Energy and Climate Management, 2026, 2(3): 9400038
https://doi.org/10.26599/ECM.2026.9400038

Article

Synergistic impact of structural macroprudential policies on climate transition risks

Shanhua Zhang[1,2], Hao Jin[1,2], Ying Fan[1,2,✉]

[1]*School of Economics and Management, Beihang University, Beijing 100191, China*
[2]*MOE Laboratory for Low-carbon Intelligent Governance(LLIG), Beihang University, Beijing 100191, China*

Received: 27 March 2026; Revised: 18 May 2026; Accepted: 2 July 2026

ABSTRACT

Central banks of all countries are paying attention to how they can achieve the temperature control goal of the Paris Agreement through climate governance policies while alleviating the climate transition risks arising from such policies. The “dual carbon” goals (carbon peaking by 2030 and carbon neutrality by 2060) proposed by China have set higher requirements for current climate policies and may necessitate more ambitious measures; however, the transition risks associated with these goals cannot be overlooked. This paper constructs an environmental dynamic stochastic general equilibrium (E-DSGE) model incorporating pollution externalities, financial frictions in the banking sector and the differentiated capital adequacy ratio (CAR) requirement policy to evaluate the impact of carbon tax policies on the macroeconomy and financial stability—the so-called “transition risks”. It also discusses the effectiveness of the differentiated CAR requirement policy in mitigating such risks. The findings are as follows: (1) carbon tax policies have a significant effect on emission reduction and promote green transformation, but they cause a significant shock on banks’ net assets, threatening financial stability and generating transition risks; (2) financial frictions, by restricting banks’ loanable funds, affect capital inputs in the production sector, affect capital goods prices and increase losses in banks’ net assets, thereby amplifying transition risks; and (3) carbon tax policies combined with the differentiated CAR requirement policy can not only achieve emission reduction targets but also mitigate the transition risks caused by carbon taxes by reducing banks’ risk exposure.

KEYWORDS

Climate transition risk, macroprudential policy, carbon pricing, financial stability, environmental dynamic stochastic general equilibrium (E-DSGE) model, climate policy coordination.

1 Introduction

To achieve the goal of limiting the global temperature increase to no more than 1.5 degrees Celsius, as envisioned in the Paris Agreement, countries worldwide are actively promoting actions to reduce their carbon emissions. China is also actively taking on the responsibility of reducing its emissions. At the United Nations General Assembly in September 2020, the Chinese government declared China’s commitment to achieve peak carbon dioxide emissions by 2030 and carbon “neutralisation” by 2060. To achieve these goals, China will likely need ambitious and expeditious climate policy actions, which may significantly impact China’s financial system. Specifically, financial institutions may incur substantial losses from their investments in high-carbon industries, which we refer to as transition risk. This risk was first proposed by Carney as follows: a significant shift in climate policies towards Paris Agreement targets could leave financial institutions holding an excess of high-risk assets, which may trigger an economic recession.

To mitigate transition risks, China can adopt certain economic and financial policy measures. Drawing on current international practices, macroprudential regulatory policies are a common tool for addressing climate transition risks, typically by encouraging financial institutions to reduce their exposure to such risks in advance. Macroprudential policies, as a category of macroeconomic regulation tools, focus on safeguarding the overall stability of the financial system and preventing systemic risks. These policies ensure the robust operation of the financial system through a series of measures, such as capital adequacy ratio (CAR) requirements, liquidity management and credit policy adjustments. Given China’s specific context, a deep understanding of the impact of climate policies on the economic and financial system, as well as the coordination between climate policies and different macroprudential policies, is of great significance for safely achieving the country’s “dual carbon” goals. This study aims to answer the following research questions (RQs):

RQ1: Which macroprudential policies should be employed to address transition risks?

RQ2: How do different degrees of climate policies (represented in this study by carbon tax policies) affect the intensity and effectiveness of macroprudential policies?

RQ3: How effective are macroprudential policies when financial frictions exist in the market?

This paper constructs an environmental dynamic stochastic general equilibrium model (E-DSGE) that encompasses the household sector, green and brown firms, the financial sector and the general government. Based on this framework, this paper first discusses the climate transition risks that may arise from the rapid implementation of carbon tax policies and evaluates whether macroprudential policies with differentiated CAR requirements can mitigate such risks. Our preference for a differentiated CAR policy stems from three advantages: (1) it maintains a constant

✉Address correspondence to yfan1123@buaa.edu.cn

aggregate CAR without disrupting macroeconomic liquidity; (2) it directly adjusts risk asset weights across the entire credit market, better capturing the credit-loss essence of transition risks; and (3) it is well-suited to address structural and long-term risks. Second, a "financial friction" mechanism is introduced, which restricts the asset size of financial institutions, leading to a contraction in market liquidity, threatening financial stability and spilling over to the real economy. Within this mechanism, the policy of structural differentiated CAR requirements is assessed. Specifically, the mitigation effect of this policy on climate transition risks is evaluated while controlling for macro risks related to CAR requirements.

2 Literature review

With the successful convening of the 29th Conference of the Parties to the United Nations Framework Convention on Climate Change, climate change issues have garnered greater attention from countries worldwide, and discussions on climate policies have become increasingly frequent. Judging from the policy practices of various countries, two common policies today to reduce carbon emissions are imposing taxes on emissions and establishing market-based carbon pricing through carbon markets. The primary climate policy for addressing climate change is incorporating the negative externalities of carbon emissions into the carbon price. Relevant studies on such policies are mainly conducted based on the real business cycle (RBC) framework, including carbon taxes, carbon markets and carbon emission intensity restrictions. Fischer and Springborn[1] explored the impacts of three climate policies—carbon taxes, carbon emission caps and carbon emission intensity regulations—on the macroeconomy and found that the last results in lower macroeconomic fluctuations and smaller welfare costs than the first two. Golosov et al.[2] studied the optimal tax rate for fossil fuels. Dissou and Karnizova[3] compared the effectiveness of carbon taxes with that of emission caps as policies for reducing emissions.

Regarding transition risks, Van der Ploeg and Rezai[4] and Rozenberg et al.[5] found that unexpected changes in climate policies may lead to the stranding of carbon-intensive capital, which is referred to as *transition risk*. To mitigate transition risks, relevant literature has discussed some climate finance policies. Chen et al.[6] discovered that green relending policies can help guide industrial structural transformation, stimulate output and investment, and be less likely to trigger significant transition risks. Wang et al.[7] argued that policies reducing the targeted green reserve requirement ratio can not only increase green credit volumes and promote a more sustainable economic structure but also avoid significant negative impacts on total output and employment, leading to a win–win outcome for both the economy and the environment. Studies on macroprudential policies to mitigate transition risks are more extensive. Campiglio[8] and Böser and Colesanti Senni[9] analysed the roles of central banks and macroprudential authorities in addressing climate change. Dafermos and Nikolaidi[10] explored the impacts of differentiated CAR policy and climate policies on physical risks and bank default rates using theoretical models. Diluiso et al.[11] discussed the policy effects of green quantitative easing and CAR policy. However, this paper does not keep the total CAR remain the same. Carattini et al.[12] found that adopting macroprudential policies (i.e., subsidising banks' green assets and taxing brown assets) reduce transition risks. Grill et al.[13] discovered that climate risks can be addressed more effectively by combining microprudential and macroprudential policies. However, their parameters are calibrated by using U.S. macroeconomic data, the model has limited explanatory power for China's economy.

There is another branch of literature related to this paper that discusses the impact of financial frictions on the macroeconomy. Financial frictions were first proposed by Bernanke and Gertler[14] and refined by Kiyotaki and Moore[15], who argued that frictions in credit markets and banking sector turmoil are important sources of macroeconomic fluctuations. Gertler and Kiyotaki[16] and Gertler and Karadi[17] discussed DSGE models incorporating the banking sector, addressing the role of financial frictions in driving macroeconomic dynamics. On the other hand, Carattini et al.[12] linked financial frictions to transition risks and found that financial frictions can amplify these risks.

Unlike previous studies, this paper adopts a differentiated CAR policy that adjust the CAR weights of green and brown capital differently while keeping the total CAR unchanged. In addition, by calibrating model parameters using China's macroeconomic data, our study provides a targeted investigation into the mitigating effect of differentiated capital adequacy ratio policies on transition risks in the Chinese context. This paper evaluates the impact of climate policy (represented by carbon tax policy) on the macroeconomy and the transition risks they pose. Then, the mitigating effect of differentiated CAR requirements policy on transition risks is discussed using an E-DSGE model that considers environmental externalities and financial frictions. Finally, the amplifying effect of financial frictions on transition risks is assessed.

3 Theoretical model

This paper constructs an E-DSGE model that integrates environmental externalities, financial frictions in the banking sector and differentiated CAR requirements policy targeting banks. The study builds directly on the frameworks of Carattini et al.[12] and Chen et al.[6], extending their approaches by incorporating differentiated CAR requirements as a macroprudential instrument to distinguish between green and brown assets, thereby incentivising banks to transition early towards green finance while reducing their exposure to climate policy shocks. The model's quantitative implications for mitigating climate transition risks are assessed through numerical simulations. The theoretical framework encompasses five sectors: households, which supply labour and optimise their intertemporal utility by making consumption-saving decisions; financial intermediaries, which allocate household savings as capital to firms while optimising their loan portfolios to maximise net present value; production firms (including both green and brown producers), which maximise their profits through input decisions, with brown firms additionally determining optimal emission reduction levels; capital producers, which ensure capital market clearing; and the government, which implements fiscal policy through tax-transfer mechanisms. The model's structural equations and optimisation conditions for each sector are formally derived in subsequent sections.

3.1 Household sector

The household sector consists of workers and bankers. Workers supply labour to both the brown and green production sectors and remit their wages to their households. Households allocate their resources between consumption and savings through financial intermediaries (i.e., banks), as direct lending to productive firms is not permitted. Bankers manage financial intermediaries and distribute dividends to households.

The household sector maximises its utility function by choosing labour supply L_t^{b}, L_t^{g} to the brown and green sectors, as well as consumption C_t and savings D_t.

$$E_0\left\{\sum_{t=0}^{\infty}\frac{\beta^t}{1-\eta}\left(C_t-\varpi\left(\frac{\left(L_t^{\mathrm{b}}\right)^{1+\rho_{\mathrm{L}}}+\left(L_t^{\mathrm{g}}\right)^{1+\rho_{\mathrm{L}}}}{1+\xi}\right)^{\frac{1+\xi}{1+\rho_{\mathrm{L}}}}\right)^{1-\eta}\right\} \tag{1}$$

where ϖ represents the disutility of labor parameter; ρ_{L}, the elasticity of substitution between labour hours allocated to the brown and green production sectors; and ξ, the inverse of the Frisch labour supply elasticity.

The household sector faces the following budget constraint:

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

where w_t^{b} and w_t^{g} represent wage levels in the brown and green sectors, respectively; R_{t-1}, the return rate on bank deposits; Ξ_t, dividend income received from bankers; Π_t, profits obtained from production sectors; and T_t, transfer payments received from the government.

The first-order conditions for the household sector's labour and consumption and labour decisions are given by

$$E_t\left(\beta\frac{U_{c,t+1}}{U_{c,t}}R_t\right)=1 \tag{3}$$

$$\varpi L_t^{\varepsilon-\rho_{\mathrm{L}}}\left(L_t^i\right)^{\rho_{\mathrm{L}}}=w_t^i,\quad i=\{\mathrm{g},\mathrm{b}\} \tag{4}$$

where, $U_{c,t}=\left\{C_t-\varpi\left[\frac{\left(L_t^{\mathrm{b}}\right)^{1+\rho_{\mathrm{L}}}+\left(L_t^{\mathrm{g}}\right)^{1+\rho_{\mathrm{L}}}}{1+\xi}\right]^{\frac{1+\xi}{1+\rho_{\mathrm{L}}}}\right\}^{-\eta}$ represents the marginal utility of consumption in period t.

3.2 Financial sector

Banks provide loans to the production sector using their own funds and savings collected from households. Their net worth accumulates $N_{j,t+1}$ based on their loan returns, minus the costs associated with managing savings.

$$N_{j,t+1}=R_{k,t+1}^{\mathrm{b}}Q_t^{\mathrm{b}}S_{j,t}^{\mathrm{b}}+R_{k,t+1}^{\mathrm{g}}Q_t^{\mathrm{g}}S_{j,t}^{\mathrm{g}}-R_tD_{j,t} \tag{5}$$

Without loss of generality, we assume that banks invest in the production sector by purchasing securities issued by firms. Let $R_{k,t+1}^{\mathrm{g}}$ be the return on investment in the green production sector; Q_t^{g}, the price of securities in the sector; and $S_{j,t}^{\mathrm{g}}$, the quantity of securities in the sector. The same applies to the brown production sector. Meanwhile, banks incur a small amount of adjustment costs in their portfolio structure. Hence, banks' balance sheets are as Eq. (6):

$$D_{j,t}=Q_t^{\mathrm{b}}S_t^{\mathrm{b}}+Q_t^{\mathrm{g}}S_t^{\mathrm{g}}-\frac{\psi}{2}\left(\frac{Q_t^{\mathrm{g}}S_t^{\mathrm{g}}}{Q_t^{\mathrm{b}}S_t^{\mathrm{b}}+Q_t^{\mathrm{g}}S_t^{\mathrm{g}}}-\bar{s}^{\mathrm{g}}\right)^2-N_{j,t} \tag{6}$$

Among them, $\frac{\psi}{2}\left(\frac{Q_t^{\mathrm{g}}S_t^{\mathrm{g}}}{Q_t^{\mathrm{b}}S_t^{\mathrm{b}}+Q_t^{\mathrm{g}}S_t^{\mathrm{g}}}-\bar{s}^{\mathrm{g}}\right)^2 Q_t^{\mathrm{b}}S_t^{\mathrm{b}}+Q_t^{\mathrm{g}}S_t^{\mathrm{g}}$ represents the cost of structural adjustment, $\bar{s}^{\mathrm{g}}$ represents the portfolio share of green assets in the steady state. By incorporating it into the net asset accumulation equation, we obtain

$$\begin{aligned}N_{j,t+1}&=R_{k,t+1}^{\mathrm{b}}Q_t^{\mathrm{b}}S_{j,t}^{\mathrm{b}}+R_{k,t+1}^{\mathrm{g}}Q_t^{\mathrm{g}}S_{j,t}^{\mathrm{g}}\\&\quad-R_t\left[Q_t^{\mathrm{b}}S_t^{\mathrm{b}}+Q_t^{\mathrm{g}}S_t^{\mathrm{g}}-\frac{\psi}{2}\left(\frac{Q_t^{\mathrm{g}}S_t^{\mathrm{g}}}{Q_t^{\mathrm{b}}S_t^{\mathrm{b}}+Q_t^{\mathrm{g}}S_t^{\mathrm{g}}}-\bar{s}^{\mathrm{g}}\right)^2-N_{j,t}\right]\end{aligned} \tag{7}$$

To control transformation risks while reducing emissions, this paper introduces a differentiated CAR requirements policy within the banking sector. The policy lowers CAR requirements for green assets and raises them for brown assets, ensuring that the total CAR remains constant to maintain macrofinancial stability. This policy is manifested in the following constraints:

$$N_{j,t}\geqslant 0.08\times\left(cr^{\mathrm{g}}Q_t^{\mathrm{g}}S_{j,t}^{\mathrm{g}}+cr^{\mathrm{b}}Q_t^{\mathrm{b}}S_{j,t}^{\mathrm{b}}\right) \tag{8}$$

where cr^{g} and cr^{b} represent the CAR requirements coefficients for green and brown assets, respectively, both of which are 1 in the absence of policy. When the differentiated CAR requirements policy is implemented, cr^{g} is reduced. To ensure that the total CAR remains unchanged in the steady state, and given that the proportion of green assets in the banking sector is 30% in the steady state, the following condition is satisfied:

$$cr^{\mathrm{b}}=\frac{1-0.3cr^{\mathrm{g}}}{0.7} \tag{9}$$

To incorporate endogenous financial risk, this paper builds on the framework of Gertler and Karadi[17] and introduces a financial friction driven by moral hazard. Specifically, this financial friction arises when bankers embezzle a proportion κ of their bank's assets in each period. However, if the assets are embezzled, depositors will detect it and force the bank into bankruptcy liquidation, eventually recovering a proportion $1-\kappa$ of their assets. Therefore, to mitigate the moral hazard of bankers, banks must satisfy the following incentive compatibility constraint:

$$V_{j,t}\geqslant\kappa\times\left(Q_t^{\mathrm{g}}S_{j,t}^{\mathrm{g}}+Q_t^{\mathrm{b}}S_{j,t}^{\mathrm{b}}\right) \tag{10}$$

where $V_{j,t}$ represents the continuation value of bank j in period t, that is, the present value of the bank's expected returns from maintaining its normal operations. This constraint ensures that the continuation value of the bank is greater than the value of its assets that can be embezzled in the current period. Financial frictions limit the scale of credit supply in the banking sector. A decline in asset prices leads to a deterioration in the balance sheet of banks, a contraction in credit supply and, subsequently, financial risks and economic recession.

Consistent with the assumption in most financial friction literature, this paper assumes that bankers exit the financial market and become workers with a probability of $1-\gamma$ in each period, preventing banks from operating entirely with their own funds. Simultaneously, an equal number of new bankers enter the market, keeping the total number of commercial banks constant. The new entrant bankers receive a share of $\zeta/(1-\gamma)$ of the total household assets as their initial net worth. Therefore, the optimisation problem faced by bank j is to choose its asset portfolio to maximise the lifetime discounted value of its net worth, subject to the differentiated CAR requirements constraints and the incentive compatibility constraints.

$$V_{j,t}=\max_{\left\{Q_t^{\mathrm{g}}S_{j,t}^{\mathrm{g}},Q_t^{\mathrm{b}}S_{j,t}^{\mathrm{b}}\right\}}E_t\times(1-\gamma)\beta\frac{U_{c,t+1}}{U_{c,t}}N_{j,t+1}+\gamma\beta\frac{U_{c,t+1}}{U_{c,t}}V_{j,t+1} \tag{11}$$

The first-order conditions of the banking sector are relatively complex and require the use of the guess-and-verify method to assume the following:

$$V_{j,t}=\varphi_t N_{j,t} \tag{12}$$

The credit spreads for the green and brown production sectors, along with the discount cost that banks incur to attract deposits, are defined as follows:

$$\chi_t^{\mathrm{b}} \equiv E_t\left[\Omega_{t+1}\left(R_{k,t+1}^{\mathrm{b}}-R_t\right)\right] \tag{13}$$

$$\chi_t^{\mathrm{g}} \equiv E_t\left[\Omega_{t+1}\left(R_{k,t+1}^{\mathrm{g}}-R_{k,t+1}^{\mathrm{b}}\right)\right] \tag{14}$$

$$\nu_t \equiv E_t\left(\Omega_{t+1}R_t\right) \tag{15}$$

Subsequently, excess returns on bank asset portfolios are derived from credit spreads.

$$\Upsilon_t=\chi_t^{\mathrm{b}}+\chi_t^{\mathrm{g}}s_t^{\mathrm{g}}-\frac{\nu_t\psi}{2}\left(s_t^{\mathrm{g}}-\bar{s}^{\mathrm{g}}\right)^2 \tag{16}$$

When both the CAR requirement and the incentive compatibility constraint satisfy the equality condition, substituting Eq. (15) yields

$$\mathscr{W}_{j,t}=\frac{\nu_t}{\left[cr^{\mathrm{b}}-\left(cr^{\mathrm{b}}-cr^{\mathrm{g}}\right)s_t^{\mathrm{g}}\right]\kappa-\Upsilon_t}N_{j,t} \tag{17}$$

The constrained Lagrangian equation is constructed as follows:

$$\begin{aligned}L_t=&\left\{\left[\chi_t^{\mathrm{b}}+\chi_t^{\mathrm{g}}s_t^{\mathrm{g}}-\frac{\nu_t\psi}{2}\left(s_t^{\mathrm{g}}-\bar{s}^{\mathrm{g}}\right)^2\right]\mathscr{W}_{j,t}+\nu_t N_{j,t}\right\}\left(1+\lambda_t\right)\\&-\lambda_t\kappa\mathscr{W}_{j,t}\left[cr^{\mathrm{b}}-\left(cr^{\mathrm{b}}-cr^{\mathrm{g}}\right)s_t^{\mathrm{g}}\right]\end{aligned} \tag{18}$$

where the total assets are

$$\mathscr{W}_{j,t}=Q_t^{\mathrm{g}}S_{j,t}^{\mathrm{g}}+Q_t^{\mathrm{b}}S_{j,t}^{\mathrm{b}} \tag{19}$$

Using the Lagrangian equation to find the first-order conditions for $\mathscr{W}_{j,t}$ and s_t^{g} yields

$$\left(1+\lambda_t\right)\chi_t^{\mathrm{b}}+\left(cr^{\mathrm{b}}-cr^{\mathrm{g}}\right)\lambda_t\left(1+\lambda_t\right)\chi_t^{\mathrm{g}}s_t^{\mathrm{g}}-\frac{\nu_t\psi}{2}\left(s_t^{\mathrm{g}}-\bar{s}^{\mathrm{g}}\right)^2=cr^{\mathrm{b}}\lambda_t\kappa \tag{20}$$

$$s_t^{\mathrm{g}}=\frac{\left(1+\lambda_t\right)\left(\chi_t^{\mathrm{g}}+\nu_t\psi\bar{s}^{\mathrm{g}}\right)+\left(cr^{\mathrm{b}}-cr^{\mathrm{g}}\right)\kappa\nu_t}{\left(1+\lambda_t\right)\nu_t\psi} \tag{21}$$

Substituting Eqs. (11) to (14) and Eq. (16) into Eq. (10) yields

$$\varphi_t=\frac{\left[cr^{\mathrm{b}}-\left(cr^{\mathrm{b}}-cr^{\mathrm{g}}\right)s_t^{\mathrm{g}}\right]\kappa\nu_t}{\left[cr^{\mathrm{b}}-\left(cr^{\mathrm{b}}-cr^{\mathrm{g}}\right)s_t^{\mathrm{g}}\right]\kappa-\Upsilon_t} \tag{22}$$

3.3 Production sector

The final product is a composite of products of the green and brown sectors. These two types of products are imperfect substitutes, with a constant elasticity of substitution ρ^Y.

$$Y_t=\left[\left(\pi^{\mathrm{b}}\right)^{\frac{1}{\rho^Y}}\left(Y_t^{\mathrm{b}}\right)^{\frac{\rho^Y-1}{\rho^Y}}+\left(1-\pi^{\mathrm{b}}\right)^{\frac{1}{\rho^Y}}\left(Y_t^{\mathrm{g}}\right)^{\frac{\rho^Y-1}{\rho^Y}}\right]^{\frac{\rho^Y}{\rho^Y-1}} \tag{23}$$

where π^{b} represents the proportion of brown products in the final product.

The firm maximises its profit by choosing its green and brown product inputs. The demand functions for these two types of products can be derived as follows:

$$Y_t^{\mathrm{b}}=\pi^{\mathrm{b}}\frac{Y_t}{\left(p_t^{\mathrm{b}}\right)^{\rho^Y}} \tag{24}$$

$$Y_t^{\mathrm{g}}=\left(1-\pi^{\mathrm{b}}\right)\frac{Y_t}{\left(p_t^{\mathrm{g}}\right)^{\rho^Y}} \tag{25}$$

where p_t^{b} and p_t^{g} are the relative prices of the brown and green products, respectively, with the price of the final product normalised to 1.

The output of each type of product is negatively affected by pollution. The production function for each product type is a Cobb-Douglas function composed of capital K_{t-1}^i and labour L_t^i.

$$Y_t^i=\left(1-d\left(X_t\right)\right)A_t\left(K_{t-1}^i\right)^{\alpha^i}\left(L_t^i\right)^{1-\alpha^i} \tag{26}$$

where X_t represents the stock of pollution, and $d(X_t)$ denotes the loss function. Following Nordhaus's (2018)[18] framework, it satisfies $d(X_t)=d_0+d_1X_t+d_2X_t^2$. A_t represents the total factor productivity shock, which follows an autoregressive process:

$$\log A_t=\rho_A\log A_{t-1}+\sigma_A\varepsilon_{A,t},\ \varepsilon_{A,t}\sim N(0,1) \tag{27}$$

The dynamic process of pollution stock is given by $X_t=\delta_X X_{t-1}+e_t+e_t^{\mathrm{row}}$, where e_t represents emissions in the current period, and e_t^{row} denotes total emissions from the rest of the world in the current period. Current emissions are generated by the production of brown enterprises, which also voluntarily choose to reduce their emissions by the following amount:

$$e_t=\left(1-\mu_t\right)h\left(Y_t^{\mathrm{b}}\right) \tag{28}$$

where μ_t represents the fraction of emissions abated, the specific functional forms follow those in Heutel (2012)[19].

$$h\left(Y_t^{\mathrm{b}}\right)=\left(Y_t^{\mathrm{b}}\right)^{\epsilon} \tag{29}$$

where ϵ represents unit elasticity of emissions with respect to brown output.

The cost of emission reduction depends on the proportion of the emission reduction and the level of output.

$$Z_t=f\left(\mu_t\right)Y_t^{\mathrm{b}} \tag{30}$$

where the specific emission reduction ratio function is

$$f(\mu_t)=\theta_1\mu_t^{\theta_2} \tag{31}$$

where θ_1 and θ_2 are abatement cost parameters. when brown enterprises fail to account for the environmental damage caused by their output in decision-making, an environmental externality arises. In our model, we assume that capital clears in each period, meaning that at the beginning of each period, firms purchase a capital stock K_t^{b} at a price Q_t^{b}. At the end of each period, they sell all undepreciated capital back to the capital goods provider, which amounts to $\left(1-\delta^{\mathrm{b}}\right)K_t^{\mathrm{b}}$ at price Q_t^{b}. However, while the objective of brown enterprises is to maximise their profit, they must pay a carbon emission tax τ_t^{e} due to their output. Thus, their profit at time t is given by

$$\Pi_t^{\mathrm{b}}=p_t^{\mathrm{b}}Y_t^{\mathrm{b}}-\tau_t^{\mathrm{e}}e_t-Z_t-w_t^{\mathrm{b}}L_t^{\mathrm{b}}-R_{k,t}^{\mathrm{b}}Q_{t-1}^{\mathrm{b}}K_{t-1}^{\mathrm{b}}+\left(1-\delta^{\mathrm{b}}\right)Q_t^{\mathrm{b}}K_{t-1}^{\mathrm{b}} \tag{32}$$

where τ_t^{e} represents the carbon tax.

Compared with brown enterprises, green enterprises do not have to pay carbon emission taxes. Their profit at time t is as Eq. (33):

$$\Pi_t^{\mathrm{g}} = p_t^{\mathrm{g}} Y_t^{\mathrm{g}} - w_t^{\mathrm{g}} L_t^{\mathrm{g}} - R_{k,t}^{\mathrm{g}} Q_{t-1}^{\mathrm{g}} K_{t-1}^{\mathrm{g}} + (1-\delta^{\mathrm{g}}) Q_t^{\mathrm{g}} K_{t-1}^{\mathrm{g}} \tag{33}$$

3.4 Capital sector

As mentioned in Section 3.3, at the end of each period, the capital in a firm's production department clears, as ensured by the capital provider. The capital provider supplies capital to the production department at the beginning of each period and recovers the undepreciated capital at the end of the period. Capital does not flow across departments.

Investing in capital incurs an adjustment cost, determined by the parameter ϕ^i, where $i \subset (\mathrm{b}, \mathrm{g})$. Each unit of new capital goods in a specific sector requires $\left(1+\frac{\phi^i}{2}\left(\frac{I_t^i}{I_{t-1}^i}-1\right)^2\right) I_t^i$ units of the final product.

The capital provider can sell the product at a price Q_t^i per unit in each period, while the cost of providing the product is normalised to 1 (since the price of the final product is normalised to 1). The capital provider's objective is to maximise profit, which in period t is given by

$$\max_{\{I_t^i\}_{i=\mathrm{g,b}}} E_0 \sum_{t=0}^{\infty} M_{0,t} \sum_{i=\mathrm{g,b}} \left(Q_t^i I_t^i - \left[1+\frac{\phi^i}{2}\left(\frac{I_t^i}{I_{t-1}^i}-1\right)^2\right] I_t^i \right) \tag{34}$$

where ϕ^i represents investment adjustment cost.

3.5 Government sector

The government transfers to households its revenue from carbon emission taxes, computed as follows:

$$T_t = \tau_t^{e} e_t \tag{35}$$

4 Parameter calibration

In our simulation of this model, we define each period as a quarter. The relevant parameters can be categorised into three groups: parameters related to the RBC model, environmental parameters and policy-related parameters. We calibrated these parameters based on real-world data. All parameters used for calibration are listed in Table 1.

Table 1 Values of calibrated parameters.

Parameter	Value	Definition
β	0.995	Discount rate
ϖ	8.954	Disutility of labor parameter
η	2	Coefficient of relative risk aversion
ξ	1.6	Frisch elasticity of labor supply
ρ_{L}	1	Intersectoral labor substitution elasticity
$\delta^{\mathrm{b}}, \delta^{\mathrm{g}}$	0.025	Capital depreciation rate
ψ	0.0001	Bank investment adjustment cost
ρ^{Y}	2	Intermediate goods substitution elasticity
π^{b}	0.711	Share of brown intermediate goods
ϕ^{i}	10	Investment adjustment cost
ρ_{A}	0.95	Autocorrelation coefficient
σ_{A}	0.007	Autoregressive variance
α^{g}	0.50	Capital share in the green sector
α^{b}	0.52	Capital share in the brown sector
γ	0.96	Bank survival rate
κ	0.3409	Degree of financial friction
ζ	0.0027	Transfer payment to new banks
$\widehat{d}_0$	−0.0076	
$\widehat{d}_1$	1.078×10^{-5}	Climate damage parameters
$\widehat{d}_2$	1.861×10^{-8}	
θ_1	0.0229	Abatement cost parameters
θ_2	2.6	
δ_X	0.9965	Emission persistence rate
ϵ	1	Emissions elasticity parameter
e_t^{row}	9.2	Emissions from other countries and regions

4.1 Parameters related to the real business cycle model

First, regarding the household sector, consistent with most of the literature, we set the subjective discount factor β to 0.995, corresponding to an annual risk-free interest rate of 2%. Following Kang and Gong[20], we set the coefficient of relative risk aversion η to 2. In line with Zhuang et al.[21], we set the Frisch elasticity of labour supply ξ to 1.6. Additionally, assuming that in the steady state, household labour supply constitutes one-third of the total time available, we calibrated the labour disutility coefficient ϖ accordingly.

Second, for the production sector, we set the capital depreciation rates δ^{b} and δ^{g} to 0.025, consistent with most of the literature[22]. Due to the relatively high investment level in China, most domestic literature sets the capital input share at 0.5[23]. However, according to Fullerton and Heutel[24], the capital intensity of the brown sector is higher than that of the clean sector. Therefore, following the parameter setting from Carattini et al.[12], this paper sets the capital input share for brown firms, α^{b}, to 0.52 and that for green firms, α^{g}, to 0.50.

As per Carattini et al.[12], we set the elasticity of substitution between labour in the two production sectors ρ_{L} to 1. Regarding the elasticity of substitution between brown and green products, the literature typically suggests a range of 2 to 4. In this study, we follow the estimation results of Papageorgiou et al.[25] and set ρ^{Y} to 2.

Referring to Chen et al.[6], we set the steady-state proportion of green capital $\bar{s}^{\mathrm{g}}$ to 0.3, and based on this, we calibrate the proportion of brown products π^{b} to 0.711. In line with most RBC models, we set the parameters for permanent total factor productivity shocks ρ_{A} and σ_{A} to 0.95 and 0.007, respectively. Consistent with the environmental DSGE literature, we set the investment adjustment cost parameter ϕ^{i} for both the brown and green production sectors to 10[19,26].

Finally, for the banking sector, we set the survival rate of banks per period γ to 0.96[27]. Following Gertler and Karadi[17] and Carattini et al.[12], we set the steady-state leverage ratio of the banking sector to 4.5. Referring to Chen et al.[6], we calibrated the financial friction parameter κ and the transfer payment parameter ζ based on the credit spread of green assets, which is 0.42%. We set the investment adjustment cost parameter for banks ψ to 0.0001, ensuring that the investment portfolio can be determined in the steady state.

4.2 Environmental-related parameters

The calibration of environment-related parameters was consistent with most of the literature on environmental DSGE models[6,12]. The climate damage parameters $\widehat{d}_0$, $\widehat{d}_1$ and $\widehat{d}_2$ were calibrated following Gibson and Heutel[28] and were set to −0.0076, 1.078×10^{-5} and 1.861×10^{-8}, respectively. Given that the functional form remained identical but the steady-state value of pollution stock in the model differed, we defined $d_{\text{scale}} = \dfrac{X_{\text{ss,model}}}{2030}$ to calibrate $d_0 = \widehat{d_0}$, $d_1 = \dfrac{\widehat{d_1}}{d_{\text{scale}}}$ and $d_2 = \dfrac{\widehat{d_2}}{d_{\text{scale}}{}^2}$. Here, 2030 gigatonnes corresponds to the pollution stock in the steady state of the Gibson and Heutel[28] model.

The parameter for abatement costs was based on Nordhaus[18]. Since our model assumes that green firms have zero emissions, the first-order coefficient θ_1 had to be adjusted according to the ratio of the total output of brown firms to the output of the final good, yielding 0.0229, while the second-order coefficient θ_2 remained constant at 2.6. The emission persistence rate was set to 0.9965.

According to statistics from the International Energy Agency, China's carbon emissions were approximately 33.7% of global emissions in 2023. Based on this, emissions from other countries and regions e_t^{row} were calibrated to be twice the steady-state level of domestic emissions.

4.3 Policy-related parameters

First, regarding the carbon tax policy, China's GDP in 2023 was approximately 126 trillion yuan, and its carbon dioxide emissions were about 12.6 billion tonnes. Thus, the proportion of China's carbon tax revenue to its GDP, calculated at a carbon price of 50 yuan per tonne, is about 0.50%. Based on this proportional relationship, the carbon tax level in the model was calculated to be 0.0052.

Second, concerning the differentiated CAR requirements policy, since our aim is to mitigate transition risks, it is necessary to lower CAR requirements for green assets while increasing them for brown assets. Referring to Diluiso et al.[11], we set cr^{g} to 0.8 and calculated cr^{b} as 1.09.

5 Numerical simulation and policy effects

We performed numerical simulations using the calibrated parameters outlined in Section 4.3. We defined four policy combinations to simulate climate transition risks arising from the carbon tax shock, the amplifying effect of financial frictions on transition risks and the mitigating effect of the differentiated CAR requirements policy on transition risks. The four scenarios are as follows: no policy and no friction (Scenario 1), carbon tax policy (Scenario 2), carbon tax policy with friction (Scenario 3) and coordinated carbon tax policy and differentiated CAR requirements policy with friction (Scenario 4). We compare Scenarios 1 and 2 to assess the impact of the carbon tax on the macroeconomy and the transition risks it poses; Scenarios 2 and 3, to analyse the amplifying effect of financial frictions on transition risks; and Scenarios 3 and 4, to evaluate the mitigating effect of the differentiated CAR requirements policy on transition risks.

5.1 Climate policy and transition risk

5.1.1 Short-term impact of carbon tax policy on the macroeconomy

We assume that in the fourth period, the carbon tax increases from 0 to 0.0052, corresponding to a carbon price of 50 yuan per tonne. The transition dynamics of key macroeconomic variables are shown in Figure 1. The results indicate that the carbon tax significantly reduces emissions and gradually decreases pollution stock, benefitting the environment. Additionally, it supports the green transformation of industries and increases green output while reducing brown output. However, it also has a considerable negative impact on macroeconomic and financial stability.

Specifically, the carbon tax causes a certain degree of decline in both total output and total investment.

In terms of output, the carbon tax increases the production costs of brown enterprises and, thus, decreases their total output.

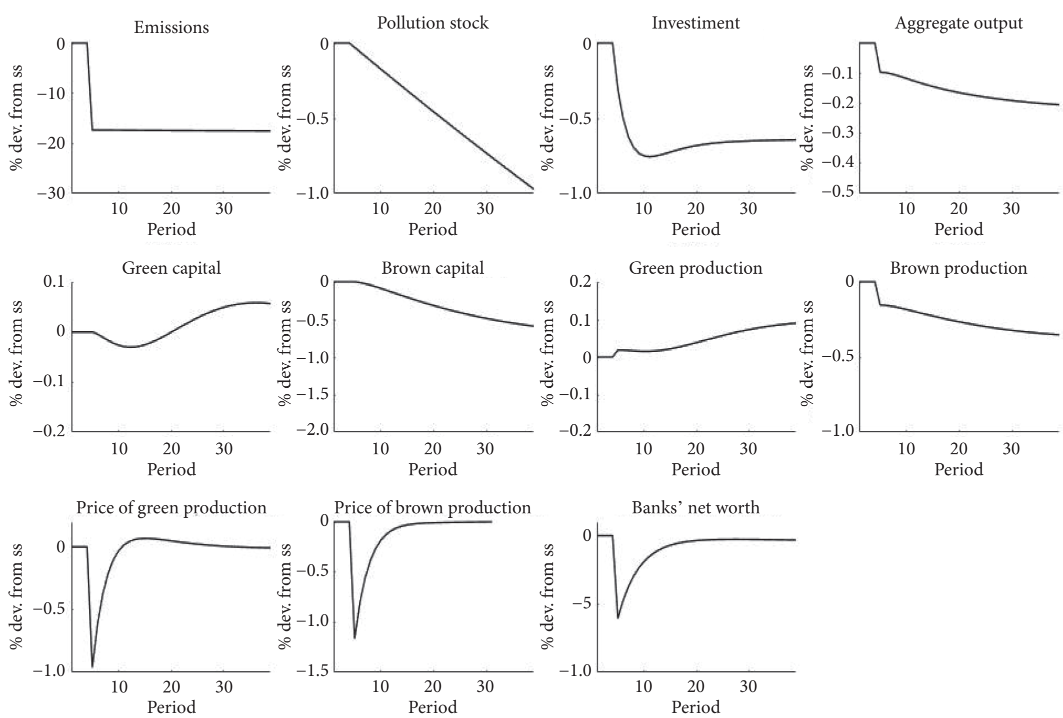

Fig. 1 Short-term impact of carbon tax policy on the macroeconomy. Note: ss means steady state.

In terms of investment, the decline in brown enterprise output due to the carbon tax significantly lowers the prices of brown assets, which, in turn, restricts banks' net assets and lendable funds, thereby also affecting green credit and the prices of green assets. Here, we consider the loss of banks' net assets as an indicator of the magnitude of transition risks, as these assets—being the equity of the financial sector—are fundamental to maintaining sector stability. A decline in banks' net assets often impacts their ability to continue operations and undermines their financial stability.

5.1.2 Long-term impact of carbon tax policy on the macroeconomy

Regarding the long-term impact of the carbon tax on the macroeconomy, we focused on the long-term steady-state values of the model. We simulated the steady-state values of variables after 2,000 periods, and some of the results are shown in the first and second columns of Table 2. First, for the environment-related variables, we found that the emission reduction ratio is mainly affected by the carbon tax. In the absence of a carbon tax, the ratio was very low. However, after the implementation of the carbon tax, the ratio increased significantly, and the corresponding emissions and pollution stock decreased.

Second, for the macroeconomic variables, we found that although the carbon tax policy will reduce output in the short term, the reduction in emissions will decrease the production losses of enterprises. In the long run, the steady-state value of the output will slightly rebound.

Finally, for the financial variables, similar to the macroeconomic variables, although the carbon tax policy has a significant short-term impact on the financial system, which is transmitted to the banking sector through the stranding of brown assets and triggers transition risks, in the long run, the carbon tax policy promotes green transformation and mitigates the negative externalities of pollution. As a result, the output of the production sector increases, and thus, the net assets of banks will also recover to some extent.

5.2 Amplifying effect of financial frictions on transition risks

This paper incorporates financial frictions in the banking sector, which significantly amplify transition risks. As shown in Figure 2, the impact of the carbon tax policy on macroeconomic variables is exacerbated under financial frictions. Compared with the scenario without frictions, in the scenario with frictions, the decline in total investment increases by one-third, and the decline in total output increases by nearly one-fourth. This is because financial frictions restrict bank lending, reducing the lendable funds available to the production sector. Due to the capital constraints of the production sector, its product prices decrease, which, in turn, gradually reduces its assets. This process further decreases banks' net assets through a feedback mechanism, thereby amplifying transition risks. In the long run, a comparison of the second and third columns of Table 2, the steady-state value of total output under financial frictions is slightly lower than that without frictions, with both green and brown outputs decreasing by more than 10%. The reduction in banks' net assets is particularly pronounced, exceeding 20%, which poses a significant transition risk and threatens financial stability.

5.3 Mitigating effect of differentiated CAR requirements on transition risks

We now consider the following macroprudential policy: reduction of the CAR requirement for green capital to 0.8 and increase of the CAR requirement for brown capital to 1.09 to maintain the steady-state total CAR requirement.

5.3.1 Short-term mitigating effect of differentiated CAR requirements on transition risks

First, as shown in Figure 3, differentiated CAR requirements have limited impact on emissions and pollution stock, slightly reducing them. This is because the differentiated CAR requirements policy leads to an increase in banks' investments in the green sector and to a decrease in their investments in the brown sector, which, in turn, reduces output in the brown sector and, thus, slightly alleviates climate issues. It is important to note that the carbon tax policy remains the primary means of addressing climate issues, as it is far more effective than the differentiated CAR requirements policy.

From a macroeconomic perspective, the implementation of differentiated CAR requirements reduces the decline in investment and output, thereby mitigating the impact of the carbon tax policy on the macroeconomy. Finally, considering the financial sector, the implementation of differentiated CAR requirements prompts it to reallocate a portion of its funds to the

Table 2 Long-term steady-state effects of different policy combinations on variables.

Variable		No policy and no friction (Scenario 1)	Carbon tax (Scenario 2)	Carbon tax + friction (Scenario 3)	Carbon tax + friction + macroprudential (Scenario 4)
Macroeconomic variables	Total output	1.57	1.59	1.5	1.47
	Green output	0.58	0.59	0.55	0.55
	Brown output	1	1.01	0.95	0.93
Financial variables	Carbon tax	0	0.0052	0.0052	0.0052
	Capital adequacy requirement for green assets	0	0	0	0.8
	Capital adequacy requirement for brown assets	0	0	0	1.09
	Net assets of banks	5.83	6.03	3.43	3.78
Environmental variables	Emission reduction ratio	0.000027	0.17	0.17	0.17
	Emissions	1	0.83	0.78	0.77
	Pollution stock	2,914	2,868	2,853	2,849

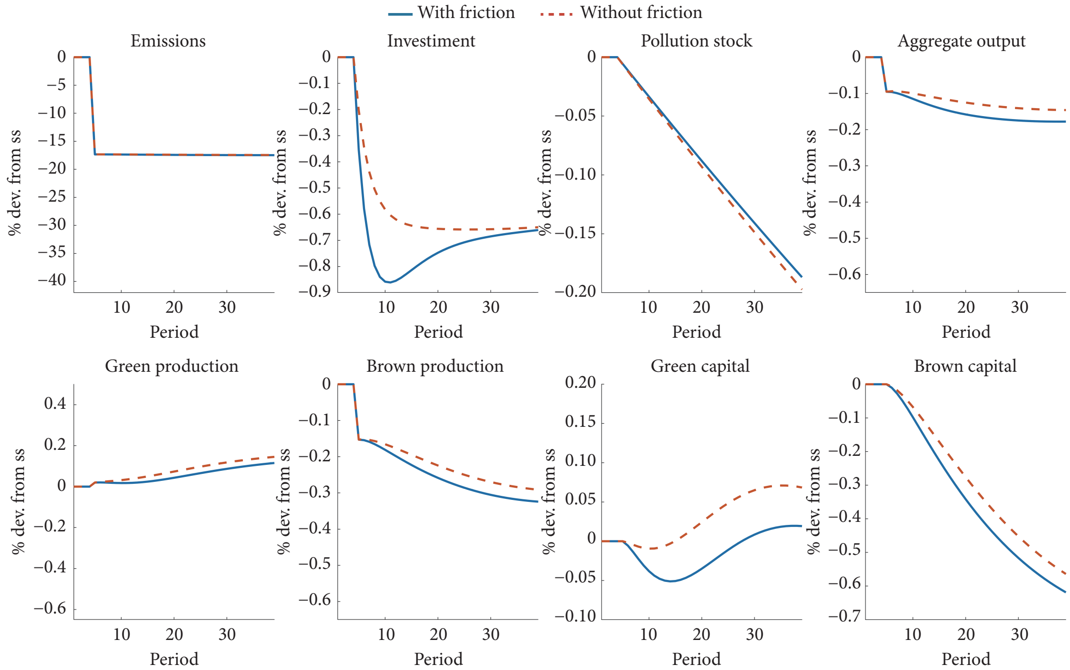

Fig. 2 Amplifying effect of financial frictions on transition risks. Note: ss means steady state.

green sector in advance. This reduces its exposure to risk when the carbon tax is imposed. When the shock of the carbon tax policy arrives, a smaller exposure to risk leads to a lower transition risk for the financial sector and, thus, to a smaller reduction in banks' net assets.

5.3.2 Long-term effects of differentiated CAR requirements

In the long run, comparing the third and fourth columns of Table 2 reveals that the differentiated CAR requirements policy, in conjunction with the carbon tax policy, enhances both green and brown output, which is favourable for macroeconomic variables. This is because the differentiated CAR requirements policy promotes green transformation, thereby reducing the negative externalities of emissions and boosting production. Meanwhile, the long-term steady-state value of banks' net assets is higher in the scenario with both the differentiated CAR requirements policy and the carbon tax policy than in the scenario with only the carbon tax policy. This is because the differentiated CAR requirements policy encourages green investment and reduces banks' exposure to risk when the carbon tax is imposed. It can be concluded that, in the long term, the differentiated CAR requirements policy can mitigate transition risks.

6 Sensitivity analysis

In this session, we conduct sensitivity analysis on two important variables.

First, we explore the impact of the carbon tax on the effectiveness of macroprudential policy from Table 3. Specifically, we increase and decrease the carbon tax by 20% and 30%, respectively, to test the robustness of the climate policy. The results show that when the carbon tax increases, bank net worth rises slightly. Under the macroprudential policy, the proportional increase in bank net worth is almost identical to that in the baseline model. When the carbon tax decreases, bank net worth falls slightly. Similarly, with the macroprudential policy in place, the proportional change in bank net worth is also largely consistent with the baseline model. These findings indicate that changes in the carbon tax do not affect the effectiveness of the macroprudential policy, and that the policy is robust.

Second, we conduct a sensitivity analysis on the CAR parameters. We vary cr^g from 0.70 to 0.90 with a step size of 0.05, and calculate the corresponding cr^b accordingly. From Table 4, we can observe that, compared to the scenario without macroprudential policy, the implementation of the differentiated CAR policy consistently increases bank net worth. As the policy intensity weakens, the positive effect on bank net worth also diminishes, but it remains positive. Thus, this policy is also robust.

7 Conclusion

With China's gradual implementation of measures to achieve its "dual carbon" goals through specific policies and the expanding industry coverage of the national carbon market, climate governance policies have become an important part of the country's macroeconomic policies. However, calibration-based calculations have revealed that the remaining emission space in China is narrowing, necessitating large-scale emission reductions. To meet these targets, ambitious climate policy measures, such as expanding the scope of carbon pricing and increasing carbon prices, may be required. However, these policies may bring transition risks that threaten financial stability. Macroprudential policies can reduce financial risk exposure while achieving climate goals.

Based on a standard DSGE model, we incorporated pollution externalities and financial frictions in the banking sector, as well as introduced carbon pricing policy and the differentiated CAR requirements policy. Within this model framework, we first investigated the impact of the carbon pricing policy on China's macroeconomic and financial stability, and introduced transition risks. We then explored the amplifying effect of the financial frictions on the transition risks. Finally, targeting transition risks, we propose the differentiated CAR requirements policy that can

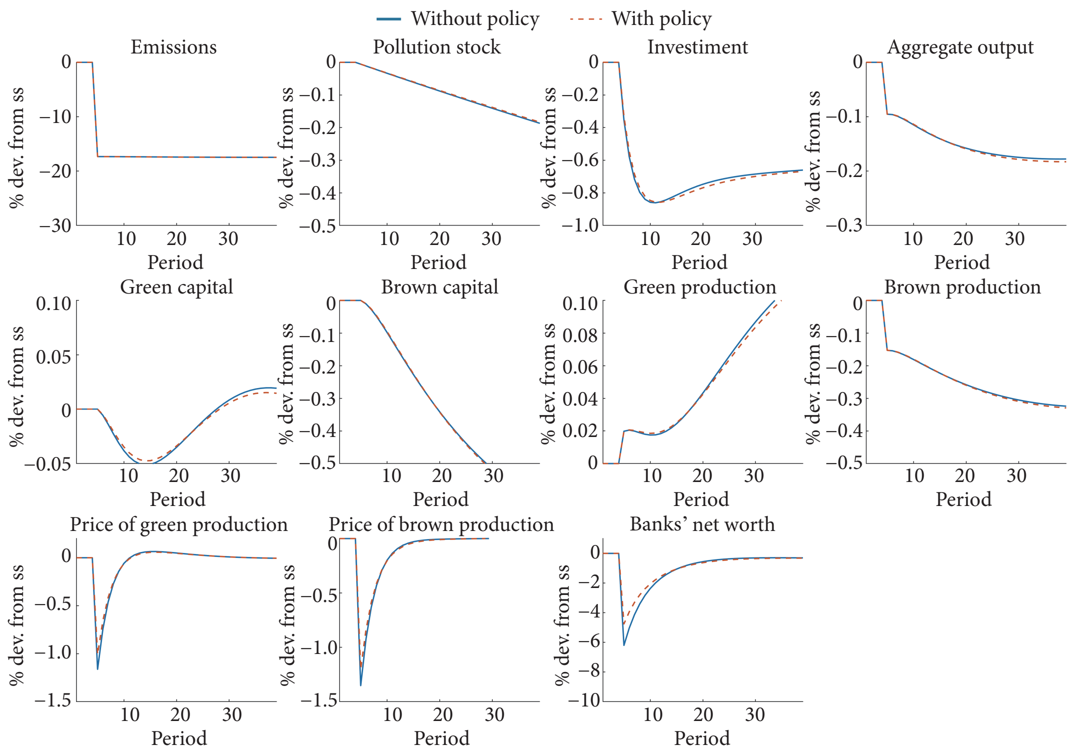

Fig. 3 Mitigating effect of macroprudential policy on transition risks. Note: ss means steady state.

Table 3 Sensitivity analysis of the carbon tax to the effectiveness of macroprudential policy.

Net assets of banks	Carbon tax + friction	Carbon tax + friction + macroprudential
Base model	3.43	3.78
20% increase in the carbon tax	3.44	3.79
20% decrease in the carbon tax	3.43	3.77
30% increase in the carbon tax	3.45	3.79
30% decrease in the carbon tax	3.42	3.76

Table 4 Sensitivity analysis of the capital adequacy requirement.

Net assets of banks	Carbon tax + friction	Carbon tax + friction + macroprudential
Base model (cr^g=0.80, cr^b=1.09)	3.43	3.78
cr^g=0.70, cr^b=1.13	3.43	4.06
cr^g=0.75, cr^b=1.10	3.43	3.90
cr^g=0.85, cr^b=1.06	3.43	3.65
cr^g=0.90, cr^b=1.04	3.43	3.59

ensure unchanged total CAR, control liquidity risks, maintain macroeconomic stability and mitigate transition risks posed by climate policy. Compared with other common accommodative macroprudential policies, the differentiated CAR requirements policy, such as structural policy, can mitigate transition risks without causing liquidity risks.

The main conclusions of this paper are as follows:

(1) The carbon tax policy is highly effective in reducing emissions and can also effectively address climate pollution issues. It achieves emission reductions by imposing taxes on brown enterprises, thereby compelling them to cut production. However, in the short term, this policy suppresses total output and investment. Moreover, by adversely affecting brown enterprises, it impacts banks' net assets through price channels, thereby generating transition risks that threaten financial stability.

(2) Financial frictions restrict banks' lendable funds, leading to credit contraction. When the production sector suffers from insufficient credit, it experiences production disruptions. These disruptions are transmitted to the financial sector, manifesting as a decline in banks' net assets, which amplifies transition risks.

(3) The combination of the carbon pricing policy and the differentiated CAR requirements policy not only reduces emissions but also mitigates transition risks by reducing banks' exposure to risk without triggering liquidity risks. This approach can attain a "win–win" outcome for climate and environmental goals, as well as financial stability.

(4) The strength of the climate policy has relatively little impact on the effectiveness of macroprudential policy, and the differentiated CAR policy is robust in addressing transition risks. Differentiated CAR policies with different levels of intensity have different mitigating effects on transition risks: the stronger the implemented differentiated CAR policy, the greater its mitigation of transition risks. However, all the effects are positive, so this policy is also robust.

Acknowledgements

We acknowledge the financial support from the Fundamental and Interdisciplinary Disciplines Breakthrough Plan of the Ministry of Education of China (No. JYB2025XDXM904) and the National Natural Science Foundation of China (No. W2412161).

Author contribution statement

Shanhua Zhang: conceptualization, methodology, formal analysis, writing – original draft, review & editing. Hao Jin: methodology, formal analysis. Ying Fan: conceptualization, writing – review & editing, supervision, funding acquisition.

Data availability

The data that support the calibration results are included in the article, and no other datasets were used in this study.

Use of AI statement

None.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

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

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

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

[4] Van der Ploeg, F., Rezai, A. (2020). Stranded assets in the transition to a carbon-free economy. *Annual Review of Resource Economics*, 12: 281–298.

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

[6] Chen, G. J., Chen, L. L., Jin, H., Zhao, X. Q. (2023). Climate transition risk and macroeconomic policy regulation. *Economic Research Journal*, 58(5): 60–78. (In Chinese)

[7] Wang, Y., Pan, D. Y., Peng, Y. C., Liang, X. (2019). China's incentive policies for green loans: a DSGE approach. *Journal of Financial Research*, (11): 1–18. (In Chinese)

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

[9] Böser, F., Colesanti Senni, C. (2020). Emission-based interest rates and the transition to a low-carbon economy. Economics Working Paper Series, No. 20/337. CER-ETH – Center of Economic Research at ETH Zurich.

[10] Dafermos, Y., Nikolaidi, M. (2021). How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis. *Journal of Financial Stability*, 54: 100871.

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

[12] Carattini, S., Heutel, G., Melkadze, G. (2023). Climate policy, financial frictions, and transition risk. *Review of Economic Dynamics*, 51: 778–794.

[13] Grill, M., Popescu, A., Rancoita, E. (2024). Climate transition risk in the banking sector: what can prudential regulation do? ECB Working Paper Series No 2910.

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

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

[16] Gertler, M., Kiyotaki, N. (2010). Financial intermediation and credit policy in business cycle analysis. *Handbook of Monetary Economics*, 3: 547–599.

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

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

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

[20] Kang, L., Gong, L. T. (2014). Financial frictions, net worth of bank and transmission of international crisis: based on multi-sector DSGE model analysis. *Economic Research Journal*, 49(5): 147–159. (In Chinese)

[21] Zhuang, Z. G., Cui, X. Y., Gong, L. T., Zou, H. F. (2016). Expectations and business cycle: can news shocks be a major source of China's economic fluctuations? *Economic Research Journal*, 47(6): 46–59. (In Chinese)

[22] Liang, Q., Hao, Y. (2019). Local government debt replacement and macroeconomic risk mitigation. *Economic Research Journal*, 54(4): 18–32. (In Chinese)

[23] Wang, X., Wang, L., Peng, Y. L., Song, X. F. (2017). A comparative study of China’s monetary policy rules: on the perspective of three rules based on the DSGE model. *Economic Research Journal*, 52(9): 24–38. (In Chinese)

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

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

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

[27] Xiong, C., Jin, H. (2021). The macroeconomic effects of local government debt—a credit misallocation perspective. *China Economic Quarterly*, 20(5): 1545–1570. (In Chinese)

[28] Gibson, J., Heutel, G. (2023). Pollution and labor market search externalities over the business cycle. *Journal of Economic Dynamics and Control*, 151: 104665.