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SOVEREIGNS ON THINNING ICE: DEBT SUSTAINABILITY, CLIMATE IMPACTS AND ADAPTATION

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A fundamental problem for sovereigns enacting climate policies is whether they can manage increasing debts as their economies suffer from adverse climate impacts. We develop stochastic debt sustainability analysis integrating a coupled climate-economy model with debt financing scenario optimisation, and stress test sovereign debt for representative countries globally under the Intergovernmental Panel on Climate Change marker narrative scenarios of climate change. The stress test combines socioeconomic and climate pathways with calibrated aleatory scenario trees of economic, fiscal and financial variables to generate forward-looking debt projections over the century. These projections incorporate climate-induced damages to economic growth, spanning the broad spectrum of impact functions from the literature. Our findings reveal significant risks to sovereign debt sustainability, particularly under high climate damages, that are large from mid-century. Expected costs increase by up to 3 percent of GDP under high climate impact in a world of regional rivalries, or 0.25 percent under low impact in a middle-of-the-road narrative, with considerable variation between countries. The long-run debts of highly impacted countries are unsustainable. We assess whether adaptation investments or fiscal consolidation can mitigate potential climate-debt crises. Public financing of reactive adaptation is a justified expenditure that breaks even but does not fully restore the debt sustainability of highly impacted high-debt countries. Maintaining public spending while ensuring debt sustainability appears infeasible under climate impacts.

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1 Introduction

The strains placed on public finance by climate change, as highlighted in the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC, 2023), raise concerns about potential sovereign defaults (Cevik and Tovar-Jalles, 2022a; Dibley *et al*, 2021). An ongoing debate on the affordability of climate mitigation and adaptation policies (Bolton *et al*, 2022; Kreibiehl *et al*, 2022) calls for large-scale climate finance (Bolton *et al*, 2024). However, to assess the ability of the public purse to finance climate actions, the impact of climate change on sovereign debt must be evaluated. Despite a burgeoning literature on climate impacts on sovereign debt pricing[1], studies on the impacts on debt sustainability are missing (Rising *et al*, 2022). We fill this gap with an interlinked climate-debt-sustainability analysis model to stress-test sovereign debts in scenarios of damage to economic growth caused by climate change. We find that debt sustainability can be jeopardised, and ask whether investments in adaptation are sufficient to avert climate-debt crises.

Integrating climate risk in debt sustainability analysis faces challenges from deep uncertainty when measuring the climate impacts using analytical models (Lempert *et al*, 2024) and tail risk (Weitzman, 2011). To describe deep uncertainty consistently, we turn to *narrative scenarios* (Climatic Change, 2014), in line with the IPCC (Kause *et al*, 2022). This approach aligns with stochastic debt sustainability analysis (SDSA), which uses *scenario trees* to describe probabilistically economic, fiscal and financial variables, and estimates debt tail risk with a coherent measure (Zenios *et al*, 2021). Scenario analysis for tail risk facilitates the linking of climate models to SDSA.

We adopt a model-based, data-driven multidisciplinary approach in which projections on the basis of narrative scenarios of coupled climate-economy models in the tradition of Nordhaus (2019) are linked with an SDSA model. These projections provide expectations that can be used to calibrate aleatory scenario trees of the economic, fiscal and financial debt determinants. A scenario optimisation model trades-off debt financing costs with the tail risk of debt refinancing to project future debt trajectories and assess sustainability with a high level of confidence. The interlinked models translate climate science into a credible sovereign risk metric for policymakers who rely on debt sustainability analysis[2].

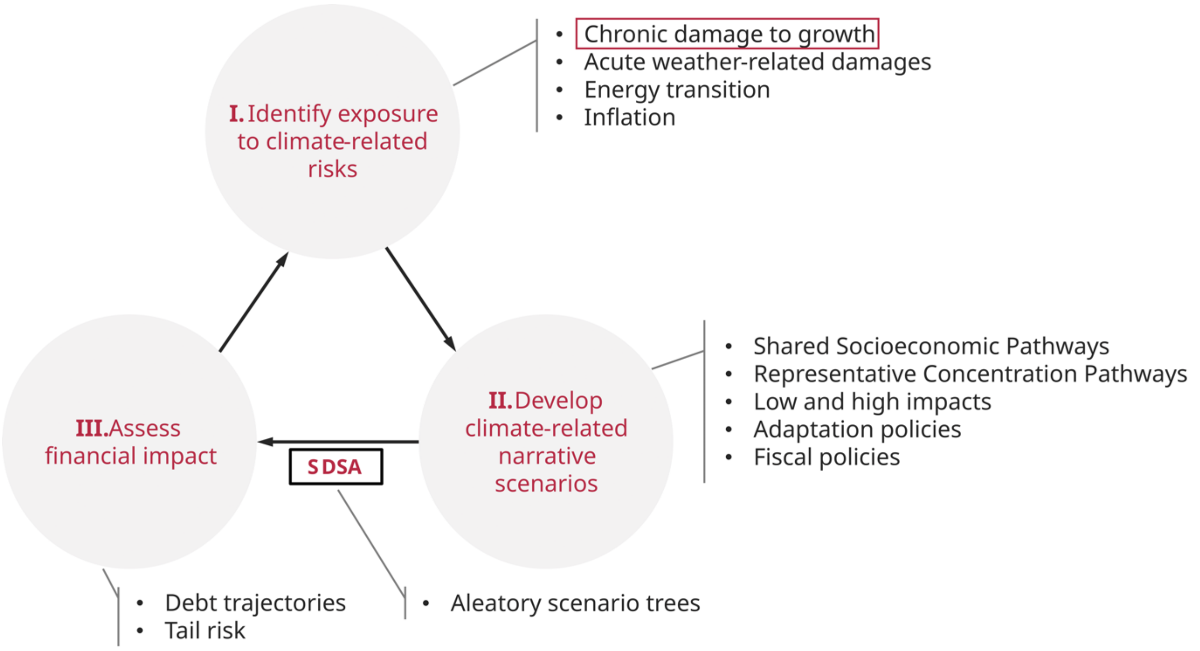
Using the model, we stress-test a sample of countries globally and find a significant shift in the cost-risk trade-off. Expected costs increase by up to 3 percent of GDP in a high climate impact scenario in a world of regional rivalries, or 0.25 percent in low impact scenario in a middle-of-the-

[1] See for example Battiston *et al* (2019), Beirne *et al* (2021), Cevik and Tovar-Jalles (2022b), Kling *et al* (2018), Kölbel *et al* (2024) and non-overlapping surveys by Campiglio *et al* (2023), Krueger *et al* (2020), Stroebel and Wurgler (2021).
[2] These include the International Monetary Fund (IMF, 2022), Bank for International Settlements (Alberola *et al*, 2023), European Central Bank (Bouabdallah *et al*, 2017), European Commission (2020), European Stability Mechanism, (Zenios *et al*, 2021), national public debt-management offices and EU member states' independent fiscal councils, and the European Fiscal Board (see https://commission.europa.eu/topics/fiscal-policy/european-fiscal-board-efb/public-finances-and-climate-change-post-pandemic-era_en).

road narrative, with considerable differences between countries. Second, the long-run debts of highly impacted countries are unsustainable and will require surpluses of up to 4 percent of GDP to stabilise. Third, adaptation investments moderate the adverse effects and break even when the government finances about one-third of the adaptation cost. Finally, we find that governments cannot sustainably maintain current levels of public spending even in a scenario of limited damages. We find that the climate effects are quite substantial from mid-century.

We develop the stress tests in three steps (sections 1.1 to 1.3, corresponding to the circles I, II and III in Figure 1) following the United Kingdom's Prudential Regulation and the Financial Conduct Authority climate risk framework (CFRF, 2021). Figure 1 shows the steps in the climate-scenario analysis process in order to stress test sovereign debt sustainability using SDSA. 'Chronic damages to growth' is the risk we have modelled specifically in this paper; 'SDSA' is the climate debt sustainability analysis model in section 2.

Figure 1: Climate stress test for sovereign debt



Source: Bruegel based on CFRF (2021).

1.1 Identify exposure to climate-related risks

The exposure of sovereign debt to climate risks is substantiated by the extensive literature on the channels leading from climate to the macroeconomy (Bolton *et al*, 2022; Volz *et al*, 2020). Sovereign debt, as a ratio to GDP, is affected by: (i) chronic effects on growth as a result of increasing temperatures, (ii) acute effects from damages arising from adverse weather events (floods, hurricanes, forest fires, etc) that can increase government spending and reduce growth, (iii) the effects from the transition to a low-carbon economy and (iv) potential effects of the above on inflation and the natural rate of interest (Mongelli *et al*, 2024) (in this paper, we focus on chronic damage to growth and potential adaptation policies).

1.2 Develop climate-related narrative scenarios

We use a state-of-the-art cost-benefit integrated assessment model (IAM) – the RICE50+ model of Gazzotti *et al* (2021) – to develop climate-related scenarios for the specific exposure we study. However, IAMs are prone to deep uncertainty. To increase the acceptance of our findings, we therefore follow Howe *et al* (2019) and develop narratives for multiple future socioeconomic and warming scenarios, climate impact functions and adaptation financing policies. We adopt the Shared Socioeconomic Pathways (SSP; Riahi *et al*, 2017) that describe future global and regional macroeconomic trajectories in the absence of new climate policies.

SSPs are widely used in the climate-economy literature to provide the baseline for climate impacts, mitigation and adaptation analyses. We combine SSPs with Representative Con- centration Pathways (RCPs; O'Neill *et al*, 2016) that describe possible future developments of anthropogenic drivers of climate change, their atmospheric concentration and radiative forcing. SSP-RCP pairs constitute a coherent framework for socioeconomic development and related global warming (Climatic Change, 2014). They provide a scenario matrix architecture to comprehensively study climate effects on debt.

We use the IPCC *marker narrative scenarios* SSP2-RCP4.5 (Fricko *et al*, 2017) and SSP3-RCP7.0 (Fujimori *et al*, 2017)[3]. SSP2 is the 'middle-of-the-road' narrative of socioeconomic and technological trends following historical patterns. SSP3 is the 'regional rivalry' narrative of international fragmentation resulting from a reversal in globalisation trends, as observed in current regional rivalries and conflicts. RCP4.5 and RCP7.0 narrate moderate or relatively high greenhouse gas emissions, corresponding to median temperature rises of circa 2.4-3.4 degrees Celsius above pre-industrial levels by 2100.

We also consider alternative sensitivities of economic growth to climate change, using *low* (Kalkuhl and Wenz, 2020) and *high* (Burke *et al*, 2015) impact functions. These functions span the broad estimates from the existing climate-economy models (see Appendix Figure B.1). Finally, we consider alternative adaptation policies that moderate the impact of climate damages on growth (Agrawala *et al*, 2011). However, these policies also incur costs that will be borne, in part, by public budgets. The narrative scenarios with different impact functions and adaptation policies provide the mean values for calibrating aleatory scenario trees for the SDSA model over a long horizon.

Of course, the model can analyse other narratives apart from those we discuss in this paper. We avoid

[3] Data for the SSP and RCP scenarios are available from the IIASA database, https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about, last accessed July 2024, and is integrated into RICE50+. The climate SDSA model could stress-test any available SSP-RCP combination.

choices that bias the results toward higher debt, and discuss situations in which such biases may creep in and how we deal with them so that our debt increase projections can be considered conservative. For instance, we use historical market volatilities to calibrate scenario trees, while climate risks can increase volatility with a further adverse impact on debt.

1.3 Assess financial impacts

We assess the climate impacts on the cost-risk trade-off and compare the resulting debt- to-GDP trajectories up to the end of the century against reference trajectories from *zero-damage* SDSA, ie without climate impacts[4]. We develop reference trajectories that assume a primary balance that stabilises each country's debt (pb*) to abstract from cross-country differences in the currently high debt levels. We then use the SDSA model to generate debt trajectories under climate-related growth narratives. We run the model on scenario trees calibrated on RICE50+ growth projections under the narratives SSP2-RCP4.5 and SSP3-RCP7.0, and, for each, under low- or high-impact functions.

The climate-impacted debt trajectories provide information about whether climate risks jeopardise sustainability. In line with the IMF's notion of sustainability (IMF, 2022), we consider an upward-trending debt trajectory as an indicator of potential future debt unsustainability, since servicing it requires an increasingly higher share of the economy's GDP and the sovereign will eventually hit its budget constraint, precipitating a debt crisis (Blanchard, 2022). To establish if the debt is sustainable, we estimate the primary balance that can stabilise the climate-impacted trajectories (pb**) and compare it against historical episodes of fiscal consolidation compiled by Eichengreen and Panizza (2016). They found that primary surpluses averaging 3 percent of GDP for up to five years have been possible, and we take this to be the threshold for feasible fiscal policies of sustainable debt.

We assess debt sustainability at a high 75 percent confidence level, which is classified as 'likely' by the IPCC (Kause *et al*, 2022). We report results for the deep uncertainty about the future socioeconomic scenarios, concentration pathways, and parameters describing climate impacts and do so at a high confidence level under aleatory uncertainty. We attach high confidence to our results if there is agreement across these tests.

We go beyond the stress tests to ask whether investments in adaptation can dampen or offset the risks to sovereign debt of climate change. Using RICE50+, we compute the cost-benefit ratios of adaptation and incorporate the trade-off into the debt dynamics using different policies in terms of who pays for the adaptation investment: the private sector entirely (no fiscal cost), the public sector entirely or some combination.

[4] End-of-century is the horizon in studies of the long-term impact of climate change (Kreibiehl *et al*, 2022). Financial regulators also use very long horizons in stress-testing physical climate risks as follows: Banco de la Republica Colombia, 80 years; Bank of England, 60; Japan Financial Services Authority and Bank of Japan, 80; People's Bank of China, 40. The European Central Bank uses GDP and greenhouse gas projections up to the end of the century, but performs banking stress tests over a 30-year horizon as a compromise between the importance of assessing the long-term impact and keeping reasonable prediction intervals.

Finally, we test whether it is possible to maintain constant nominal public spending when facing climate impacts, and document a tension between public spending and sustainable debt, which may not be reconcilable under climate change.

To our knowledge, this is the first study of the effects on debt sustainability of chronic damages from climate change and adaptation effects. We develop an SDSA-IAM methodology (section 2), calibrate aleatory scenarios on climate narratives (section 3), stress-test a sample of countries (section 4), and ask whether the climate effects can be offset through adaptation or fiscal consolidation (section 5). Finally, we ask if it is possible to reconcile constant public spending with debt sustainability (section 6) and conclude (section 7).

1.4 Literature review

The literature on the risks to sovereign debt from climate change is at an early stage but growing, albeit with limited analytical modelling. Bolton *et al* (2022) and Volz *et al* (2020) discussed the channels from climate to debt. Kreibiehl *et al* (2022) discussed the strains on public finance. Dibley *et al* (2021) assessed the challenges for countries with high debt levels. Empirical works using historical data have established that vulnerable countries pay more in servicing their debts and are more likely to be excluded from capital markets (Kling *et al*, 2018), that both climate change and resilience matter for the cost of government borrowing (Beirne *et al*, 2021) and that rising temperatures are detrimental to the creditworthiness of emerging economies (Boehm, 2021). Cevik and Tovar-Jalles (2022a) went beyond borrowing costs to study the probability of default and showed that vulnerable countries face higher default risks, which can be reduced by investing in adaptation. Akyapı *et al* (2024) found large but not always statistically significant effects of weather shocks on fiscal aggregates.

Forward-looking analyses of climate risks to sovereign debt risk are scant. IAMs provide forward-looking climate and macroeconomic projections, and a large variety of models has been developed since the seminal DICE model of Nordhaus (1993) because of the leading role that IAMs play in climate policy research and assessment (Cointe *et al*, 2019). Cost-benefit and process-based IAMs are used to perform impact analysis integrated with mitigation and adaptation policies (Weyant, 2017). The former focus on estimating critical aggregate parameters such as the social cost of carbon (Metcalf and Stock, 2017), while the latter are the backbone of the IPCC Working Group III on mitigation (Skea *et al*, 2021). The linking of IAMs with SDSA to assess the climate effects on debt through various channels was suggested by Zenios (2022).

We develop an interlinked model for chronic damages and adaptation to stress test several countries and evaluate alternative government policy responses. Since we assume no mitigation, the difference between detailed-process and cost-benefit IAMs becomes quite narrow, and we employ RICE50+ from Gazzotti *et al* (2021). This is a benefit-cost optimisation model based on, but widely expanding, DICE. With RICE50+, we maximise the geographical resolution and explainability of the results. A work close to ours is Klusak *et al* (2023), who trained a random forest machine-learning model to predict sovereign ratings and then used empirically calibrated long-term macroeconomic effects of climate change to project future ratings. We go beyond credit ratings to assess debt sustainability. An increasing risk of non-sustainability, as we find, implies downgrading, as Klusak *et al* (2023) found, but lower ratings do not necessarily imply unsustainable debt. We answer the sustainability question, uncovering the mechanisms leading from climate change to downgrading. Recent forward-looking studies have modelled the risk to sovereign debt from transition to a low-carbon economy (Kellner and Runkel, 2023; Mammetti and Zenios, 2024; Seghini, 2024) but have not considered the problems from damages or adaptation.

Our study integrates models of different paradigms to advance the climate-debt literature in several directions. First, we go beyond measurement of climate impact through a single indicator, such as bond yields or credit ratings, to compute the distribution of future debt trajectories with a tail-risk measure and assess sustainability. Second, we consider the deep uncertainty about climate impacts using narrative SSP-RCP scenarios and low- and high-impact functions that span the broad space generated by an extensive literature on this topic. Third, we shed light on the effects of government adaptation policies. Finally, we document a challenge in prioritising debt sustainability or government spending.

2 Methods

We describe the interlinked model. We follow the SDSA model of Zenios *et al* (2021) that solves a Pareto optimisation model to minimise the costs of debt financing subject to a tolerable level of refinancing risk with sustainability conditions. The model generates debt stock and flow dynamics with an associated tail-risk measure to optimise debt financing. For IAM, we use RICE50+ (Gazzotti *et al*, 2021) to generate, among other variables, country-level granular projections of GDP under narrative scenarios for different impact functions or adaptation policies. These narrative scenarios are the expected values on which we calibrate the scenario trees of economic growth, fiscal stance, and interest rates for the SDSA model, including also the costs and benefits from adaptation.

2.1 The debt sustainability analysis model

2.1.1 Model setup

We start with the legacy debt D_0 of a sovereign with primary balance PB_t, at time t, and nominal economic output Y_t determined by its growth rate g_t. If i_{t-1} denotes the *effective nominal interest rate* on debt, the *debt stock* is given by $D_t = (1+i_{t-1})D_{t-1} - PB_t$, and the *gross financing needs* are given by the *flow* variable $GFN_t = i_{t-1}D_{t-1} + A_t - PB_t$, where A_t denotes debt stock amortization. Debt *financing decisions* $X_t(j)$ denote the nominal amount issued with maturities denoted by $j = 1, 2, . . . , J$ to satisfy

$$\sum_{j=1}^{J} X_t(j) = GFN_t. \tag{1}$$

The nominal interest rate on the issued debt is determined by the risk-free rate (r_{ft}) plus a risk premium on the sovereign debt, modeled as a function of the debt-to-GDP ratio (Zenios *et al*, 2021). The interest rate for instrument *j* issued at *t* is given by $r_t(j) = r_{ft} + \rho(d_t, j)$. Here, $d_t = D_t/Y_t$ and $\rho(d, j) = a_j + \hat{\rho}(d)$ are the premia for the *j*th instrument maturity, with a_j's the *term premia* for debt of different maturities and $\hat{\rho}(d)$ the risk premium as a function of debt stock. $r_t(j)$ determines the effective interest rate on the debt stock as a function of the issued debt through financing decisions $X_t(j)$.

2.1.2 Stochastic debt financing optimisation

Scenario trees

We introduce aleatory uncertainty in growth, fiscal stance and risk-free interest rates using a discrete-time-and state-space scenario tree. We denote time by $t = 0, 1, 2, \ldots T$, where T is our risk horizon, and *states* at *t* by $\nu \in N_t$. The number of states at *t* is N_t, with a total number of states *N*. Not all states at *t* can be reached from every state at $t - 1$, and $a(\nu)$ denotes the unique *predecessor* of state ν. $\mathcal{P}(\nu)$ denotes the set of states on the unique *path* from the *root state* 0 to ν, with all information at $m \in \mathcal{P}(\nu)$ known since *m* precedes ν. Each path leading to a terminal state $\nu \in N_T$ is a *scenario* with probability $\text{Prob}^{(\nu)}$, the product of conditional probabilities on the path. Data and variables are state-dependent, indexed by ν and $\tau(\nu)$ denotes the time of ν.

The tree need not be binomial, and we estimate simultaneously the levels and conditional probabilities using moment matching (Høyland and Wallace, 2001) to generate trees that match the moments with a relatively small number of scenarios. Specifically, we solve a global optimisation problem estimating the level of the state variables and the associated conditional probabilities so that at each period, their mean values, standard deviations, and correlations match input data (Consiglio *et al*, 2016). For growth, the means match the RICE50+ projections. For fiscal stance, the means match the five-year forecasts from the IMF World Economic Outlook, subsequently converging to a value that stabilises long- term debt in the absence of climate damage or adaptation. Mean values of the risk-free forward rates are matched to the market expectations from the yield curve. We also match the historical standard deviations and correlations. For details, see section 3.

The states ν refer to a scenario tree calibrated to the RICE50+ projections under a narrative scenario, ie $\nu \doteq \nu(\text{SSP-RCP})$. For simplicity of notation, we do not use SSP-RCP superscripts in formulating the state-dependent model and we specify the narratives when reporting results.

Debt dynamics and the risk measure

We introduce state-dependent financing decisions, $X_t^\nu(j)$, to obtain state-dependent debt trajectories on the tree. The debt financing equation (1) on the tree becomes

$\sum_{j=1}^{J} X_t^{\nu}(j) = \mathrm{GFN}_t^{\nu}$, (2)

for $\nu \in \mathcal{N}_t$, and $t = 0, 1, 2, \ldots T$, where $\mathrm{GFN}_t^{\nu} = i_{t-1}^{a(\nu)} D_{t-1}^{a(\nu)} + A_t^{\nu} - \mathrm{PB}_t^{\nu}$, and D^{ν} is obtained from the state-dependent stock equation as $D_t^{\nu} = \left(1 + i_{t-1}^{a(\nu)}\right) D_{t-1}^{a(\nu)} - \mathrm{PB}_t^{\nu}$. The debt stock and flow, as ratios to GDP, are given by $d_t^{\nu} = D_t^{\nu}/Y_t^{\nu}$ and $\mathrm{gfn}_t^{\nu} = \mathrm{GFN}_t^{\nu}/Y_t^{\nu}$.

The effective interest rate on debt i_t^{ν} is obtained from the state-dependent interest on the issued financing instruments $r_t^{\nu}(j) = r_{ft}^{\nu} + a_j + \hat{\rho}(d_t^{\nu})$.

We use the distributions of the stock and flow ratios on the scenario tree to assess debt sustainability. We consider debt sustainable when stock is on a non-increasing trajectory in the long run with a high probability (Blanchard, 2022), and refinancing needs are below a threshold that markets can finance with high probability. If flows exceed the threshold, the sovereign can face a liquidity crisis, and if the stock keeps increasing, the sovereign will face a solvency crisis.

To obtain model results with high confidence, Zenios *et al* (2021) introduced a tail-risk measure of the gross financing needs, using *conditional-Value-at-Risk* (CVaR; Artzner *et al*, 1999), defined as the expected value of financing needs above the right α percentile.

If *gfn* denotes the gross financing needs stochastic variable over all periods, the CVaR of flow is given by $\Psi(\mathrm{gfn}) \doteq \mathbb{E}(\mathrm{gfn} \mid \mathrm{gfn} \geq \mathrm{gfn}^{\diamond})$; $gfn^{\diamond}$ is the Value-at-Risk defined as the right α-percentile of the gross financing needs, ie the lowest value of *gfn* such that the probability of gross financing needs less or equal to $gfn^{\diamond}$ is greater or equal to α. If $\Psi(gfn)$ is bounded by a threshold that markets can finance, then debt can be refinanced with a (high) probability α[5].

Optimal debt financing with sustainability conditions

The SDSA model optimises debt financing to minimise the expected *net interest payment* subject to acceptable levels of refinancing risk and sustainability of debt stock.

Interest payments on state ν consist of interest on legacy debt I_t^{ν} plus service payments on the debt created by financing decisions. We calculate the service payments on a path leading to ν exploiting the tree structure. Let $\mathrm{CF}_t^{\nu}(j, m)$ denote the nominal amount of interest due at state ν of period *t*, per unit of debt $X_{\tau(m)}^{m}(j)$ issued at state *m* of an earlier period τ (*m*) on path $\mathcal{P}(\nu)$. This amount is computed from scenarios of the term structure of interest rates and the maturities of the issued debt. The state-dependent net interest payment that the issuing sovereign controls through the financing decisions is given by

[5] The flow threshold is set between 15 percent and 20 percent in Bouabdallah *et al* (2017, p. 29).

$$\text{NIP}_t^\nu = I_t^\nu + \sum_{m\in\mathcal{P}(\nu)} \sum_{j=1}^{J} X_{\tau(m)}^m (j)\text{CF}_t^\nu(j,m). \qquad (3)$$

Recall the dependence of the SDSA variables on narrative scenarios under projections from RICE50+ through growth impacts or adaptation costs, and we solve a Pareto model for each SSP-RCP narrative scenario to minimise the expected cost of debt subject to the flow risk bounded by a parameter ω:

$$\text{Minimize}_X \sum_{\nu\in\mathcal{N}_t,\, t=0,1,2,\dots,T} \text{Prob}^{(\nu)}\ \text{NIP}_t^\nu \qquad (4)$$

$$\text{s.t.} \qquad \Psi(\text{gfn}) \leq \omega. \qquad (5)$$

Issuing debt at the lowest-yield maturity lowers the financing cost but increases refinancing risk when all maturing debt must be refinanced. Varying ω, we obtain efficient frontiers of the trade-off between debt financing cost and refinancing risk. If ω is below the threshold that markets can finance, we ascertain, with high confidence, that financing needs can be met. However, debt stock is higher for lower ω and may be put on an increasing, unsustainable trajectory, so there is a tension between stock and flow.

Zenios *et al* (2021) imposed a constraint on the inter-temporal rate of change of debt, using the CVaR risk measure of the debt stock ratio, ie $\Psi\left(\frac{\Delta d^\nu}{\Delta t}\right) \leq 0$. However, if debts are not sustainable, as our research question seeks to establish, the model with both flow and stock constraints has no feasible solution. Instead, we solve for the minimum cost solution for an intermediate ω and check if the debt stock trajectories are non-increasing with a high probability. If debt stock turns out to be increasing, we use a model extension (Zenios *et al*, 2021, section 6) to optimise fiscal adjustments that stabilise debt in the long run with high probability. Introducing variable z_t to denote adjustments as a proportion of GDP, we write the debt financing equation (2) as

$$\sum_{j=1}^{J} X_t^\nu (j) + z_t Y_t^\nu \geq \text{GFN}_t^\nu. \qquad (6)$$

$z_t Y_t^\nu$ is the part of gross financing not financed by issuing debt; it is the required fiscal adjustment that increases the primary balance to repay debt. To obtain the minimum adjustments, we add a penalty term $M\sum_{t=0}^{T} z_t$ to (4), where *M* is a large constant.

We compute the temporal average of the estimated fiscal adjustment over the periods for which such an adjustment is warranted and call it the *debt-stabilising primary balance* pb*. If pb* is below the 3 percent threshold from Eichengreen and Panizza (2016), we conclude that there is a feasible fiscal policy to render debts sustainable[6].

[6] SDSA is a partial equilibrium model without feedback from increasing primary balance to economic growth, so our debt estimates are optimistic (Gechert *et al*, 2024).

2.2 The RICE50+ coupled climate economy model

We use RICE50+ to obtain GDP growth projections under the SSP-RCP narratives and for different impact functions or adaptation policies. We describe here the relevant aspects of the model, in which unabated economic activity produces emissions that influence temperatures with a concomitant impact on economic activity. The model treats emissions as endogenous, determined by two decision variables that reflect climate policies: the abatement rate controlling emission reductions and the savings rate controlling capital accumulation. For our analysis, we constrain the model to follow the specified narrative outcomes. That is, we assume fixed saving rates so that GDP follows the pathways implied by SSP2 or SSP3 and constrain emissions to generate pathways consistent with RCP4.5 or RCP7.0. These macroeconomic projections are subject to the Lucas critique since agents do not adjust their behaviour following policy and climate changes. Nevertheless, we isolate the direct effect of climate change on debt sustainability without the confounding indirect effects. RICE50+ is a discrete-time model with five-year time steps, and we interpolate its projections to the annualised SDSA model using Stineman (1980).

2.2.1 Climate impacts

We calculate the impact of climate change on GDP under the temperature projections from RCP4.5 and RCP7.0. The temperature-contingent impact factor Ω_t is estimated empirically (see subsection 3.2.2) and leads to a GDP $\tilde{Y}_t = \frac{Y_t}{\Omega_t}$, in which ~ denotes climate-impacted variables. The temporal impact function is given by

$$\Omega_{t+1} = \left(\iota_{t+1}^{k} + \frac{1}{\Omega_t + 1}\right)^{-1} - 1 \qquad (7)$$

where ι^k is the climate impact factor calibrated to the estimates of Kalkuhl and Wenz (2020) ($k = L$, for low) and Burke *et al* (2015) ($k = H$, for high) impact functions.

Kalkuhl and Wenz (2020) captured both transitory and persistent damages by

$$\iota_t^L = \beta_1^L \Delta T_t + \beta_2^L \Delta T_{t-1} + \beta_3^L T_{t-1} \Delta T_t + \beta_4^L T_{t-1} \Delta T_{t-1}, \qquad (8)$$

with T_t temperature levels and ΔT_t temperature change with one-year lagged ΔT_{t-1}. The β^L's are estimated from historical country GDP and climate data. Burke *et al* (2015) captured persistent climate impacts in addition to the baseline impact from

$$\iota_t^H = \beta_1^H (T_t - \bar{T}) + \beta_2^H (T_t^2 - \bar{T}^2), \qquad (9)$$

where T is the temperature under the narrative RCP and $\bar{T}$ is the baseline temperature without further global warming, defined as the average country temperature between 1980 and 2010. β^H and β^H are empirically calibrated on country-level data.

The econometric estimations of GDP-temperature relationships reflect past trends (Newell *et al*, 2021) and are criticised for missing some risks (Rising *et al*, 2022) and their out-of-sample accuracy. Nevertheless, the functions we use span the best available science of the economic impact of climate change (see Appendix Figure B.1, Panel A). The low-impact function assumes that temperature has both a level and a growth effect on income, ie a temporary and a permanent effect, with projected GDP losses below 10 percent even in high-warming scenarios. The high-impact function assumes a quadratic relationship between temperature and output growth and projects major economic disruption from climate change. It is remarkably close to recent estimates by Kotz *et al* (2024); see Appendix Figure B.1, Panel B. We use both of these functions to capture model uncertainty in quantifying the climate change effect on growth (subsection 3.2.2).

2.2.2 Adaptation

Investments in adaptation can reduce climate damage if global warming materialises, and we introduce adaptation and its financing in SDSA. We follow Agrawala *et al* (2011), the seminal work integrating aggregate adaptation effects into IAMs. They distinguished adaptation investments with contemporaneous benefits (*reactive adaptation*, such as disaster relief or recovery, or energy expenditures for heating or cooling) from those with delayed benefits (*proactive adaptation*, such as building coastal protection infrastructure or installing heating and cooling units). They also considered *adaptive capacity*, such as early warning systems, linked to the level of economic development and investments in R&D.

They estimated adaptation cost curves, dynamically linking adaptation cost with the benefits from reduced climate damages. The benefits result from adaptation actions, which are the aggregation of imperfectly substitutable proactive and reactive adaptation, which is, in turn, an imperfect substitute for adaptive capacity building. Adaptation is endogenously determined in RICE50+ by optimising investments in proactive adaptation, adaptive capacity building and reactive adaptation expenditures using cost-benefit analysis (Bosello and Cian, 2014). Capacity building includes an exogenous component that depends on the GDP of a shared socioeconomic path. Overall, this approach accounts for improvements in general socioeconomic conditions, eg through technological innovations, and also from specific adaptation decisions. The cost curves assume decreasing marginal damage reduction from adaptation, implying that more efficient measures are enacted first.

The optimal investments in the three adaptation components are aggregated through nested constant elasticity of substitution functions to form the adaptation quantity Q_t.

This quantity is transformed by

$$\Theta_t = \frac{1}{1+Q_t^{\epsilon}} \quad (10)$$

to obtain the adapted GDP input to SDSA, $\widetilde{Y}_t^{\mathrm{A}} = \frac{Y_t}{\Omega_t}\Theta_t$, with reduced climate damages. ϵ is a region-specific adaptation efficiency parameter.

From RICE50+, we obtain projections of the adapted GDP and the investment costs for different types of adaptation. We link these projections to SDSA by decomposing the primary balance to account for a fiscal revenue increase from the adapted GDP and the adaptation investments paid by the government.

2.3 Fiscal policies

In standard SDSA, the primary balance is an aggregate fraction of GDP without specifying government revenues and spending. Decomposing the primary balance into its revenue and expenditure components allows us to incorporate increased revenues as a result of improved GDP following the public spending on adaptation, but also the cost of this spending. It also allows us to consider alternative fiscal policies for a government facing the impact of climate change to (i) adjust its primary balance to ensure debt sustainability, or (ii) keep *constant spending* in nominal value. Governments with adversely affected GDP will have to adjust (decrease) the primary balance to provide the same levels of services to their citizens. In contrast, those that are positively affected can maintain (or increase) spending. We consider the two boundary cases of prioritising debt sustainability or constant spending to preserve the services provided to citizens, but the model can also evaluate the impact of intermediate policies.

We decompose the primary balance equation $PB_t = R_t - G_t$ where R_t is the nominal value of public revenues and G_t is the nominal amount of public primary expenditure. Assuming tax revenues are a constant fraction τ of nominal GDP, we have $R_t = \tau Y_t$.

Using this decomposition, we model the adaptation effects on SDSA through higher GDP (revenues) and adaptation investments (cost). The additional tax revenues for the government under the improved GDP from an adaptation policy are given by

$$\widetilde{\Delta R}_t^{\mathrm{A}} = \tau\left(\widetilde{Y}_t^{\mathrm{A}} - \widetilde{Y}_t\right), \tag{11}$$

where superscript A denotes the adapted variables, $\widetilde{Y}_t^{\mathrm{A}}$ is the GDP level under climate change with adaptation, and $\widetilde{Y}_t$ is without adaptation. Using γ_t^p to denote public investment in adaptation under an exogenously specified policy p, as a proportion of GDP, we obtain the primary balance equation with the revenue increase from adaptation and the adaptation cost as

$$\widetilde{PB}_t^{\mathrm{A},p} = \widetilde{PB}_t + \tau\left(\widetilde{Y}_t^{\mathrm{A}} - \widetilde{Y}_t\right) - \gamma_t^p \widetilde{Y}_t^{\mathrm{A}}. \tag{12}$$

$\widetilde{PB}_t^{\mathrm{A},p}$ is the primary balance input to SDSA under adaptation.

We can also write government spending as $G_t = \tau Y_t - PB_t$. If, under climate change, the government maintains a constant tax rate and its primary balance a constant fraction of GDP, its spending will become

$$\tilde{G}_t = \tau\tilde{Y}_t - pb_t\tilde{Y}_t. \tag{13}$$

To maintain constant public spending under climate impacts, the government needs a primary balance

$$\widetilde{PB}_t^c = \tau\tilde{Y}_t - G_t. \tag{14}$$

Using $\widetilde{PB}_t^c$ as *dd* the input to SDSA, we can assess whether a government can maintain constant spending without jeopardising debt sustainability.

3 Interlinked model scenario calibration

We stress test sovereign debts under climate change for different (i) country characteristics, (ii) socioeconomic and warming scenarios, (iii) economic sensitivity to climate change, and (iv) government policies (Table 1). For (i), we test six countries from different continents covering a wide range of GDP *per capita*, debt-to-GDP ratio and vulnerability to climate change (see Appendix Figure A.1). These countries are Australia (high GDP *per capita*, low debt-to-GDP ratio, medium climate vulnerability), Brazil (low GDP *per capita*, medium debt ratio, high climate vulnerability), Finland (high GDP *per capita*, low debt ratio, and, uniquely, low or positive climate effects), India (low GDP *per capita*, high debt ratio, high climate vulnerability), Italy (high GDP *per capita*, high debt ratio, high climate vulnerability) and Tanzania (low GDP *per capita*, low debt ratio, high climate vulnerability). For (ii), we test two IPCC marker scenarios that are considered intermediate (Climatic Change, 2014; O'Neill *et al*, 2016). For (iii), we consider low and high sensitivities spanning the spectrum of climate impacts from the literature; and for (iv), we consider different adaptation policies, and fiscal policies that prioritise debt sustainability or public spending.

We discuss next the data sources and scenario calibration.

Table 1: Stress tests design

Dimension	Elements
Countries	Australia, Brazil, Finland, India, Italy, Tanzania
Socioeconomic and warming paths	SSP2-RCP4.5, SSP3-RCP7.0
Sensitivity to climate change	Low, High
Government policy priorities	Adaptation, debt sustainability, public spending

Source: Bruegel. Note: This table displays the design of the stress test for differences across countries, combinations of shared socioeconomic pathways with representative concentration paths leading to different warming levels, low or high climate impact estimates based on Kalkuhl and Wenz (2020) and Burke *et al* (2015), respectively, and government adaptation policies or priorities relating to debt stabilisation or the level of public spending.

3.1 Aleatory scenarios

We use the following sources to obtain expected values, volatilities and correlations to build the scenario tree for interest rates, GDP growth and primary balance:

Interest rates (r_{ft}). We use spot rates to compute five-year forward rates as the risk-free debt refinancing rate. We use the yield curve of AAA-rated bonds from the European Central Bank. We select yield curves for low interest rates (Blanchard, 2022) so that our SDSA results with climate impact are rather optimistic. The curve is from October 2018 with long-term spot rates of about 1.2 percent; see Appendix Figure A.2, Panel A. These yield curves are the calibrated tree mean values. The premia are reported in Appendix Figure A.2, Panel B. For non-AAA-rated European bonds, we approximate the risk premium over the risk-free rate by the average difference of the yields of the most liquid 10-year bond over the AAA-rated, using yearly data from 2000 to 2022. For Australia and India, we compute country-specific spreads as the average difference between the 10-year bond yields from the World Government Bonds and the US government bond yields from FRED. For Brazil and Tanzania, the values are below the (very high) historical averages in line with our experimental design of avoiding choices that bias the results in favour of greater climate impact[7].

GDP growth (g_t). We obtain country real GDP growth projections from RICE50+ under the SSP narrative scenarios and adjust with projected long-term inflation projections from the IMF World Economic Outlook (WEO) report of 2022 (Appendix Figure A.2, Panel B) to derive nominal GDP growth. These projected growth rates are the calibrated tree mean values without climate impacts. The narrative scenarios for the RICE50+ projections, including climate impacts, are described in the next subsection.

Primary balance (pb_t). We use the WEO projections, in percent of GDP, up to 2027, and beyond that, we increase linearly within fifteen years to an estimated long-term primary balance that stabilises the debts in the absence of any climate damages (pb^*) under the SSP narratives. These are the primary balance mean values of the calibrated tree. Thus, the scenario trees are calibrated, assuming that countries stabilise their current debts if necessary. In this way, our climate stress tests on debt sustainability are not compounded by any sustainability concerns under zero climate damages.

Standard deviations and correlations. The scenario tree is calibrated to match the second-order moments, including correlations, estimated using twenty years of data just before the 2020 pandemic. For parsimony, we use the cross-country average in all tests; see Appendix Figure A.2, Panel C.

Using this data, we calibrate a scenario tree for each country using moment matching (Consiglio

[7] Modelling a nonlinear risk premium $\hat{\rho}(d)$ that increases with increasing debt, as in Zenios *et al* (2021), further exacerbates the debt problem. For parsimony, we perform all tests with the constant average premium. The results are qualitatively consistent but quantitatively stronger when using the nonlinear function.

et al, 2016) so that the first moments of the state variables match the projections of interest rates, GDP growth, and primary balance and second moments match the standard deviations and correlations. Matching volatilities and correlations to their historical estimates assumes that climate change does not fundamentally alter the volatilities and correlation structure. This underestimates the potential effect of climate risk on volatility, so the adverse debt effects we estimate are generally on the conservative side.

Legacy debt (D_0). The term structure of outstanding marketable debt securities is mainly drawn from domestic currency issuances from each country's official websites. Specifically, we use the Australian Office of Financial Management, Tesouro Nacional Transparente for Brazil, Finland's and Italy's finance and economy ministries and the Reserve Bank of India[8]. For Tanzania, we use Eikon. The initial debt-to-GDP ratios do not align perfectly with figures from other sources, such as the IMF or Eurostat, as these organisations often include non-marketable debt. Hence, our stress tests are for the marketable fractions of the countries' total debts.

Tax rates (τ). The tax rates are from the WEO as follows: Australia 27.8 percent, Brazil 32.3 percent, Finland 43.3 percent, India 18.1 percent, Italy 42.4 percent, Tanzania 11.8 percent.

3.2 Narrative scenarios

We obtain the RICE50+ growth projections under narratives of shared socioeconomic paths, representative concentration pathways and climate impact functions. Table 2 displays the average historical nominal and real growth rates from 1980 to 2020 and the projected average growth rates up to the end of the century under the shared socioeconomic pathways SSP2 and SSP3.

Table 2: Projected growth rates under shared socioeconomic paths SSP2 and SSP3

	Real			Nominal		
Country	Hist.	SSP2	SSP3	Hist.	SSP2	SSP3
Australia	3.0	1.8	1.2	6.0	4.4	3.7
Brazil	2.2	1.8	0.7	7.6	4.8	3.8
Finland	2.1	1.3	1.3	4.8	3.2	3.2
India	6.0	3.0	1.8	7.2	6.9	5.7
Italy	0.9	1.1	0.6	4.1	3.1	2.6
Tanzania	5.0	5.1	4.1	5.7	9.3	8.2

Source: Bruegel.

[8] See https://www.aofm.gov.au/securities (Australia), https://www.tesourotransparente.gov.br/temas/divida-publica-federal/estatisticas-e-relatorios-da-divida-publica-federal (Brazil), https://www.dt.mef.gov.it/it/debito_pubblico/dati_statistici/scadenze_titoli_suddivise_anno/ (Italy), https://www.rbi.org.in/scripts/FS_PDS.aspx (India).

3.2.1 Zero-climate-damage narratives

Projections without any climate impact are for the SSP2 and SSP3 narratives. The regional-rivalries SSP3 is characterised by lower growth compared to the middle-of-the-road SSP2; Table 2 shows the average long-term growth projections. SSP2 projections are generally lower than the recent historical averages, suggesting that the very large growth rates of the recent past are expected to slow down later in the century. We validate the short-term growth projections without climate damages against the WEO. We find them very close and slightly lower under the adverse SSP3 narrative, as expected; see Appendix Figure B.4. We use these narratives to obtain zero-climate-damage reference debt trajectories in section 4.1 against which to evaluate climate impacts.

3.2.2 Climate-impact narratives

We consider the marker narratives SSP2-RCP4.5 and SSP3-RCP7.0 (Climatic Change, 2014). The former couples intermediate societal vulnerability with an intermediate emissions radiative forcing level, while the latter combines relatively high societal vulnerability with high forcing. In each marker scenario, the economic sensitivity to climate change is modelled using the low- and high-impact functions from Kalkuhl and Wenz (2020) and Burke *et al* (2015), respectively.

We use the coefficients of the preferred specification of Kalkuhl and Wenz (2020, Table 4, column 5) for the low-impact function. Their full specification captures both transitory and persistent damages from temperature. However, since the long-term growth effect is statistically not significant, it is dropped from the RICE50+ implementation in line with (8). We implement (8) adjusting the one-year temperature differences to the five-year time step of RICE50+.

Implementing the high-impact function (9), as originally published, leads to massive GDP gains in cold countries. RICE50+ caps the maximum possible gain at 100 percent of GDP, so Finland has more moderate improvements[9]. In contrast, the negative impacts on all other warm countries are unaltered from the original. Our estimated global average damages are higher than the original since any positive impacts on some countries are capped. However, the adverse effects on most countries match the original.

The GDP growth-rate change under climate impact, and assuming no adaptation, is persistent. Hence, even if the growth effects may seem small – see Appendix Figure B.3 – they cumulate to significant changes in GDP levels over time, compared to those without climate damage (Table 3). Under high impact, the damages for warm countries including Brazil, India and Tanzania are in the range of 60 percent to 80 percent by the end of the century. Damages are also high for Australia and Italy, ranging from 20 percent to 50 percent of their potential GDP. Damages under low impact are significantly less but still rather substantial at more than 10 percent for the warm countries in

[9] The effect of the cap can be observed in the difference between the capped and uncapped damage functions of Figure B.1, Panel B. They are particularly noticeable for Finland, with its growth rate reverting to the average once GDP increases by 100 percent; see online Appendix Figure B.3.

the SSP3-RCP7.0 climate scenario. Finland is, uniquely, projected to gain under high impact, and remain unaffected by climate change under low impact. Overall, climate impacts are noticeable from about 2040 and quite substantial from mid-century, but they vary across countries, especially in the adverse climate scenario.

Table 3: Climate damages to GDP, selected countries

		Low					High				
SSP-RCP	Country	2030	2050	2070	2100	Avg.	2030	2050	2070	2100	Avg.
SSP2-RCP4.5	World	1	3	4	5	3	4	18	35	60	26
	Australia	0	2	3	5	2	2	10	23	45	19
	Brazil	1	3	5	7	4	4	24	49	77	38
	Finland	0	0	0	0	0	-8	-56	-138	-155	-92
	India	1	4	7	10	5	4	24	53	83	41
	Italy	0	2	3	3	2	1	4	10	22	9
	Tanzania	1	3	5	7	4	3	23	47	76	37
SSP3-RCP7.0	World	1	3	5	9	4	4	17	37	68	28
	Australia	0	2	4	8	4	2	11	27	56	22
	Brazil	1	3	7	12	6	5	26	52	84	41
	Finland	0	0	0	1	0	-8	-57	-139	-156	-93
	India	0	3	8	16	6	4	23	53	88	41
	Italy	0	2	4	7	3	1	4	12	32	11
	Tanzania	1	3	7	12	6	4	25	52	84	41

Source: Bruegel. Note: This table displays changes to country GDP up to the end of the century resulting from climate change, in percentage points, assuming no adaptation. We display changes from the projections with zero climate damages for the marker narrative scenarios SSP2-RCP4.5 and SSP3-RCP7.0 under low and high climate impact functions. Positive values denote damages, and negative values are benefits. 'Avg.' is the average damage across the century, and 'World' denotes the global GDP impacts.

3.2.3 Adaptation narratives

To obtain adaptation narratives, we recalibrate Agrawala *et al* (2011) to the regional aggregation and damage functions of our stress tests. For our high-impact function, adaptation appears more effective than in the original calibration, which scales linearly following the cost-benefit logic. However, the IPCC Sixth Assessment Report notes with high confidence that adaptation will become less effective at higher levels of warming (Lee *et al*, 2023), and we recalibrate the adaptation function to reflect the diminishing effectiveness.

We recalibrate (10) so that the residual damages are no less than 75 percent of the original at high levels of adaptation; this is an optimistic estimate that large regions with high damages can reach. The recalibrated adaptation factor is

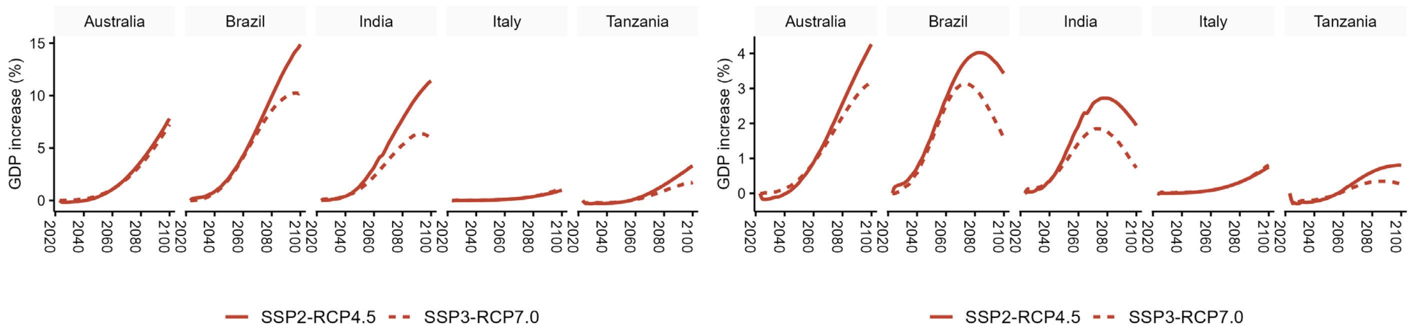
$$\Theta_t^R = \left(\frac{1}{1+Q_t^a}\right)^{\epsilon^b - c}. \tag{15}$$

We use the efficiency parameter ϵ in the range 0.2 to 0.9 from the reference and find that for a = 0.5, b = 0.1, c = 0.7, the adaptation factor closely follows the benefits of Agrawala *et al* (2011, Figure 8) for their range of damages, and converges to a long-term value of about 0.75 of their estimates with our high-impact function; see Appendix Figure B.2 for the original and the recalibrated functions. Our recalibration under low impact for SSP2-RCP4.5 obtains global damages of approximately 5 percent of GDP at the end of the century, in line with Agrawala *et al* (2011). Hence, we are more conservative under high impact in line with the IPCC Sixth Assessment Report and follow the original paper for low impact. We also align with current estimates of the adaptation benefit-cost ratio of between 2:1 and 10:1 (Global Commission on Adaptation, 2019), with ratios of around 4:1 and as high as 8:1 at the end of the century, and present values from 2:1 to 3:1.

Figure 2 illustrates the GDP increases under the optimal level of adaptation from RICE50+, or, equivalently, the reduction in climate economic damages. Panel A displays the improvements in adapted GDP, reaching up to 15 percent for some countries and, by design, being more effective in the mild climate scenario. Panel B displays the improvements as a proportion of the zero-damage GDP, which are much lower since adaptation has a marginal effect on the non-climate-damaged GDP (up to 4 percent). Table 4 reports the costs of the different types of adaptation, as a fraction of GDP.

Figure 2: Reduced climate damages due to adaptation

(a) Improvements over high climate damages GDP (b) Improvements as a fraction of zero-damage GDP



Source: Bruegel.

We use this calibration to analyse reasonable narrative adaptation scenarios and shed light on their interaction with fiscal sustainability, following the best available science. These scenarios are subject to the same caveats as Agrawala *et al* (2011) – that they may impose a more precise representation of adaptation dynamics than the underlying knowledge allows. Our model can, of course, accommodate any country-specific calibration of adaptation.

Table 4: Adaptation cost

	SSP2-RCP4.5				SSP3-RCP7.0			
Country	All	Proactive	Reactive	Capacity	All	Proactive	Reactive	Capacity
Australia	0.84	0.51	0.32	0.02	0.90	0.57	0.31	0.02
Brasil	2.46	0.77	0.47	1.22	2.24	0.93	0.46	0.85
India	1.32	0.49	0.62	0.20	0.96	0.37	0.47	0.12
Italy	0.12	0.08	0.02	0.01	0.16	0.11	0.03	0.02
Tanzania	0.38	0.18	0.15	0.05	0.29	0.15	0.10	0.05

Source: Bruegel. Note: This table displays the cost of proactive and reactive adaptations and for building adaptive capacity until the end of the century, in % of GDP. We display the RICE50+ estimates for the marker narrative scenarios SSP2-RCP4.5 and SSP3-RCP7.0 under the high climate impact function.

4 Debt stress tests to climate change

We first develop reference debt trajectories without climate damage under SSP2 and SSP3 and establish their credibility by benchmarking them against projections from the IMF Article IV reports. We then perform the climate stress tests under the two marker narratives SSP2-RCP4.5 and SSP3-RCP7.0, and for low- and high-impact functions, assuming, first, that no adaptation takes place. The model can also be calibrated to other narratives. We optimise debt financing with 3-, 5-, 10-, and 30-year maturity bonds. The calibration starts in 2020 with a horizon to the end of the century. For debt financing optimisation, we set α to a very strict value of 0.95. We consider debt stock sustainable if the 75th percentile is not upward-sloping, in line with the IPCC classifying a 75 percent confidence level as 'likely' (Kause *et al*, 2022).

The SDSA model is implemented using GAMS. Solver BARON is used to fit the aleatory trees on RICE50+ projections, and CONOPT is used to solve the model. RICE50+ is implemented using GAMS with CONOPT as the solver. The RICE50+ data are post- processed using R libraries to generate inputs for the SDSA model, and the outputs are analysed to produce graphs and tables.

4.1 Debt sustainability without climate effects

We develop the reference debt trajectories using zero-damage GDP projections with the interest rates and WEO primary balance projections up to 2027 from section 3.1. Tests performed with the historical average primary balance past 2027 revealed precarious debt positions for some countries. To isolate the climate effects from debt-sustainability concerns under the current high debt levels, we estimate the long-term primary balance that will stabilise the debt trajectories, given the projected growth, as would be pursued by prudent governments or imposed *ex post* by international institutions for sovereigns asking for financial assistance. We keep the WEO short-term primary balance projections until 2027, and past that, we estimate the long-term primary balance pb^* to be (linearly) achieved within fifteen years to ensure that the 75th percentile of the debt stock trajectories is non-increasing. We obtain the reference debt projections by running the zero-damage SDSA with these primary balances.

We validate the short-term of our reference projections against projections from the IMF Article IV reports, finding that they follow the same trends and, in most cases, are pretty close; see Appendix Figure B.5. For Brazil, our debt trajectories are optimistic compared to the IMF's, because of the low spreads we used for this country compared to historical averages. Overall, we consider that this test validates our zero-damage SDSA[10]. The reference projections until the end of the century are shown in Figure 3 with the pb* for each country and SSP shown in the boxes. These are the zero-damage, stabilised reference scenarios. Because of lower projected growth under SSP3, the debt levels are higher than in SSP2. The stabilising primary balance is conditional on the trend in the tail and not on its level, so even with a higher pb*, a stabilised debt trajectory may have a higher tail debt level. Also, the pb* is the same for every scenario in the tree, and stabilising the 75th percentile can significantly lower debt under favourable scenarios, as we observe for Brazil and India. Still, our objective is to stabilise debts with high probability; in favourable scenarios, the primary balance can be reduced.

The debt-stabilising primary balance varies widely, from -1.6pp of GDP for Australia to +2.4pp for Brazil. It is higher than the historical averages for India and Tanzania and, under SSP3, also for Brazil and Italy. To keep their debts under control, these countries should exert greater fiscal discipline than in the past. Australia, Finland and Tanzania can still run primary deficits under both SSPs, implying they have fiscal space to accommodate additional borrowing. Brazil, Italy and India, under SSP3, must run surpluses to avoid exploding debt dynamics. The required surpluses are within the 3 percent threshold of historical episodes of fiscal consolidation. Still, this data suggests that any adverse climate effects will make it more challenging for Brazil, India and Italy to stabilise their debts.

4.2 Climate effects on debt financing cost-risk trade-off

To assess the climate effects on the risk-cost trade-off, we run the model under the marker narratives and display the efficient frontiers in Figure 4. The y-axis shows the expected cost and the x-axis shows the risk of debt refinancing. In each panel, we display the zero-damage frontiers (black), the low climate-impact frontiers (Panel A, pink) and the high-impact ones (Panel B, red) for both marker narratives.

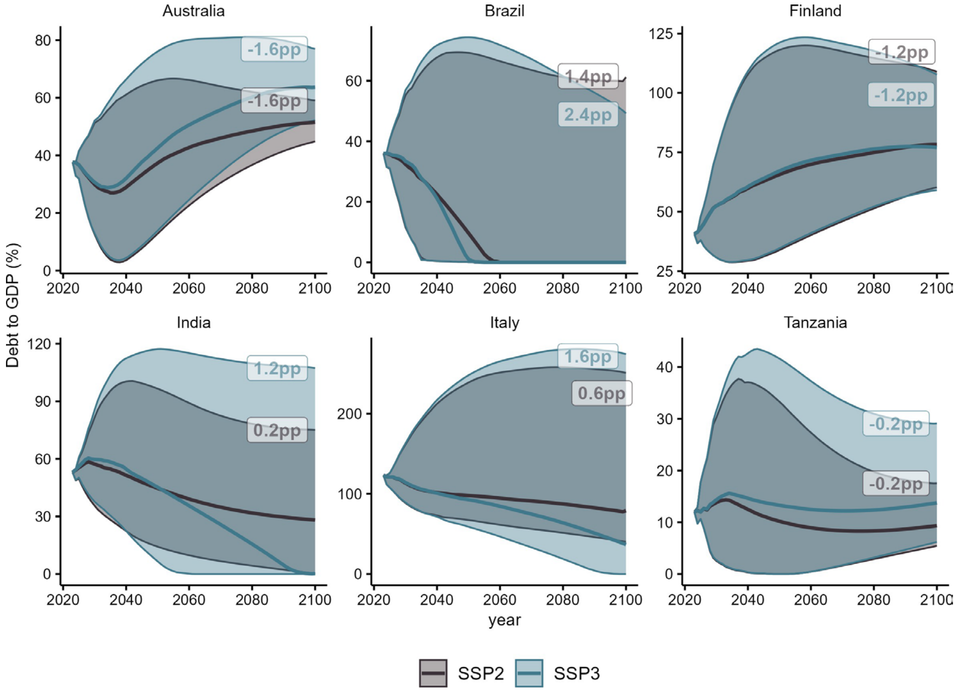
We observe that the frontiers shift towards higher cost and risk with climate change. The shifts are rather small for Australia, Finland and Tanzania under low climate impact (Panel A) but quite substantial for Brazil, India and Italy, and they are somewhat greater under the SSP3-RCP7.0 narrative. The frontier shifts are exacerbated under high climate impacts (Panel B). For Brazil, India and Italy, we notice increases in the expected cost of debt ranging from 1 percent of GDP (Italy) to 6 percent (Brazil) with large increases in refinancing risk. For Australia and Tanzania, the increase in cost is less than one percentage point, while Finland experiences a reduction of expected cost by about 0.5 percent, and a

[10] Further validation of the original SDSA model can be found in applications for the *Ufficio parlamentare di bilancio* (Italy), HM Treasury (United Kingdom), the Finnish Ministry of Finance, the Dutch State Agency Treasury, the Cyprus Auditor General and the Bank of Japan, some of which are published in the literature (Alberola *et al*, 2023; Consiglio *et al*, 2023; Zenios *et al*, 2021).

slight reduction in refinancing risk.

Overall, climate change adversely shifts the cost-risk trade-off of sovereign debt financing. The impact on warmer countries can be quite large under high-impact functions and adverse climate narratives. We test next whether this shift jeopardises sustainability.

Figure 3: Country debt ratios in the long run without climate effects



Source: Bruegel. Note: this figure displays the debt-to-GDP ratio (in %) until the end of the century in the absence of climate damages under growth projections from the shared socioeconomic pathway narratives SSP2 and SSP3. Lines indicate median values and the inter-quantile range. We assume that countries run long-term debt-stabilising primary balances (pb*) to stabilise the 75th percentile of the debt ratios. pb* is displayed in the boxes as a fraction of GDP in percentage points (pp).

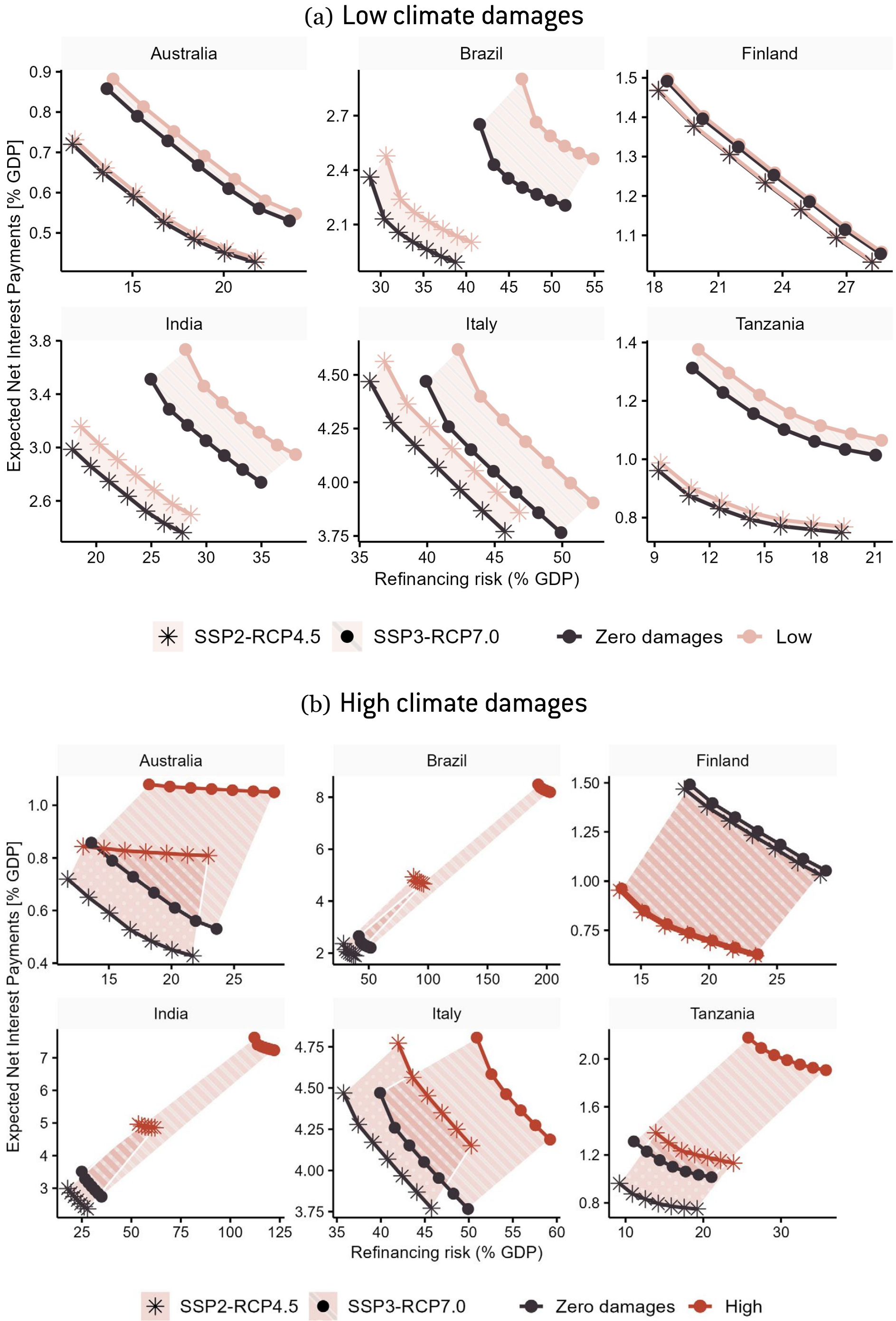
4.3 Climate effects on debt sustainability

We zoom in on the debt-stock trajectories at the intermediate points of the frontiers. We display the trajectories for both marker narratives in Figure 5. For comparison, we overlay the fan charts under low climate impact (pink, Panel A) or high impact (red, Panel B) to the zero-damage (grey).

The debt trajectories are adversely affected in most cases, with the 75th percentile shifting upwards. Under low climate impacts, the debt changes are rather small and do not adversely affect debt sustainability except for Brazil and India, where the 75th percentiles trend upward. This holds for both marker narratives, with a more substantial impact under SSP3-RCP7.0. Under high climate impact, the shifts are quite significant, especially large under SSP3-RCP7.0. Country debts shift towards non-sustainable trajectories, with the shift becoming noticeable from the mid-2040s. Finland is the sole exception, experiencing a debt reduction.

These tests show that climate change can adversely impact debt sustainability. This is in line with Klusak *et al* (2023), who found sovereign creditworthiness downgrading from rising temperatures, and SDSA uncovers the mechanism for such downgradings. However, the magnitude of the impact is subject to deep uncertainty. It can be a few percentage points under low-impact functions, but it can be extremely large under high-impact for both marker narratives, potentially precipitating debt crises.

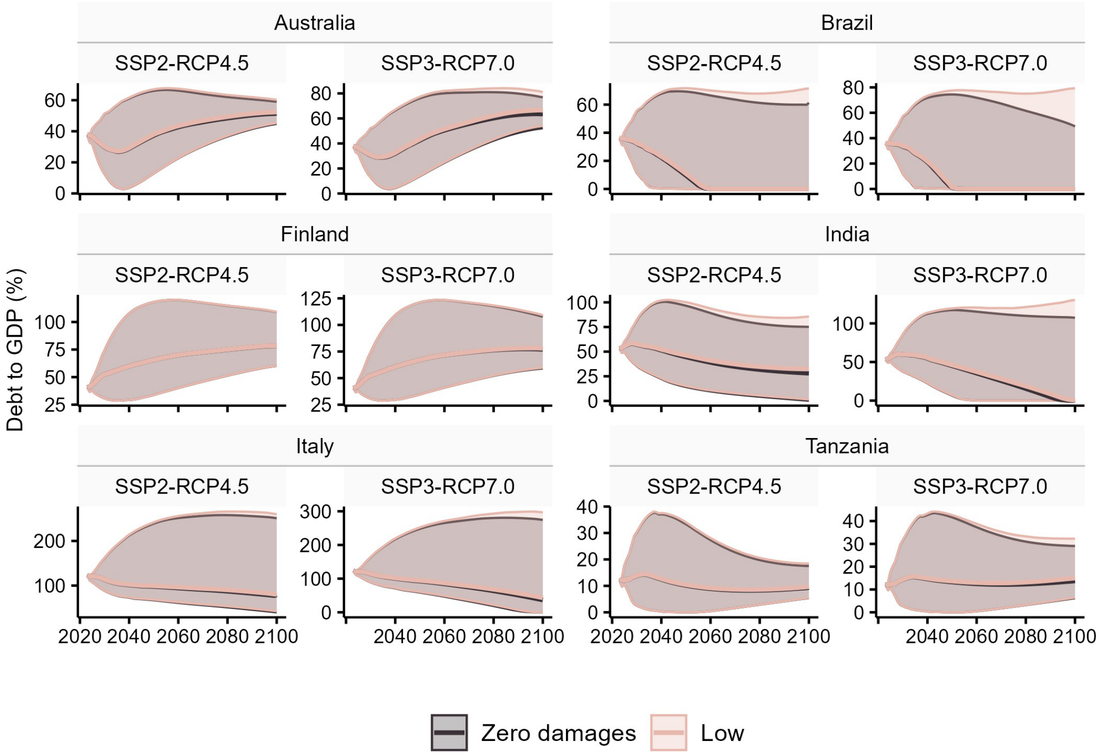
Figure 4: The cost-risk trade-off under climate damages



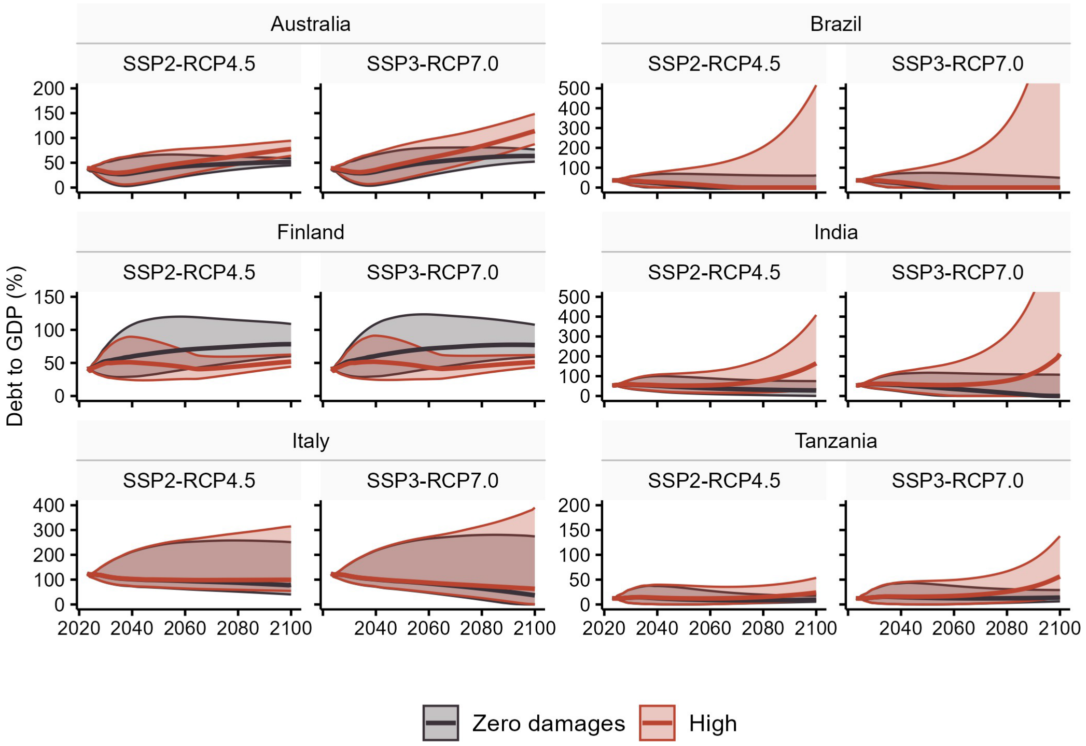
Source: Bruegel. Note: This figure displays the trade-off between the expected cost of debt financing and refinancing risk for (a) low climate damage and (b) high climate damage functions. In each panel, we display the results for the marker narrative scenarios SSP2-RCP4.5 and SSP3-RCP7.0, and the shaded areas indicate the shift of the trade-off from zero-damage (black lines) to climate damages (light or dark red) for each marker narrative.

Figure 5: Climate impact on country debts in the long run

(a) Low climate damages



(b) High climate damages



Source: Bruegel. Note: this figure displays the debt-to-GDP ratio (%) up to the end of the century under (a) low climate damage and (b) high climate damage functions (light or dark red shaded, respectively) for the marker narrative scenarios SSP2-RCP4.5 and SSP3-RCP7.0, overlaid on the zero-damage debt ratios (grey shaded). Lines indicate median values and the interquartile range.

5 Offsetting the climate change impact on debt

We now turn to options for offsetting the adverse climate debt effects. We investigate whether adaptation policies can avert potential debt crises by softening the climate impact but at a potential cost to the public purse. We also assess the level of fiscal consolidation required to offset the climate impact on debt and ask whether governments can sustain their current level of (nominal) spending with sustainable debt under climate change.

5.1 Can adaptation avert a potential debt crisis?

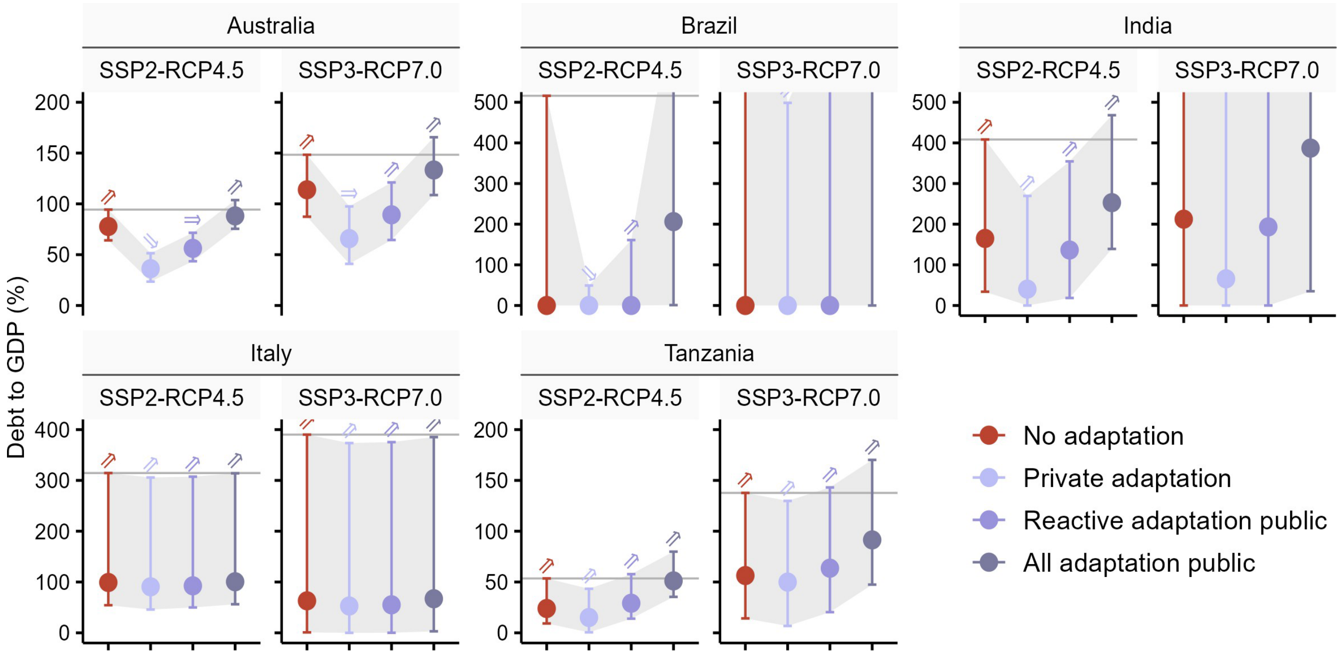
We study the potential of adaptation to dampen the upward pressure on debt dynamics under the high-impact function, when adaptation would be especially needed. We explore three policy options for financing the total level of adaptation optimised by RICE50+. First, adaptation is fully privately funded; second, the government pays only for reactive adaptation (eg disaster relief expenditure), which ranges from 1/5th to half of total adaption, with a cross-country average of 1/3rd (Table 4), while the private sector finances proactive adaptation and adaptive capacity; third, adaptation is fully government funded. The first option gives the best-case debt estimate under adaptation, and the third provides the worst case. To put things into perspective, the World Bank reports that less than 2 percent of adaptation investments come from the private sector (Tall *et al*, 2021).

We incorporate into SDSA the RICE50+ projections for adapted GDP (Figure 2) and adaptation costs (Table 4) for different adaptation policies under the marker narratives. In Figure 6, we display the range of end-of-century debt ratios and provide as a reference (horizontal line) the 75th percentile without adaptation. We observe a U-shaped relationship. Starting from no-adaptation (red dots), the fully private adaptation (light violet) is uniformly beneficial, although only marginally for Italy and Tanzania. If the government funds reactive adaptation (violet), the debt ratio is lowered in most cases, but if the government fully funds adaptation (dark violet), the benefits do not outweigh the costs.

While adaptation may reduce the debts, it does not necessarily restore sustainability, as shown by the double arrows above the whiskers in Figure 6. Horizontal or downward- sloping arrows signify stable or declining 75th debt percentile, and upward-sloping denote exploding debt. With the exception of Australia and Brazil in SSP2-RCP4.5, the arrows show that even the most favourable adaptation policy does not solve the climate-induced debt sustainability problem. This raises the question of whether adaptation lowers the fiscal effort required to deal with exploding debt dynamics, and we turn to this issue next.

The policy implication is that public financing of reactive adaptation – with the rest of the adaptation financed by the private sector – can have a small positive effect on debt sustainability that covers its cost or breaks even. This result aligns with a broad consensus that a significant part of adaptation expenditures will have to be borne by governments, but also highlights the limits of adaptation in averting a potential debt crisis.

Figure 6: Adaptation effect on debt ratios



Source: Bruegel. Note: This figure displays the end-of-century debt ratios with climate change adaptation under high climate damages. It shows the inter-quartile range of debt for different adaptation policies, with the horizontal line denoting the 75th percentile without adaptation. The double arrow at the top of each interquartile range indicates the direction of the debt ratio; horizontal or downward-pointing signifies stable or declining debts, and upward-pointing signifies unsustainable debt trajectories.

5.2 Can fiscal consolidation avert a potential debt crisis?

We explore whether fiscal consolidation can restore debt sustainability under high climate damage. We estimate the long-term primary balance pb** to stabilise the climate-impacted debts of Figure 5 with high confidence, ie non-increasing 75th percentiles. We report the results in Table 5 under the column 'Debt' for both marker scenarios and low- and high-impact functions. We also give the historical primary balance 'Hist.' and the zero-damage stabilising balance pb*. For low-impact and either narrative scenario, pb** is not higher than pb* for Australia, Finland or Tanzania. Warmer countries (Brazil, India, Italy) would require modest increases in their primary balances by 0.2 percent of GDP under SSP2-RCP4.5. Under SSP3-RCP7.0, the increases go up to a significant 0.6 percent (Italy). Under high impact, the increases are much larger. Under SSP2-RCP4.5 they are 1.4 percent (Brazil), 2.0 percent (India), 1 percent (Italy) and 0.6 percent (Tanzania), and under SSP3-RCP7.0 they are 1.6 percent (Brazil), 2.6 percent (India) and 1.8 percent (Italy). Australia can still run deficits, albeit at a lower rate, and Finland can slightly increase deficit spending.

Adjusting the primary balance can potentially stabilise debt, pointing to fiscal consolidation as a possible policy solution to climate-induced debt stress. However, the debt-stabilising primary balance for Brazil (4.0 percent), India (3.8 percent) and Italy (3.4 percent), under the high-impact function and adverse narratives, would exceed the 3 percent threshold and can be considered challenging compared to historical episodes of fiscal consolidation. Looking also at the size of the required fiscal adjustment, we notice a modest increase of primary balance by 0.6 percent for Australia and Tanzania under SSP2-RCP4.5, but an excessively larger 3.6 percent for India under SSP3-RCP7.0; such large corrections can be considered unrealistic (IMF, 2022). Fiscal consolidation may not be viable for all countries.

We return to whether adaptation could reduce the required primary balance below the threshold. We look at the worst-case SSP3-RCP7.0 scenario under the high impact function – when fiscal consolidation is the most challenging and adaptation is the most effective – and compute the stabilising primary balance with adaptation (pb^{**A}); see column (12) of Table 5. Compared to the stabilising balance under identical climate conditions but with no adaptation (column 9), we observe that the stabilising balance is lower. For Italy, it is reduced from 3.4 percent to 3.0 percent, which can be considered feasible, but for Brazil and India, it remains above the threshold. We consider this an important result with significant policy implications for establishing the value and limitations of adaptation.

Table 5: Primary balance to achieve government objectives

			SSP2-RCP4.5				SSP3-RCP7.0					
			Debt (pb^{**})		Spending			Debt (pb^{**})		Spending pb^{**A}		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Country	Hist.	pb^{*}	Low	High	Low	High	pb^{*}	Low	High	Low	High	High
Australia	-1.2	-1.6	-1.6	-1.0	-2.1	-9.5	-1.6	-1.6	-0.2	-2.5	-12.1	-0.4
Brazil	0.7	1.4	1.6	2.8	0.0	-28.4	2.4	2.6	4.0	0.3	-36.4	3.7
Finland	0.2	-1.2	-1.2	-1.0	-1.4	NA	-1.2	-1.2	-1.0	-1.5	17.3	NA
India	-4.0	0.2	0.4	2.2	-1.1	-22.1	1.2	1.4	3.8	-0.5	-24.1	3.6
Italy	1.0	0.6	0.8	1.6	-0.4	-3.7	1.6	2.2	3.4	-0.1	-4.2	3.0
Tanzania	-0.7	-0.2	-0.2	0.4	-0.7	-11.1	-0.2	-0.2	0.8	-1.0	-15.5	0.6

Source: Bruegel. Note: this table reports the long-term primary balance pb^{**} (in % of GDP) required to achieve the government objective of debt stabilisation ('Debt') and the average primary balance to maintain a constant nominal level of spending ('Spending') under different combinations of shared socioeconomic paths and representative concentration pathways (SSP-RCP) or climate-damage functions (low, high), together with the historical average primary balance 'Hist.' and the debt-stabilising primary balance pb^{*} under zero climate damages. It also displays the debt-stabilising primary balance under adaptation pb^{**A} for the worst-case climate scenario when climate damages are greatest and adaptation is most effective. Finland is not subject to adaptation as it stands to benefit from the climate change scenarios.

6 Public spending under climate change

We further characterise fiscal consolidation by examining the nominal amount of public spending reduction. We use the setup of section 2.3 in which governments keep a constant tax rate so that their expenditures are reduced, in nominal terms, from the climate damages to GDP; see eqn. (13). Figure 7 shows this reduction as a proportion of the no-damages spending averaged over the century. We observe that the reduction from climate change when running the zero-damage pb* is quite large (circles) but only marginally larger when running pb** (squares). Hence, most of the reduction in public spending is caused by climate damages and not by any fiscal adjustment to fix climate-induced debt stress. The yellow arrows show that, for low climate impact, the average reduction is up to 7.5 percent. For high impact, reductions can be almost 50 percent for the warmer countries and 15 percent to 25 percent for Australia and Italy.

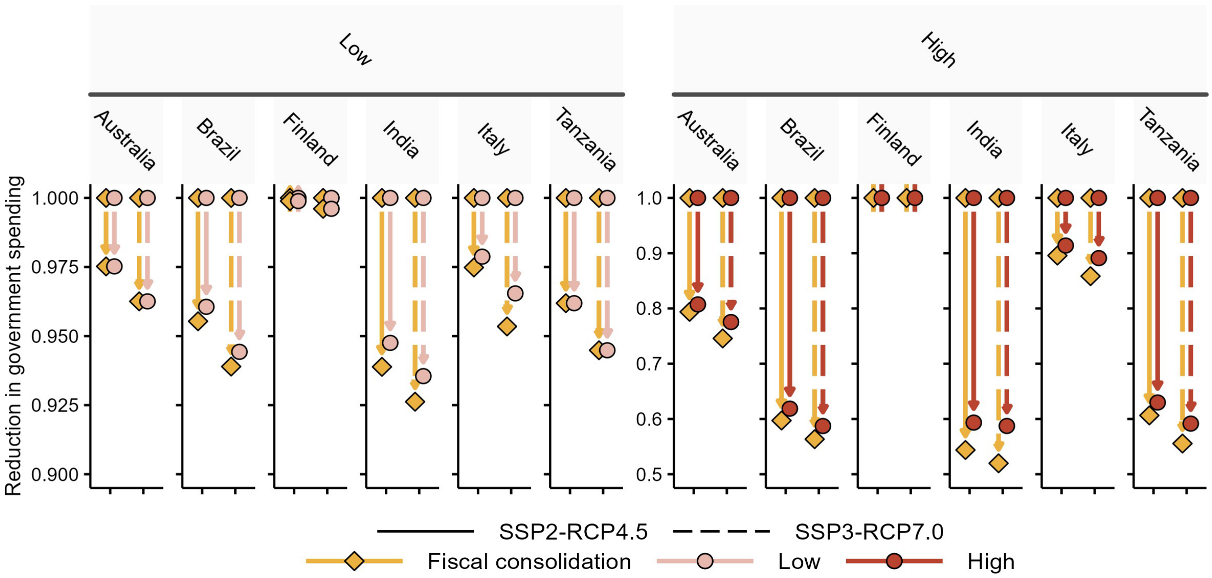
We include this foregone spending in the SDSA model to evaluate the effect on the debt of a government policy of constant spending in the face of climate change. We summarise the results in Figure 8, which displays the interquartile range of debt-stock ratios at the end of the century for low and high damage functions under the different climate narratives. Pink and red lines are for the low- and high-impact functions, respectively, and running the zero-damage pb* which implies a reduction in nominal spending. The blue lines are for constant spending using eqn. (14) in the SDSA. On top of each whisker, we indicate the debt-trajectory trend by a double arrow. We also display the zero-damage interquartile debt ratio by the grey band around the mean value black line. Upward-pointing solid arrows show that the 75th quantile is beyond the y-axis scale with an upward trend.

At first sight, and as in section 4.3 and Figure 5, under low damages, the debt is sustainable for all countries, except Brazil and India, which experience modest increases. However, the government spending will be lower by 2.5 percent to 7.5 percent as shown in Figure 7. If the governments maintain constant spending, instead, the debt ratio increases markedly for all countries, even under low climate impact. The additional spending needs to be debt-financed by substantial deficits, as reported in columns (5) and (10) of Table 5.

Under high climate impacts, the reduction in government spending (Figure 7) is about 10 percent for Italy, 20 percent for Australia and 40 percent for the other countries. For the governments to maintain constant spending, they would have to run implausibly large deficits (columns (6) and (11) of Table 5) with skyrocketing debts. Maintaining levels of public spending seems impossible with high climate impact.

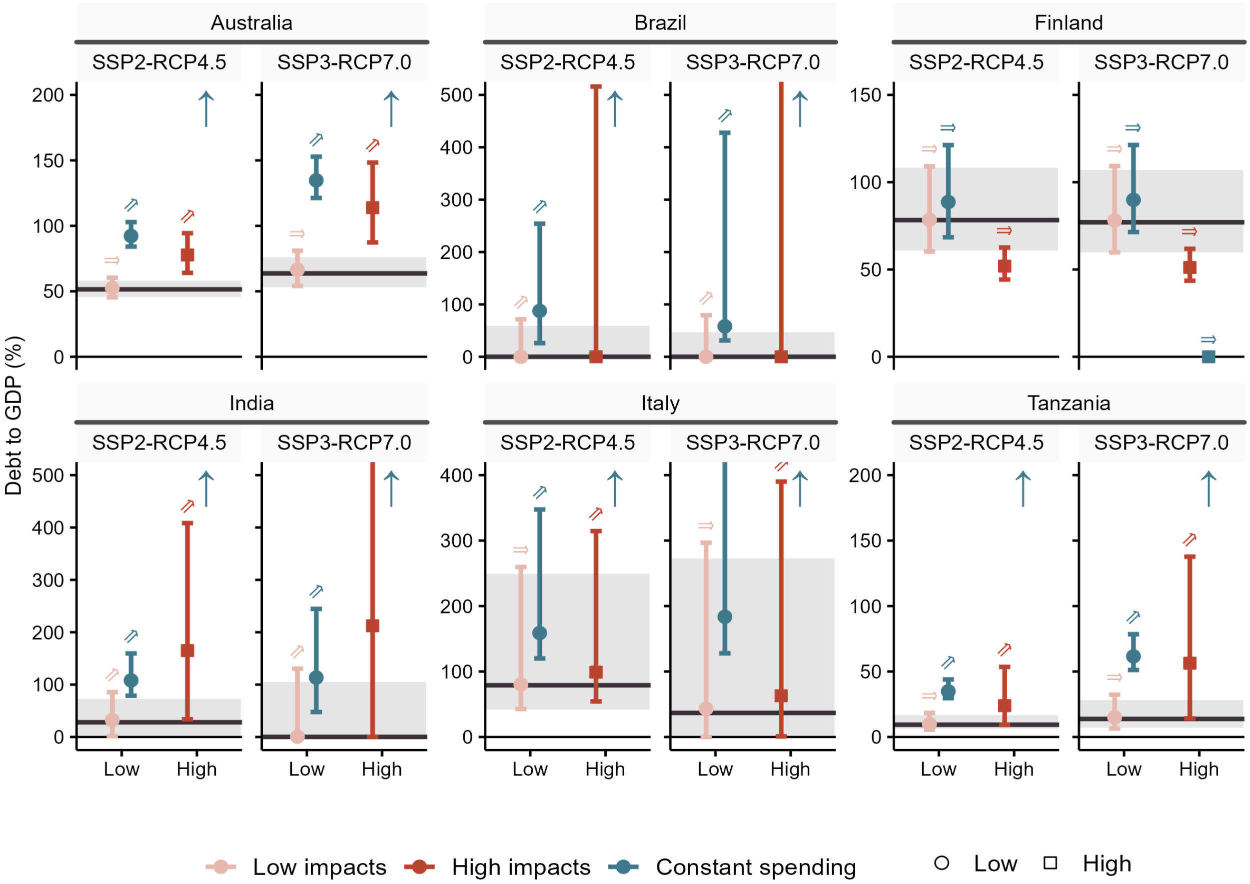
In summary, it appears unrealistic for most countries to expect to maintain constant public spending through borrowing under both climate-change narratives. Under low damages, public spending has to be slightly lower but under high damages, the reductions can be very large for the vulnerable countries.

Figure 7: Climate damages to government spending



Source: Bruegel. Note: this figure displays the proportional reductions to nominal value government spending under low and high climate damage functions for the marker narrative scenarios SSP2-RCP4.5 and SSP3- RCP7.0. Average spending per year until the end of the century in the zero-damage scenario is normalised to one and circles denote the proportional reduction due to climate change. The yellow arrows (squares) denote the reduction when stabilising debt under climate change (pb**), while the pink and red (circles) are obtained using the zero-climate-damage stabilising primary balance (pb*).

Figure 8: Climate impact on debt levels and trends at 2100



Source: Bruegel. Note: this figure displays the country debt-to-GDP ratio at the end of the century. Each panel displays the median and the interquartile range under low and high climate damage functions for the marker narrative scenarios SSP2-RCP4.5 and SSP3-RCP7.0 and for different government policies of stabilising debt or maintaining constant spending. The grey area displays the interquartile range of the zero-damage reference scenario, with the black line indicating the median. Double arrows at the top of each whisker indicate the trend of the debt ratio trajectory; horizontal or downward-pointing signifies stable or declining debts, and upward-pointing signifies unsustainable debt trajectories. The upward-pointing blue arrows in some panels signify that the debt ratios are excessively high with unstable increasing debt trajectories outside the range of the y-axis.

7 Conclusion

We stress-test sovereign debt sustainability under the impact of climate change, encompassing the critical uncertainties of future growth represented by narrative socioeconomic paths, climate warming scenarios and low and high economic sensitivity to climate change. We also consider government responses to climate economic impacts through adaptation investments or fiscal consolidation. To perform these tests, we develop a climate debt-sustainability analysis model, linking debt financing scenario optimisation with an integrated assessment model from climate economics. Our work showcases the value of integrating models belonging to different paradigms to study the complex climate effects on sovereign debt.

We start from a zero-damage reference scenario of long-term debt projections, assuming that countries follow policies to stabilise their currently high debts if necessary, to document the climate change impact on debt. Under the middle-of-the-road climate narrative SSP2-RCP4.5 and low climate impact functions, the debt increases are modest, and debts can be stabilised with additional fiscal effort of up to 0.2 percent of GDP. However, under the adverse narrative of regional rivalries SSP3-RCP7.0 and high climate impact, significant additional fiscal effort is required to stabilise debts, ranging from 1.8 percent of GDP (Italy) to 2.6 percent (India). Adaptation to climate change can help mitigate the adverse debt effects, but the costs break even only if the public purse finances, on average, one-third of the adaptation. And adaptation cannot restore debt sustainability.

We consider government policy responses to the adverse debt effects, either to stabilise public debt or maintain the level of public spending. We present results from two boundary cases in which the government reduces public spending to maintain public debt sustainability or resorts to borrowing to maintain constant public spending in the presence of climate damages to the economy. A trade-off emerges between these two policies. Sustaining public debt on a stable trajectory is possible with additional fiscal effort that can be challenging to achieve under extreme climate scenarios and high damage functions. However, climate damages imply a significant reduction in public spending. A constant spending policy requires excessively large deficits and unsustainable debts.

Neither policy option is safe, and any intermediate strategy is going to either be politically risk for lowering public spending or risk insolvency with increasing debt. Across narrative scenarios and damage functions, we provide robust evidence that there is no safe way for governments to navigate a world in which major economic risks from climate change cannot be ruled out. Our results corroborate the adage that there can be no public finance sustainability without environmental sustainability. Governments will find themselves walking on ice that is thinning over time.

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Appendix A: Data

Figure A.1: The representative countries

The figure displays the climate vulnerability (y-axis) and the debt level (x-axis) for the countries in our sample, with the size of the bubble denoting GDP *per capita*. For climate vulnerability, we obtain an indicative estimate of the changes of GDP at the end of the century by averaging over the SSP-RCP combinations and the low and high climate damage functions.

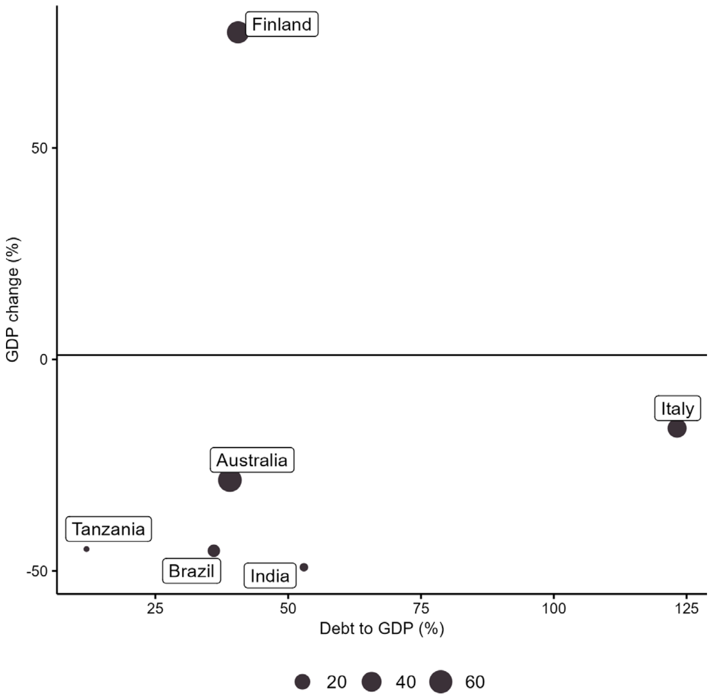
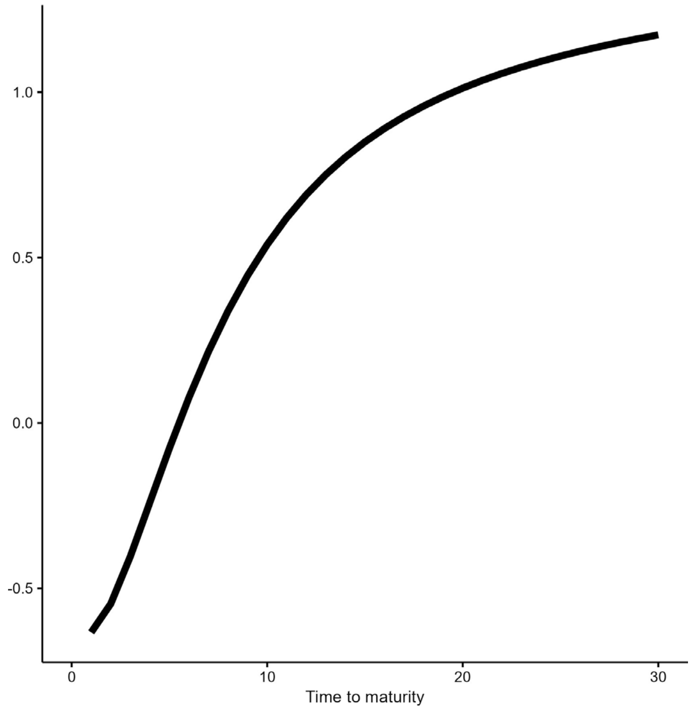


Figure A.2: Yield curves

This figure displays (a) the euro-area AAA yield curve and (b) the long-term inflation and risk premium of non-EU countries over the euro-area yields in basis points.

(a) Yield curve



(b) Long term inflation and risk premia

	Inflation	Premium
Australia	2.55	100
Brazil	3.03	200
Finland	1.80	30
India	4.00	500
Italy	2.00	200
Tanzania	4.10	500

(c) Volatilities and correlations

	StdDev	Correlation		
		GDP growth	Primary balance	Risk-free rate
GDP growth	3.5	1.00	0.60	0.15
Primary	2.5	0.60	1.00	0.50
Risk-free rates	1.5	0.15	0.50	1.00

Appendix B: RICE50+ integrated assessment model projections

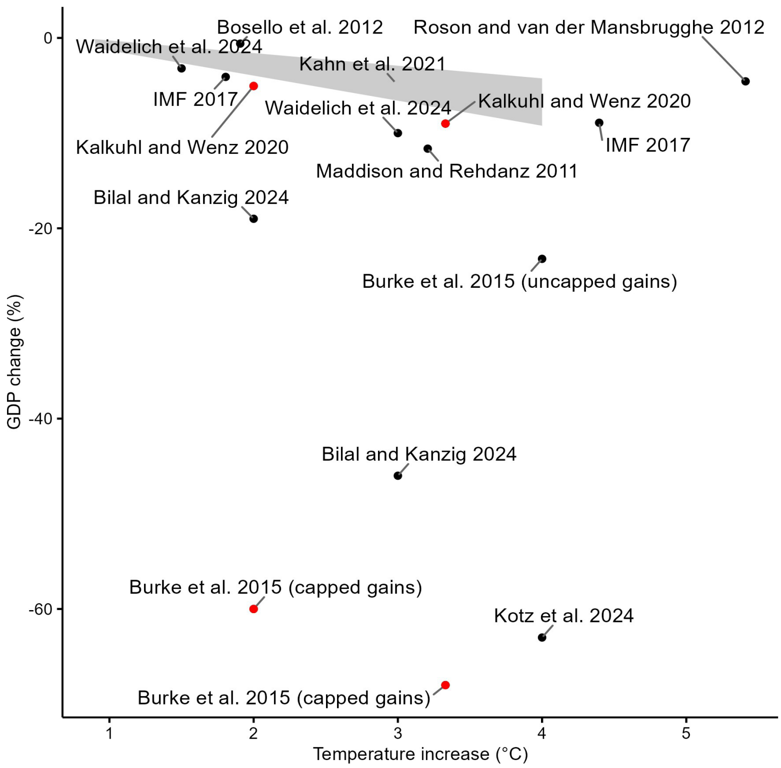
Validation of impact functions

Figure B.1: Validation of the impact functions

This figure displays estimates of the climate impact functions we used within the broader literature.

(a) displays the impact on global GDP at different projected temperature increases for the models by Bilal and Känzig (2024), Bosello *et al* (2012), IMF (2017), Maddison and Rehdanz (2011), Roson and van der Mensbrugghe (2012), Waidelich *et al* (2024) (black dots), the range of estimates from Kahn *et al* (2021) (shaded area), and the models we use (red dots). (b) displays a regional comparison of the high-impact function (Burke *et al*, 2015), with capped upside gains noticed by the flattening curve for Central Asia/Russia, with the estimates by Kotz *et al* (2024).

(a) Global comparison of multiple impact functions



(c) Regional comparison Burke *et al* (2015) with Kotz *et al* (2024)

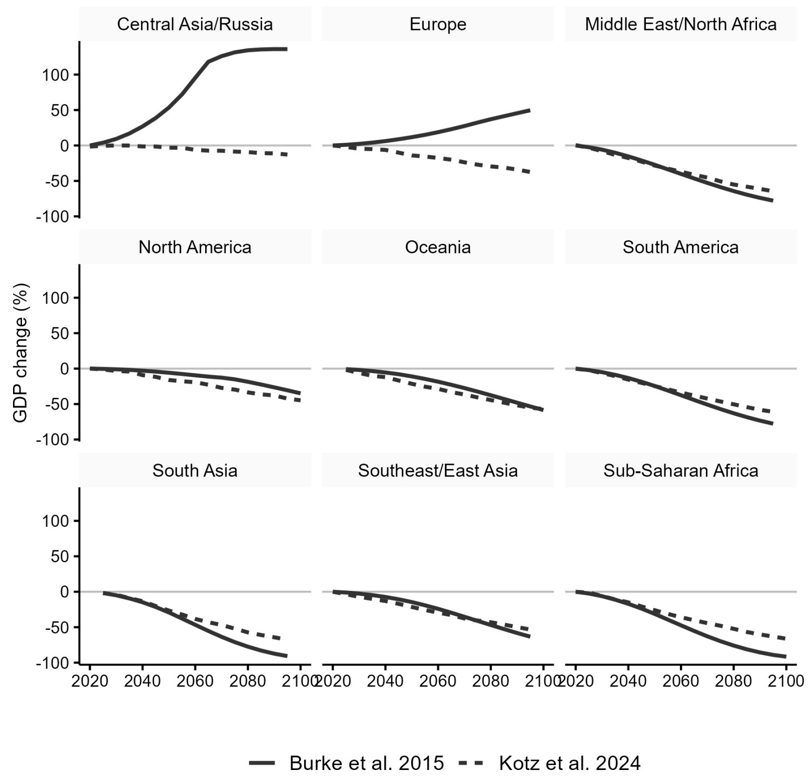
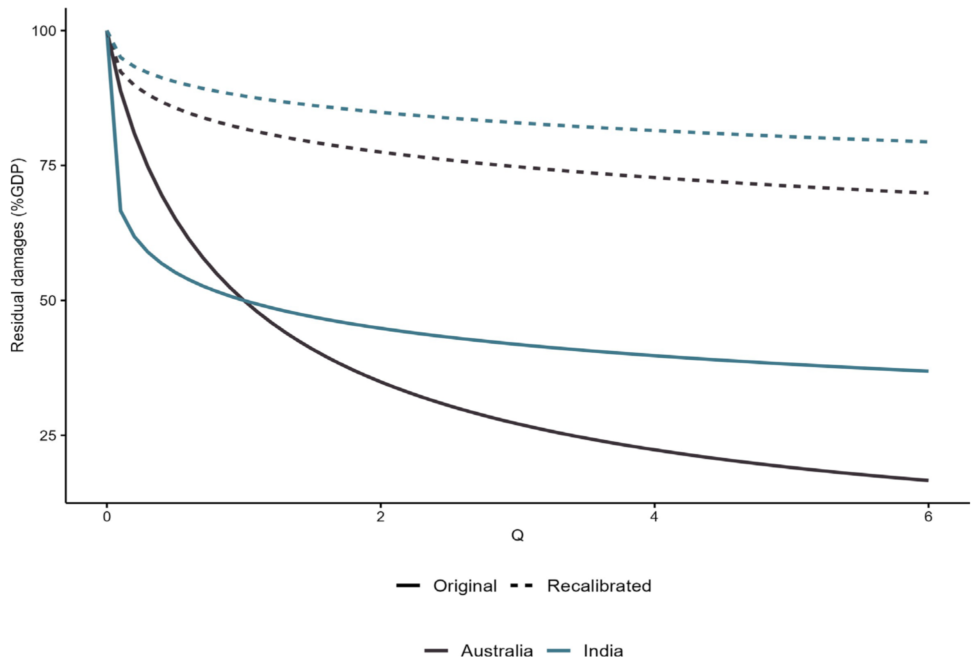


Figure B.2: Adaptation function for high impact

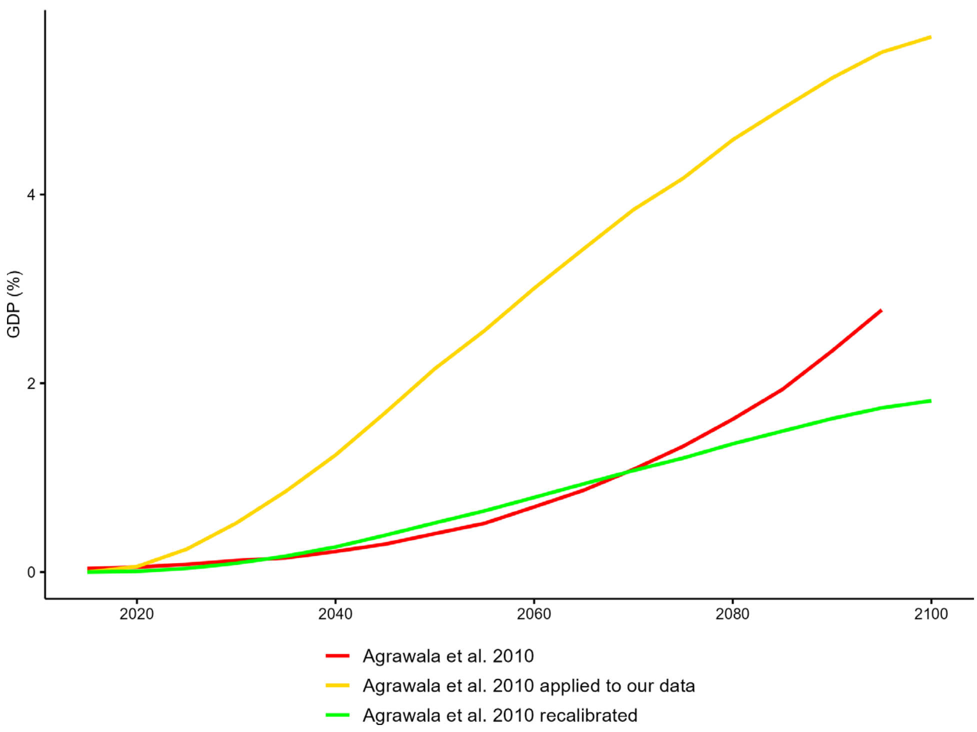
This figure displays results with the recalibration of the adaptation function $\Theta = g(Q)$ to determine the residual damages (y-axis) for different levels of adaptation Q (x-axis). (a) displays the original calibration (dashed lines) applying the adaptation effects obtained by Agrawala *et al* (2011) under low climate damages to high climate damages. Our recalibration (solid lines) converges to residual damages of about 75 percent of the no-adaptation damages, aligning with the estimates of the reference.

(b) displays the benefits from adaptation from Agrawala *et al* (2011) under their low-damage function (red), with the recalibrated function under our low damages function (green), and when applying their adaptation function to our low damage function (yellow).

(a) Residual damages



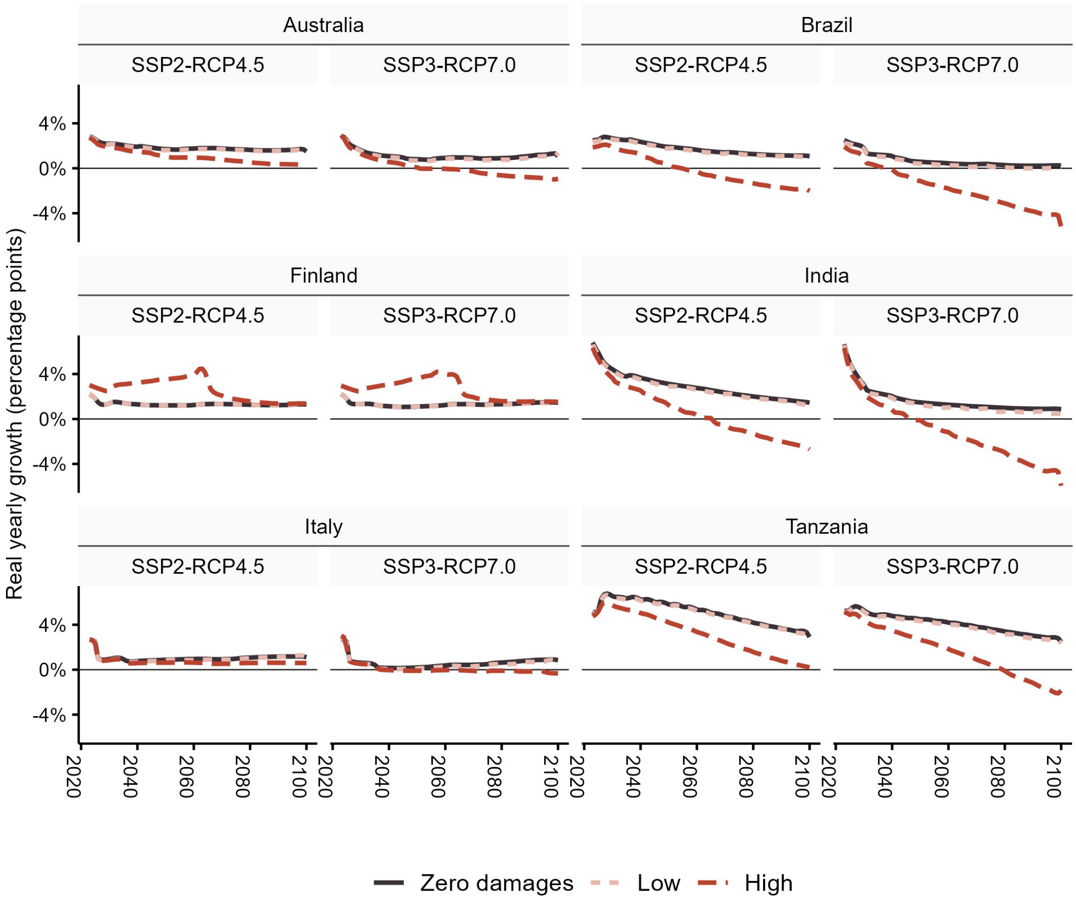
(b) Adaptation benefits



RICE50+ projections under climate narratives

Figure B.3: RICE50+ projections of GDP growth under climate narratives

This figure displays the country GDP growth rates without ('Zero') and with low and high climate damages under different combinations of shared socioeconomic pathways and representative concentration pathways (SSP-RCP).



Validation of RICE50+ projections

Figure B.4: Validation of the RICE50+ growth projections without climate effects

This figure displays the countries' GDP under growth projections from RICE50+ under SSP2 and SSP3 and the IMF *World Economic Outlook* 2022 over a five-year horizon. Lines indicate median values and the interquartile range.

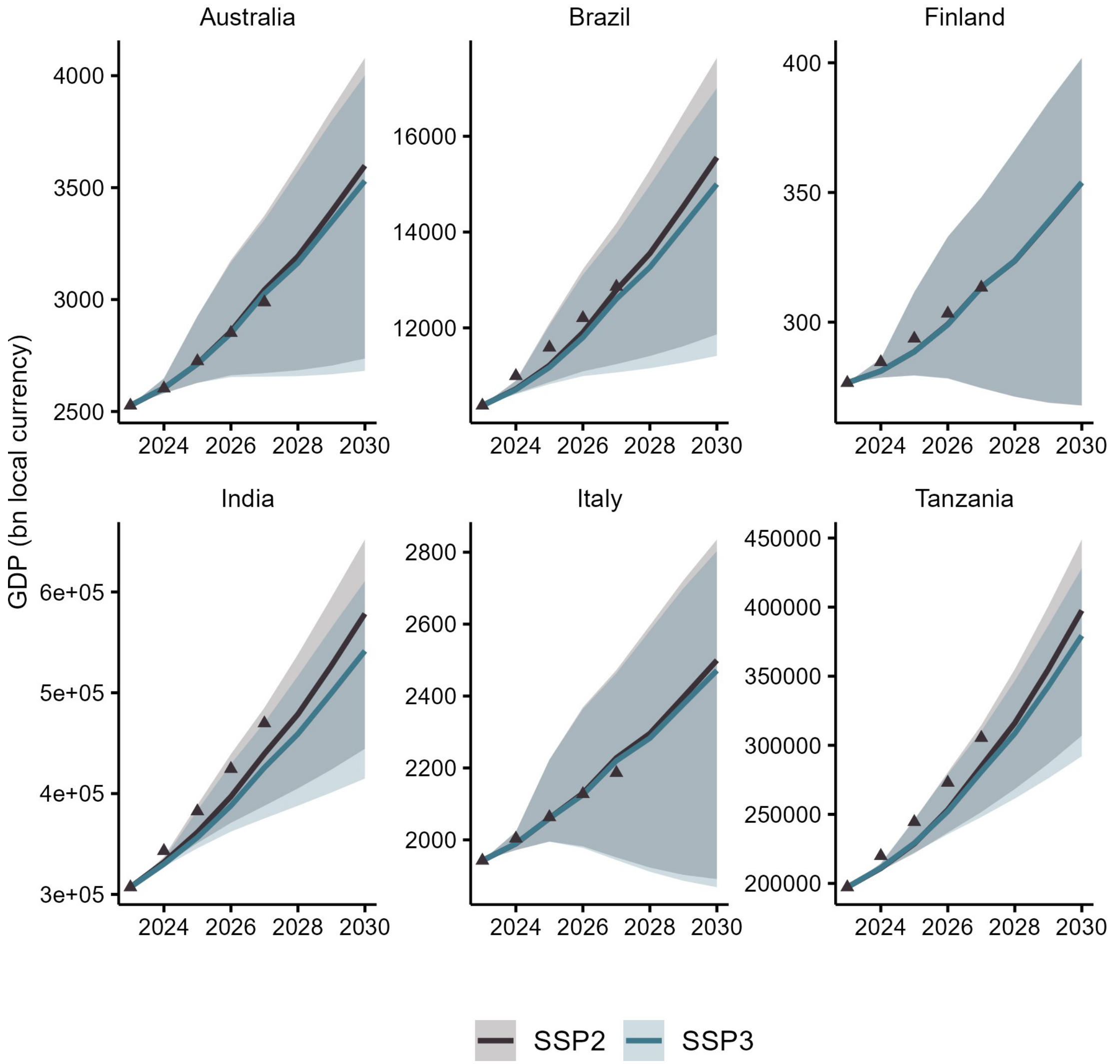
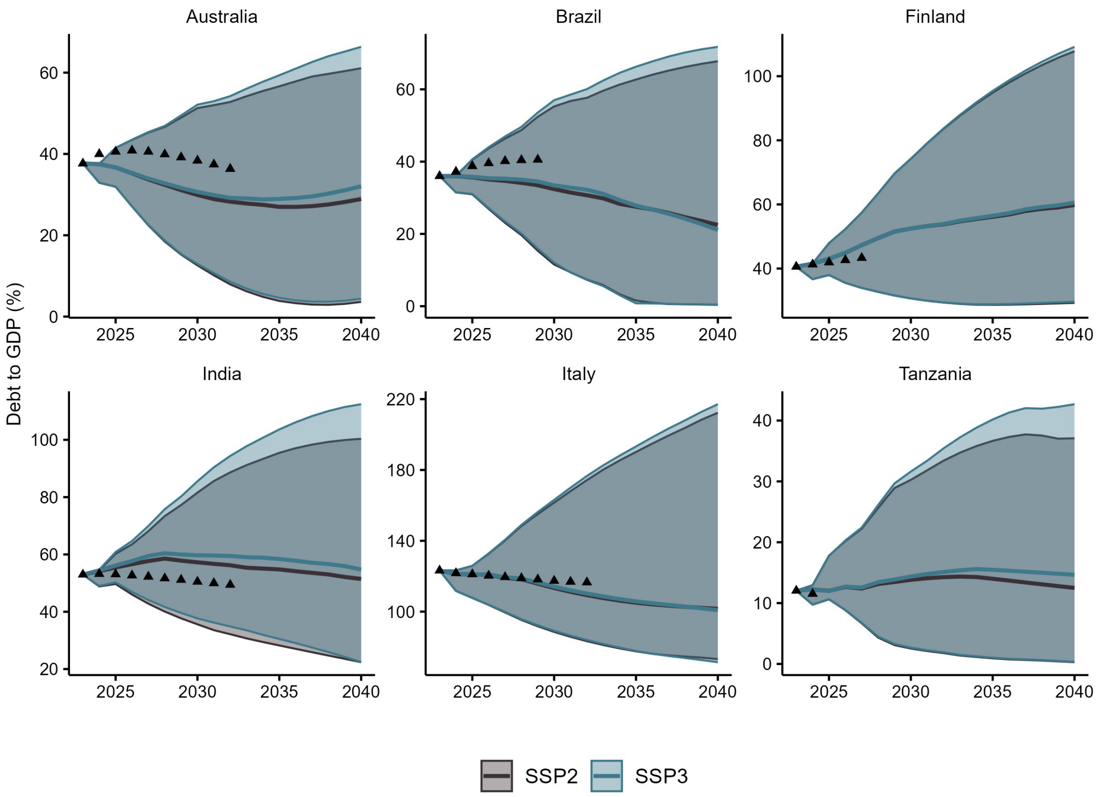


Figure B.5: Consistency of zero-damage debt projections with IMF Article IV

This figure shows the debt-to-GDP ratios under zero climate damage using the SSP projections and the short-term projections from the IMF Article IV report. Reports are from 2022 for Australia, Belgium, Germany*, India, Italy, Portugal*, the UK* and the US*, and 2021 for Austria, Finland*, France, the Netherlands and Spain. For the * countries, the starting IMF debt-to-GDP ratio is scaled to match the 2023 starting ratio from the sources of our analysis. Lines indicate median values and the interquartile ranges.



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