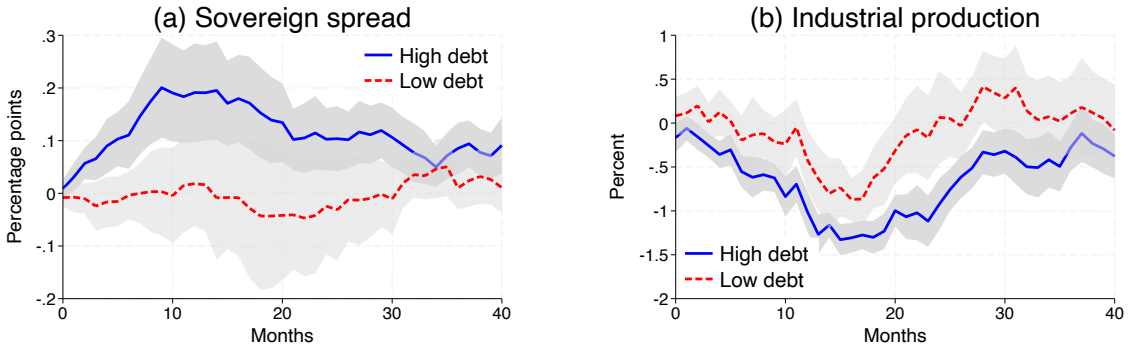
A Empirical evidence: Data and Robustness

Figure A.1: EU carbon price and carbon policy shocks



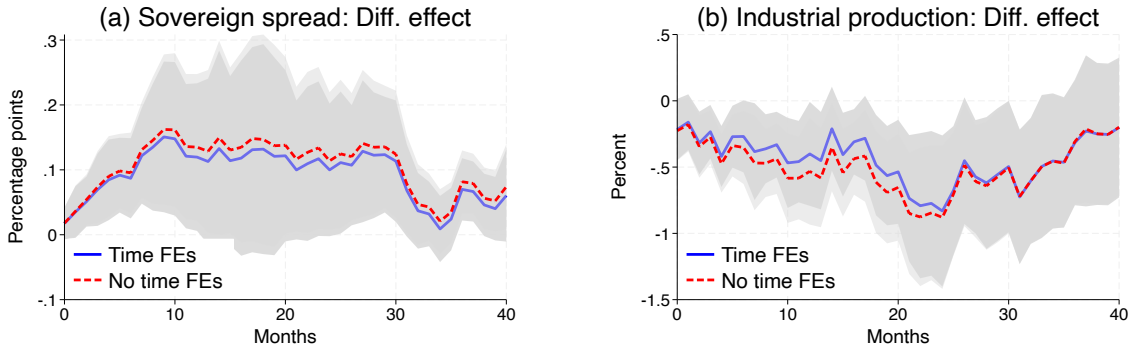
Note: The figure plots the EU carbon price, measured as the price of the EU emissions allowance (EUA) futures contract, and the carbon policy shocks constructed by Känzig (2025).

Figure A.2: Dynamic Responses to a Carbon Policy Shock: High- vs Low-Debt Countries. Controlling for Emissions Intensity



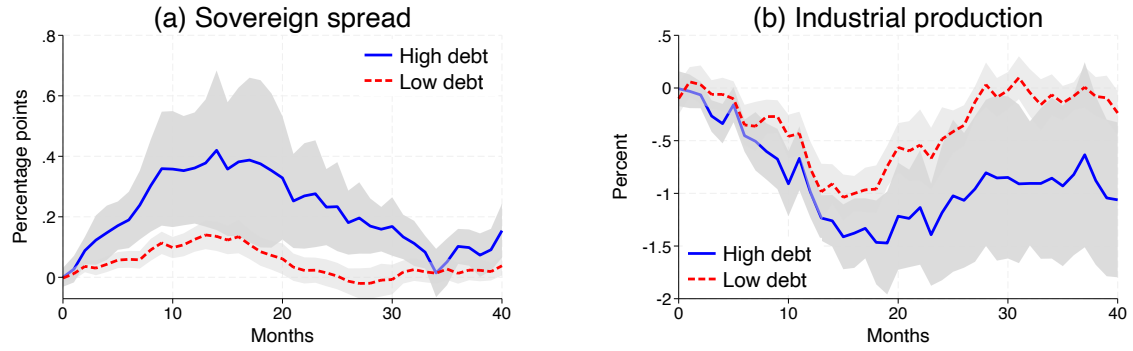
Notes: The figure plots the impulse responses of sovereign spreads and industrial production to a carbon policy shock in countries with high and low sovereign debt-to-GDP ratios, controlling for country-level emissions intensity dummy interacted with the carbon policy shock. High-debt countries are defined as countries with the average sovereign debt-to-GDP ratio above the median in the sample. High-emissions intensity countries are defined as those with the average intensity above the sample median. Shaded areas report 90% confidence bands. Robust standard errors are clustered at the country level.

Figure A.3: Dynamic Responses to a Carbon Policy Shock: High- relative to Low-Debt Countries. Controlling for Time Fixed Effects



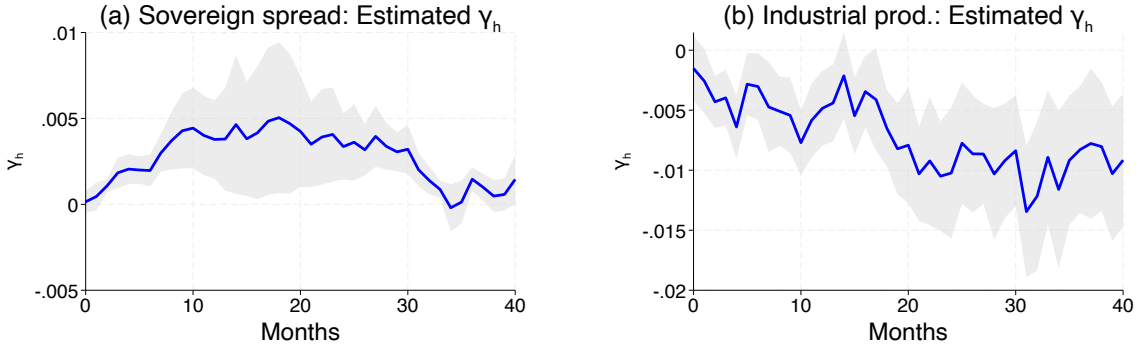
Notes: The figure reports the differential responses of sovereign spread and industrial production to a carbon policy shock in high- relative to low-debt countries, estimated with and without time fixed effects. High-debt countries are defined as countries with the average sovereign debt-to-GDP ratios above the sample median. Shaded areas report 90% confidence bands. Robust standard errors are clustered at the country level.

Figure A.4: Dynamic Responses to a Carbon Policy Shock: High- vs Low-Debt Countries. Alternative Definition of High-Debt Dummy



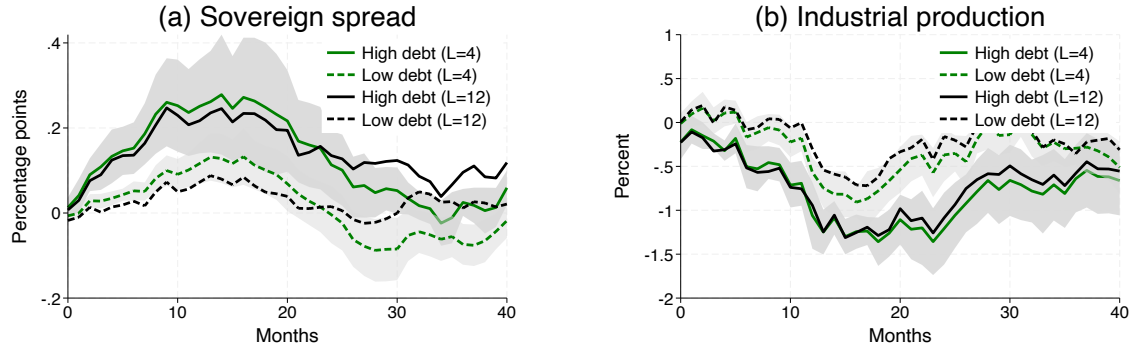
Notes: The figure compares the impulse responses of sovereign spreads and industrial production to a restrictive, unit carbon policy shock in high- and low-debt countries. High-debt countries are defined as those with average sovereign debt-to-GDP ratios above the 75th percentile. Shaded areas report 90% confidence bands. Robust standard errors are clustered at the country level.

Figure A.5: Dynamic Responses of Sovereign to a Carbon Policy Shock: Continuous Measure of Average Debt-to-GDP Ratio



Notes: The figure plots estimates of coefficient γ_h for sovereign spreads (Panel (a)) and industrial production (Panel (b)) in the following local projections: $y_{i,t+h} = \alpha_{i,h} + \gamma_h Debt\text{-}to\text{-}GDP_i \times CPShock_t + \sum_{l=1}^{L} B_{h,l} X_{i,t-l} + \delta_{t,h} + \varepsilon_{i,t+h}$, where $Debt\text{-}to\text{-}GDP_i$ denotes average government debt-to-GDP ratio (measured in %) for country i, and $\delta_{t,h}$ is time FEs. Shaded areas report 90% confidence bands. Robust standard errors are clustered at the country level.

Figure A.6: Dynamic Responses to a Carbon Policy Shock: High- vs Low-Debt Countries. Alternative Lag Lengths



Notes: The figure compares the impulse responses of sovereign spreads and industrial production to a restrictive, unit carbon policy shock in high- and low-debt countries under different lag length L in equation (2). High-debt countries are defined as those with average sovereign debt-to-GDP ratios above the sample median. Shaded areas report 90% confidence bands. Robust standard errors are clustered at the country level.

B Solution algorithm

This section closely follows Mihalache (2025).

1. **Initialization**

   (a) Fix parameter values and functional forms for $u(C, L)$, $\lambda(A)$, and $d(X)$.

   (b) Construct grids for the states A, X, B, τ_e, and the transition matrices for the TFP shock A and the carbon tax τ_e.

   (c) Set initial guesses:

$$\begin{aligned} q(B', X, A, \tau_e) &= \frac{\kappa}{1 + r - \delta} \\ v_0^{nd}(B, X, A, \tau_e) &= \frac{u(Y(X, A) - B),\ L(X, A))}{1 - \beta} \\ v_0^{d}(X, A, \tau_e) &= \frac{u\left(Y(X, A - h(A)),\ L(X, A - h(A))\right.}{1 - \beta} \end{aligned}$$

2. **Update**

   (a) Use v_0 and v_0^{nd} to construct v_1^d, subject to the respective constraints:

$$v^d(X, A, \tau_e) = \max_{C,L} \left\{ u(C, L) + \beta(1 - \pi)\mathbb{E}_{A', \tau_e' | A, \tau_e} v^d(X', A', \tau_e') + \beta\pi\mathbb{E}_{A', \tau_e' | A, \tau_e} V(0, X', A', \tau_e') \right\}$$

   (b) Use q_0 and v_0 to construct the net-of-taste-shocks value of choosing B', i.e., the auxiliary function w:

$$w(B, X, A, B', \mu) \equiv u(C, L) + \beta\mathbb{E}_{A', \tau_e' | A, \tau_e} v(B', X', A', \tau_e')$$

   subject to the corresponding constraints.

   (c) Construct v_1^{nd} and choice probabilities $\Pr(B' = b_i | A, X, B, \tau_e)$ using the following

equations:

$$\Pr(B' = b_i|A, X, B, \tau_e) = \frac{\exp\left(\frac{w(B,X,A,\tau_e,b_i)-\overline{w}(B,X,A,\tau_e)}{\rho}\right)}{\sum_j \exp\left(\frac{w(B,X,A,\tau_e,b_j)-\overline{w}(B,X,A,\tau_e)}{\rho}\right)}$$

$$v^{nd}(B, X, A, \tau_e) = \overline{w}(B, X, A, \tau_e) + \rho \log\left[\sum_j \exp\left(\frac{w(B, X, A, \tau_e, b_j) - \overline{w}(B, X, A, \tau_e)}{\rho}\right)\right]$$

$$\overline{w}(B, X, A, \tau_e) \equiv \max_{B'} w(B, X, A, \tau_e, B')$$

(d) Use v_1^{nd} and v_1^d to construct v_1 and $\Pr(d = 1|B, X, A)$ using the following equations

$$\Pr(d = 1|B, X, A, \tau_e) = \frac{\exp\left(\frac{v^d(X,A)-\overline{v}(B,X,A,\tau_e)}{\eta}\right)}{\exp\left(\frac{v^d(X,A,\tau_e)-\overline{v}(B,X,A,\tau_e)}{\eta}\right) + \exp\left(\frac{v^{nd}(B,X,A,\tau_e)-\overline{v}(B,X,A,\tau_e)}{\eta}\right)}$$

$$v(B, X, A, \tau_e) = \overline{v}(B, X, A, \tau_e) + \eta \log\left[\exp\left(\frac{v^d(X, A, \tau_e) - \overline{v}(B, X, A, \tau_e)}{\eta}\right) + \cdots\right.$$
$$\left.\cdots + \exp\left(\frac{v^{nd}(B, X, A, \tau_e) - \overline{v}(B, X, A, \tau_e)}{\eta}\right)\right]$$

$$\overline{v}(B, X, A, \tau_e) \equiv \max\{v^d(X, A, \tau_e), v^{nd}(B, X, A, \tau_e)\}$$

(e) Use borrowing $\Pr(B' = b_i|B, X, A, \tau_e)$ and default $\Pr(d = 1|B, X, A, \tau_e)$ choice probabilities, together with q_0, to obtain q_1 using the equation:

$$q(B', X, A, \tau_e) = \frac{1}{1+r}\mathbb{E}_{A',\tau_e'|A,\tau_e}(1 - \Pr(d' = 1|B', X', A', \tau_e)) \cdots$$
$$\cdots \left[1 + \delta \sum_j \Pr(B'' = b_j|B', X', A', \tau_e')q(b_j, X', A', \tau_e')\right]$$

3. **Convergence check**. If $||v_1 - v_0||$, $||v_1^d - v_0^d||$, $||q_1 - q_0||$ are below the convergence threshold, stop. Otherwise, update these objects and return to step 2.