Under Pressure: Sovereign Debt Challenges in a Warming World

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Climate adaptation: a growing challenge for public finances

Climate change is already costly – and costs are rising

- Over $280 billion globally in damages from extreme weather in 2023 (Swiss Re)
- Heatwaves, wildfires and floods are disrupting supply chains, damaging infrastructure and straining public finances

Future risks without stronger adaptation

- Global GDP losses by 2050 (NGFS, 2024):
  - 8% in a net zero scenario
  - Over 15% under current policy trends

Adaptation finance is increasing, but remains insufficient

- G7 spending: approx. $40 billion/year - far below the levels required to ensure economic resilience
- The adaptation gap is even more pronounced in developing economies.

Key challenges

- Adaptation protects mainly public goods → limited private returns
- In advanced economies, aging populations, high debt, and structural deficits limit room for additional spending without raising debt-to-GDP.

Adaptation versus mitigation: policy tradeoffs and fiscal implications

Adaptation creates a fiscal tradeoff

- *Short term*: increases public spending and debt
- *Long term*: reduces climate damages and eases fiscal pressure

Mitigation helps too, with stronger private sector engagement

- Carbon pricing and clean technologies offer revenue streams
- Mitigation spreads the cost burden and supports debt sustainability
- Effective and more efficient when private incentives are aligned (Seghini and Dees, 2024)

Model based analysis

- Extended DSGE model includes adaptation investment
- Modeled and calibrated with insights from Heutel, 2012, Annicchiarico and Di Dio, 2015, Corsetti et al., 2013, and Darracq Pariès, Jacquinot, and Papadopoulou, 2016
- Simulations explore:
    - Adaptation versus damage tolerance
    - Complementarities with mitigation policies

Literature review: climate risks and fiscal sustainability

Climate change and sovereign risk

- Growing literature on macrofinancial impacts of climate change, but fewer studies focus on sovereign risk and debt sustainability
- Cevik and Jalles, 2022: climate vulnerability → higher bond yields; resilience → lower costs
- Bolton et al., 2022: call for climate-linked sovereign instruments and debt relief

Adaptation and fiscal costs

- Aligishiev, Massetti, and Bellon, 2022: adaptation ≈ 1.5% of GDP/year; varies by exposure
- High returns, but limited private investment → public sector leads
- Barrage, 2020: climate shocks exacerbate fiscal pressure

Mitigation and fiscal space

- Mitigation imposes short-term costs, improves long-term fiscal sustainability
- Seghini, 2023, Klusak et al., 2021: carbon-intensive exposure raises financing costs

Dynamic modeling approaches

- Calcaterra et al., 2024, Fried, 2022: adaptation improves debt trajectories, but high-impact scenarios challenge fiscal stability
- Barrage, 2024: mitigation and adaptation considerations must be integrated to both avoid rising sovereign risk and improve welfare

This paper

- Bridges gaps by integrating adaptation, mitigation, and debt sustainability in a dynamic General Equilibrium framework

Key results

- **Adaptation–debt trade-off:** investing in adaptation entails short-term fiscal costs but reduces long-term climate damages, supporting growth and debt sustainability.
- **Inaction is costly:** allowing climate damages to materialize weakens economic performance and increases fiscal pressures over time.
- **Complementarity of policies:** combining adaptation with mitigation eases macroeconomic strains and improves long-term debt dynamics more effectively than isolated policies.

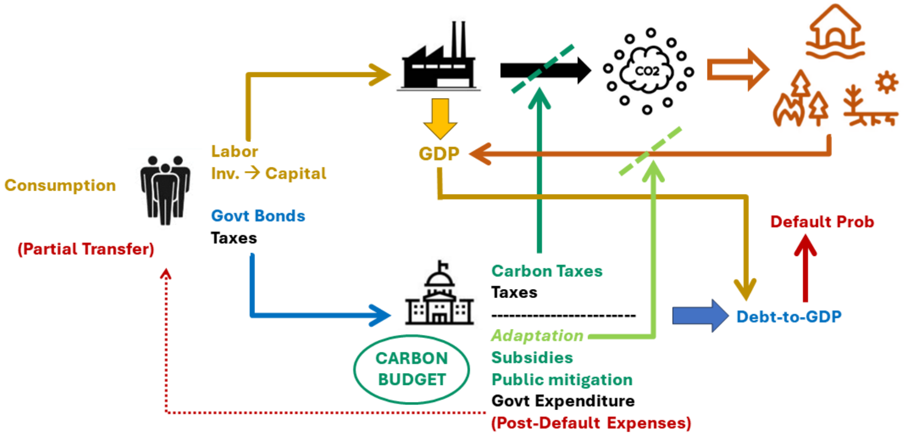


Figure: The model's structure. Variables between parentheses are not null only in case of default on government debt.

The Macro-climate model

- Carbon budget in line with the Paris Agreement and IPCC indications: $\sum_{j=0}^{+\infty} E_j \leq \bar{E}_0^n$
- Emissions are a by-production of GDP: $E_t(i) = \xi_t[1 - m_t(i) - m_t^g]Y_t(i)$
- Standard Cobb-Douglas production function $\Longrightarrow$ without or with climate damages.
- Each firm i maximizes profits, produces an unique good Y, remunerates labor and capital, pays abatement costs and carbon taxes: $\Pi_t(i) = Y_t(i) - W_t L_t(i) - R_t^k K_t(i) - (1 - s_t^A)A_t(i) - \tau_t^E E_t(i)$
- Private and public abatement costs: $A_t = \theta_1[m_t]^{\theta_2} Y_t, \quad A_t^g = \theta_3[m_t^g]^{\theta_4} Y_t; \quad \theta_3 = \theta_1, \quad \theta_4 < \theta_2$
- The representative household consumes, works, invests in capital, pays lump-sum taxes and invests in risky government bonds.

  In case of sovereign default she is compensated only by $(1 - f)$ of the lost value

  $\Longrightarrow R_t \approx (1 - f\vartheta \text{PD}_{t+1})R_t^d$

▸ Model appendix

Fiscal Policy and Abatement Costs

- Investors evaluate PD according to:

$$b_M e^{\epsilon_t} < b_t \quad \text{where} \quad \epsilon_t \sim N(0, \sigma_B) \tag{1}$$

b_M: fiscal limit in terms of maximum sustainable government borrowing-to-GDP ($b_t \equiv \frac{B_t}{Y_t}$), subject to uncertainty $\Longrightarrow$ PD writes as a standard normal c.d.f.:

$$\text{PD}_{t+1} = \Phi\left(\frac{\ln(b_t) - \ln(b_M)}{\sigma_B}\right) \tag{2}$$

- Consolidated government budget constraint: ▸ Govt budget contraint

$$B_t = B_{t-1} R^d_{t-1} - S_t \tag{3}$$

- Consolidated primary surplus :

$$S_t = \tau^C_t C_t + \tau^K_t R^K_t K_t + \tau^L_t W_t L_t - T_t - G_t + \tau^E_t E_t - s^A_t A_t - A^g_t - I^{Ad}_t \tag{4}$$

- Debt stabilization function:

$$\tau_t = \phi_\tau[\tau_{t-1} + \phi_b(b_t - b_{t-1}) + \phi_y(y_t - y_{t-1})] + (1 - \phi_\tau)[\tau_* + \phi_b(b_t - b_*) + \phi_y(y_t - y_*)]$$

Public investment in adaptation

- Adaptive capacity depends on the ratio between the protective capital stock K^{Ad} and endangered classical forms of capital K:

$$Q_t^{Ad} = \left(\alpha_1 \frac{K_t^{Ad}}{D_f(H_t^G) K_t} \right)^{\alpha_2}, \tag{5}$$

$$K_t^{Ad} = (1 - \delta^{Ad}) K_{t-1}^{Ad} + I_t^{Ad}, \tag{6}$$

where δ^{Ad} is the depreciation rate of adaptation stock, and I_t^{Ad} denotes public investments in adaptation stock.

- Final good production function:

$$Y_t(i) = \bar{Z}[1 - D_f(H_t^G)(1 - Q_t^{Ad})] K_t(i)^{\kappa} [Z_t L_t(i)]^{1-\kappa} \tag{7}$$

- Damage function à la Dietz and Venmans, 2019:

$$D(H_t^G) = 1 - \exp\left\{ -\frac{\gamma_1}{2} \mathcal{T}_t^2 \right\}, \text{ where } \mathcal{T}_t = \gamma_2 H_t^G. \tag{8}$$

Calibration

- Quarterly calibration. ▸ Parameters
- Follows existing literature for the traditional Neoclassical model aspects.

Climate damage funtion :

- $\gamma_2 = 0.00053$ captures the linear relationship between excess global mean temperature and global cumulative emissions, highlighted by Dietz and Venmans, 2019
- $\gamma_1 = 0.08$ reinforces the parameter proposed by Dietz and Venmans, 2019 by a factor of 4, to match the strength of climate damages caused by increasing global temperatures, estimated by Bilal and Känzig, 2024.

Transition Setup:

- Global cumulative CO_2-equivalent emissions till 2024: 2650 $GtCO_2$
- Global carbon budget under 1.5° with 50% prob: 235 Gt CO_2 (IPCC, 2023) $\Rightarrow$ Fair per-capita national budget: France: 1.9 Gt CO_2.
- Private abatement cost function coefficients calibrated to match a (detrended) long-term carbon tax for France of US$ 1000 per ton of CO_2, in the case of a transition to $1.5^\circ C$ with 50% probability, achieved only through carbon pricing (in line with D'Arcangelo et al., 2022 and Quinet et al., 2019).
- French carbon intensity of GDP: $\xi_0 = 0.17$ (ourworldindata.org).

Calibration

Adaptation: ▸ Parameters

- The convexity parameter α_2 of the adaptation function is calibrated following Barrage, 2024;
- α_1 is calibrated to ensure that the steady state required ratio of investment in adaptation to GDP i^{ad}/y matches 2%, to construct an adaptive capacity of 20% under a 3° scenario.
- δ^{Ad} is calibrated to 2% annually.

Public debt sustainability:

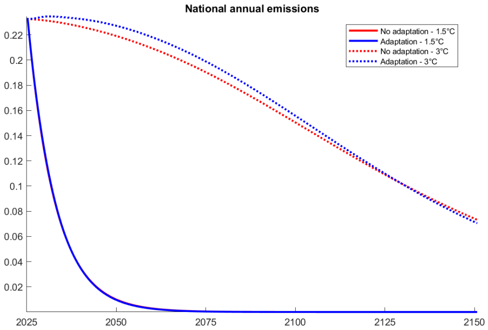
- Log-normal probability of default parameters determined in order to match government risk premia with current evidence.
- National fiscal limits in line with the least adverse evidence provided by Collard, Habib, and Rochet, 2015 and Seghini, 2023.
- Consolidated haircut $f\vartheta = 0.21$, reasonably conservative for advanced economies: product of high haircut $\vartheta = 0.7$ and fraction $f = 0.3$ (post-default government expenditure as a fraction of investors' lost value $\vartheta_t R^d_{t-1} B_{t-1}$)
- Total public expenditure defined as constant in volume, equal to 20% of GDP in the initial period.[1]

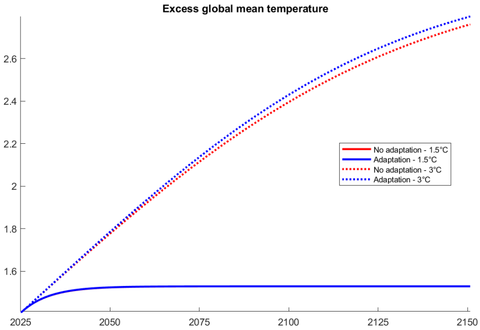
[1] data.worldbank.org

Results

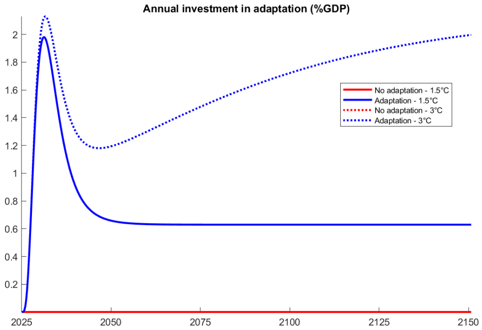
- Two transition scenarios:
  (1) Paris agreement's scenrario 1.5°C (solid lines)
  (2) Slower transition scenario 3°C (dotted lines);
- Two variants:
  (1) With adaptation (blue lines)
  (2) Without adaptation (red lines);
- Two ways to finance the transition:
  (1) Public abatement
  (2) Private through carbon tax;
- Model calibrated for France.
- Analysis of public debt dynamics until 2150 with a focus on the first 25 years (2025-2050).
- Macroeconomic impacts assessed through:
  - GDP level
  - Private consumption level

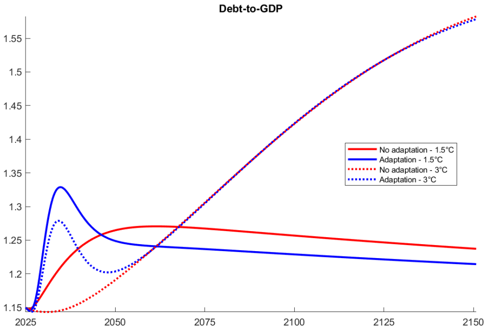
Emission trajectories and impact on temperature



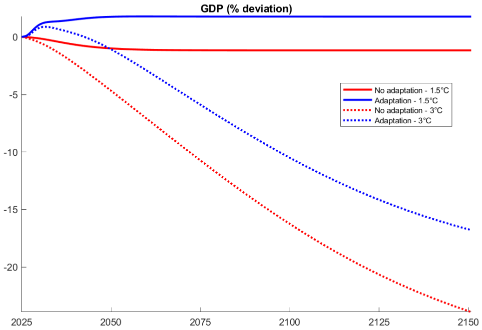


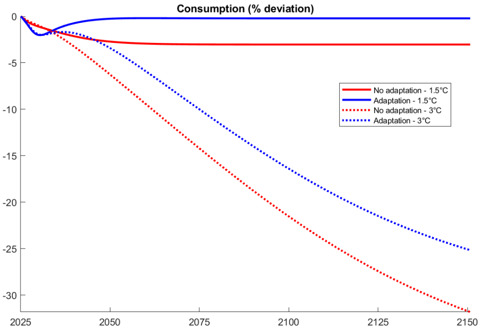
Adaptation effort and impact on public debt





Macroeconomic impacts





Simulation 2: Financing Mitigation through Private Sources

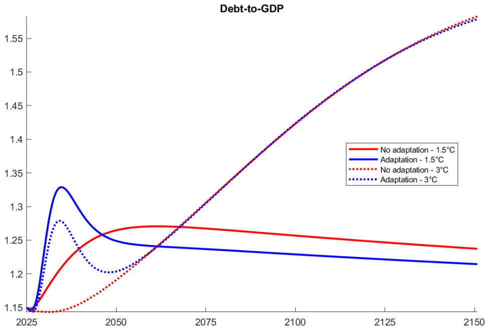
Key Idea: The second set of simulations shows how financing mitigation through private sources (via carbon taxation) reduces the fiscal costs of climate change for public finances.

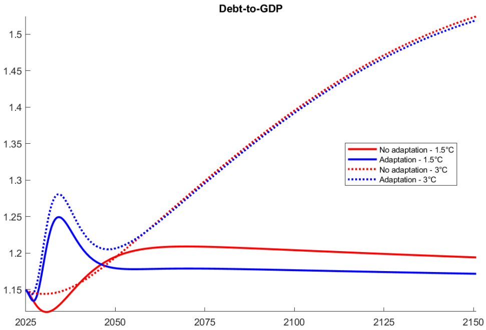
- Carbon taxation generates revenue, strengthening public finances.
- The public expenditures for adaptation benefit from larger fiscal space.
- But private financing has a cost on the private sector.

Main result:

- The main difference is in the trajectory of the public debt-to-GDP ratio.
- Adaptation expenditures have a reduced impact on public debt when mitigation is financed by private sources.
- Differences in macroeconomic impacts are more limited.

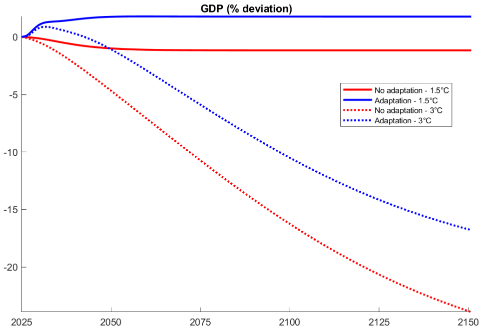
Comparing debt profiles with public (left) and private (right) financing of mitigation

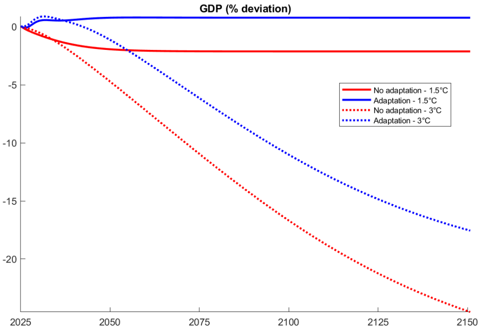




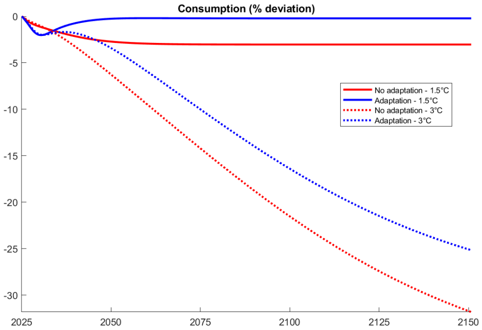
Simulation 2: Financing Mitigation through Private Sources

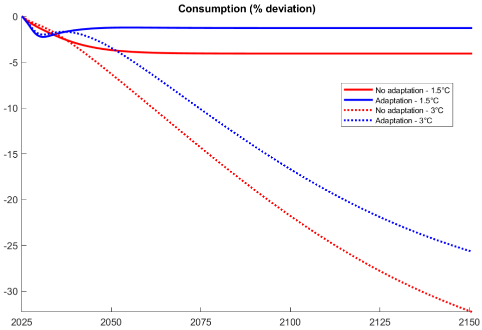
Comparing GDP profiles with public (left) and private (right) financing of mitigation



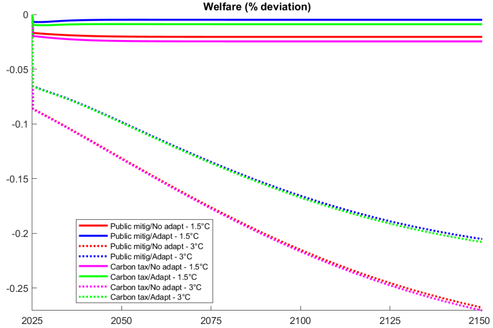


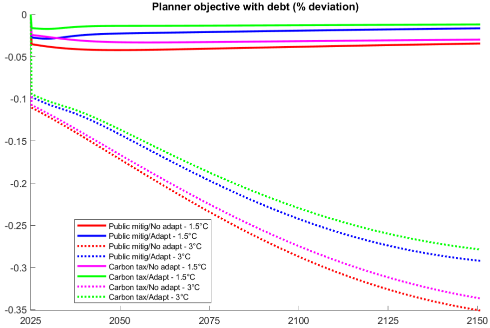
Comparing consumption profiles with public (left) and private (right) financing of mitigation





Evaluating the Planner objective when not caring for debt accumulation vs when caring

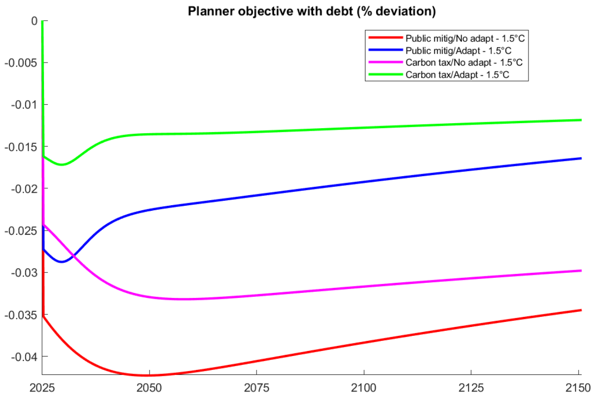




$$V_t = \left(\ln C_t - \mu_L \frac{L_t^{1+\sigma_l}}{1+\sigma_l} \right) + \beta \mathbb{E}_t V_{t+1}$$

$$V_t^d = \left(\ln C_t - \mu_L \frac{L_t^{1+\sigma_l}}{1+\sigma_l} - \mu_d \frac{d_t^{1+\sigma_d}}{1+\sigma_d} \right) + \beta \mathbb{E}_t V_{t+1}^d$$

Evaluation of the Planner Objective when caring for debt accumulation



$$V_t^d = \left(\ln C_t - \mu_L \frac{L_t^{1+\sigma_l}}{1+\sigma_l} - \mu_d \frac{d_t^{1+\sigma_d}}{1+\sigma_d} \right) + \beta \mathbb{E}_t V_{t+1}^d$$

▶ Maximization

Concluding Remarks

- **Climate change poses major fiscal and economic risks.**
- **Mitigation is the most effective long-term strategy:** ambitious policies limiting warming to 1.5°C greatly reduce GDP losses and debt pressures.
- **Adaptation helps but is costly:** reduces damages, yet requires substantial upfront public investment.
- **Policy implications:**
  - Act immediately on ambitious mitigation (carbon pricing, private sector engagement).
  - Use adaptation strategically to protect against unavoidable damages while managing debt sustainability.
  - Delayed action increases risks of worsening fiscal imbalances, reduced welfare, and long-term instability.

Only ambitious mitigation ensures resilience and fiscal sustainability.

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Appendix – Mitigation Rule and Global Emissions

Mitigation rule:

$$m_t + m_t^g = \left(\frac{H_{t-1}}{\bar{E}_0^n}\right)^p, \quad m_t = \int_0^1 m_t(i)di \tag{9}$$

$$\frac{m_t^g}{m_t + m_t^g} = \theta \tag{10}$$

Global cumulative emissions:

$$H_t^G = H_{-1}^G + \frac{\bar{E}_0^G}{\bar{E}_0^n} H_t = H_{t-1}^G + \frac{\bar{E}_0^G}{\bar{E}_0^n} E_t, \tag{11}$$

where $\bar{E}_0^G$ and $\bar{E}_0^n$ are respectively the global and the national carbon budget from 2025 onward.

▸ Back to Model

Appendix – Firm's FOCs

$$(\delta L_t(i)) \quad \Theta_t(i) D_f(H_t^G) K_t(i)^{\kappa} (1-\kappa) Z_t^{1-\kappa} L_t(i)^{-\kappa} = W_t \tag{12}$$

$$(\delta K_t(i)) \quad \Theta_t(i) D_f(H_t^G) \kappa K_t(i)^{\kappa-1} (Z_t L_t(i))^{1-\kappa} = R_t^k \tag{13}$$

$$(\delta m_t(i)) \quad \tau_t^E \xi_t = (1 - s_t^A) \theta_1 \theta_2 [m_t(i)]^{\theta_2 - 1} \tag{14}$$

$\Theta_t(i)$: Lagrange multiplier associated to (7) and the marginal cost's component attached to labor and capital.[2]

$$\Theta_t = \frac{(W_t)^{1-\kappa} \left(R_t^k\right)^{\kappa}}{D_f(H_t^G) Z_t^{(1-\kappa)} \kappa^{\kappa} (1-\kappa)^{(1-\kappa)}} \tag{15}$$

$$MC_t = \Theta_t + (1 - s_t^A) \theta_1 m_t^{\theta_2} + \tau_t^E \xi_t (1 - m_t - m_t^g) \tag{16}$$

▸ Back to Model

[2] (12) & (13) $\Longrightarrow \frac{K_t(i)}{L_t(i)} = \frac{\kappa}{1-\kappa} \frac{W_t}{R_t^k}$.

Appendix – Household's FOCs [3]

$$(\delta C_t) \quad \frac{1}{C_t} = \lambda_t \tag{17}$$

$$(\delta L_t) \quad \mu_l L_t^{\sigma_l} = \lambda_t W_t \qquad \Rightarrow \text{MRS}_t \equiv -\frac{U_{l,t}}{U_{c,t}} = C_t \mu_l L_t^{\sigma_l} = W_t \tag{18}$$

$$(\delta B_t) \quad \frac{\lambda_t}{\beta \mathbb{E}_t\left[\lambda_{t+1}\right]} = \mathbb{E}_t\left[(1 - f\vartheta_{t+1})R_t^d\right] \tag{19}$$

$$\begin{aligned}(\delta I_t) \quad \lambda_t &= \lambda_t^k\left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}}\right] + \beta\mathbb{E}_t\left[\lambda_{t+1}^k S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right] \\ &= \lambda_t^k\left[1 - \frac{\iota}{2}\left(\frac{I_t}{I_{t-1}} - e^z\right)^2 - \iota\left(\frac{I_t}{I_{t-1}} - e^z\right)\frac{I_t}{I_{t-1}}\right] + \beta\mathbb{E}_t\left[\lambda_{t+1}^k \iota\left(\frac{I_{t+1}}{I_t} - e^z\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right]\end{aligned} \tag{20}$$

$$(\delta K_{t+1}) \quad \lambda_t^k = \beta\mathbb{E}_t\left[\lambda_{t+1}R_{t+1}^k\right] + \beta(1-\delta)\mathbb{E}_t\left[\lambda_{t+1}^k\right] \tag{21}$$

▸ Back to Model

[3]
$$\mathcal{L}_t = \mathbb{E}_t\sum_{i=0}^{\infty}\beta^i\left\{\ln C_{t+i} - \mu_L\frac{L_{t+i}^{1+\sigma_l}}{1+\sigma_l} + \lambda_{t+i}\left[\begin{array}{c}(1-f\vartheta_{t+i})R_{t+i-1}^d B_{t+i-1} + W_{t+i}L_{t+i} + \Pi_{t+i} + \\ +R_{t+i}^k K_{t+i} - T_{t+i} - I_{t+i} - C_{t+i} - B_{t+i}\end{array}\right] + \lambda_{t+i}^k\left[(1-\delta)K_{t+i} + I_{t+i}\left[1 - S\left(\frac{I_{t+i}}{I_{t+i-1}}\right)\right] - K_{t+i+1}\right]\right\}. \tag{22}$$

In case of default, govt pays lump-sum transfers V_t to households for compensation and is forced to unexpectedly face additional public expenditure (unexpected debt restructuring or reputational costs) $G_t^d \equiv f \vartheta_t B_{t-1} R_{t-1}^d$, which corresponds to a proportion f of financial losses.[4]

Government budget constraint:

$$B_t = (1 - \vartheta_t) B_{t-1} R_{t-1}^d - S_t + V_t + G_t^d, \tag{23}$$

$D_t \equiv d_{t-1} Y_{t-1} \equiv B_{t-1} R_{t-1}^d$: face value of debt to be repaid at t, which is decided in the previous period $t-1$.

▸ Back to Model

[4] In a similar fashion to Corsetti et al. (2013), the sum of G_t^d and each period's transfers V_t is arranged such that the real debt level remains unaltered in case of sovereign default.

- Debt stabilization equation :

$$\tau_t = \tau(y_t, y_{t-1}, y_*, b_t, b_{t-1}, b_*, \tau_{t-1}, \tau_*). \tag{24}$$

- Resource constraint:

$$Y_t = C_t + I_t + G_t + G_t^d + A_t + A_t^g + I_t^{Ad} \tag{25}$$

Back to Model

Detrending $\Longrightarrow$ The rules of rescaling are:

$$x_t \equiv \frac{X_t}{e^{zt}} \quad \text{for } X = \{C, Y, \Pi, K, I, W, A, S, V\}, \quad b_t^z \equiv \frac{B_t}{e^{zt}} = b_t y_t, \quad \lambda_t^Z \equiv \lambda_t e^{zt},$$

$$P_t^E \equiv \tau_t^E e^{-\omega t}, \quad e_t \equiv \frac{E_t}{e^{(z-\omega)t}}, \quad h_t^G \equiv \frac{H_t^G}{e^{(z-\omega)t}}$$

Lower case letters denote detrended variables, starred variables denote steady-state values.

Appendix – Calibration

Parameter	Value	Description
κ	0.33	Capital share of GDP
β	0.99	Discount factor
σ_l	1	Inverse of the Frisch elasticity of labor supply
μ_L	19.841	Disutility of labor
δ	0.025	Quarterly depreciation rate of capital
ι	15	Capital adjustment cost coefficient
θ	[0,1)	Share of public contribution over total mitigation efforts (Seghini and Dees, 2024)
s_A	0	Public subsidies to private mitigation efforts (for simplicity)
θ_1	0.023	Private abatement cost function coefficient (Seghini and Dees, 2024)
θ_2	1.8	Private abatement cost function convexity parameter (Seghini and Dees, 2024)
θ_3	0.023	Public abatement cost function coefficient (Seghini and Dees, 2024)
θ_4	1.044	Public abatement cost function convexity parameter (Seghini and Dees, 2024)
H^G_{-1}	2650	Cumulative global Gt CO_2 emissions until 2024
$\bar{E}^G_0$	240	Global carbon budget 2024 (Gt CO_2-e), 1.5°C at 67% probability
$\bar{E}^n_0$	1.9	Carbon budget per capita 2024 (Gt CO_2-e, France)
ξ_0	0.17	GDP carbon intensity (France)
ω	0.005	Average quarterly degrowth in carbon intensity 1990–2020 (France)
p	[0.9, 3]	Mitigation function parameter determining the speed of the transition
γ_1	0.08	Damage function parameter (to match Bilal and Känzig, 2024)
γ_2	0.00053	Conversion parameter of global GtCO_2 into excess global mean temperature (Dietz and Venmans, 2019)
δ^{Ad}	0.00125	Quarterly depreciation rate of adaptation capital
α_1	0.0002	Adaptation cost parameter, to match a ratio of investment in adaptation to GDP of 1% for an adaptive capacity of 20%
α_2	0.2	Adaptation cost parameter (Barrage, 2024)
Q_*	0.2	Final target of adaptive capacity in the adaptation scenarios
ρ^{Ad}	0.99	Parameter determining the speed of adaptation
$\bar{Z}$	1	TFP in the steady state (France)
z	0.005	GDP growth rate (France)
g	0.2	Public expenditure as fraction of GDP in the initial period
d_0	1.1	Initial debt-to-GDP (France)
b_M	1.7	Fiscal limit (France)
σ_B	0.08	Parameter of the probability of default
ϑ	0.7	Haircut in case of public default
f	0.3	Post-default government expenditure as a fraction of lost value
ϕ_τ	0.999	Stabilization function parameter for ϕ_τ
ϕ_y	0.995	Stabilization function parameter
ϕ_b	0.3	Stabilization function parameter

Appendix – Calibration

- Objective of Lump-Sum Tax: to stabilize the debt-to-GDP ratio to its final steady-state value, b_*, and to gradually reach the consistent long-term lump-sum tax value, τ_*.
- Parametrization of (24) captures the generally limited tax buoyancy in the short-term, highlighted by empirical studies on tax responsiveness (Cornevin, Flores, and Angel, 2023):
  - ϕ_τ: smoothness weight on past values.
  - ϕ_b: response of τ_t to debt-to-GDP values.
  - ϕ_y: response of τ_t to the output gap.

▶ Back to Calibration

Appendix – Welfare maximization and the optimal adaptive capacity

Social planner's problem: committed choice of $_t$ in order to maximize the planner objective, defined as:

$$\max_{Q_t} V_t = \left(\ln C_t - \mu_L \frac{L_t^{1+\sigma_l}}{1+\sigma_l} \right) + \beta \mathbb{E}_t V_{t+1}, \tag{26}$$

$$\text{or} \quad \max_{Q_t} V_t^d = \left(\ln C_t - \mu_L \frac{L_t^{1+\sigma_l}}{1+\sigma_l} - \mu_d \frac{d_t^{1+\sigma_d}}{1+\sigma_d} \right) + \beta \mathbb{E}_t V_{t+1}^d, \tag{27}$$

subject to all the equations describing the competitive equilibrium.

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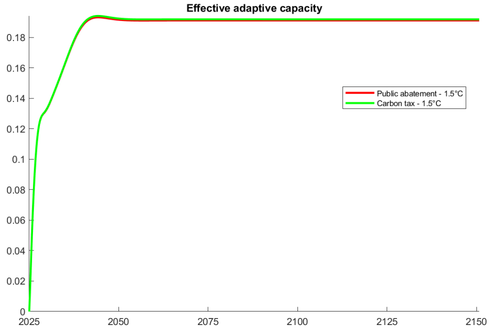
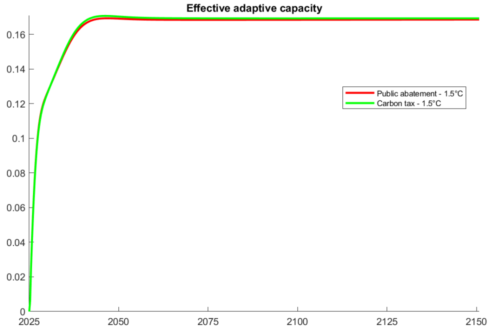
Appendix – Maximizing the Planner objective when not caring for debt accumulation vs when caring



$$\max_{Q_t} V_t$$



$$\max_{Q_t} V_t^d$$

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