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Climate Resilience and the Adaptation Trap: A Macroeconomic Framework for Joint Fiscal–External Sustainability*

António Afonso† José Alves‡ João Jalles§ Sofia Monteiro**

January 2026

Abstract

Climate change is reshaping sovereign risk and macroeconomic stability by amplifying fiscal and external fragilities. This paper develops a unified framework to assess how climate vulnerability and resilience jointly influence fiscal–external solvency. We construct a market-based sustainability index that integrates time-varying fiscal and external reaction coefficients – estimated using Schlicht's (2021) method-weighted by sovereign yields. Using a global panel of more than 60 economies (1981–2024), we document four key findings. First, structural vulnerability exerts a large and persistent drag on sustainability, even after controlling for macro fundamentals, as higher exposure magnifies expected losses and tightens financing conditions. Second, resilience does not display a strong unconditional effect but significantly mitigates the adverse impact of vulnerability, acting as a state-contingent stabilizer. Third, local projections with smooth transition (LP-STAR) reveal sharp nonlinearities: identical climate shocks trigger modest, short-lived effects in low-vulnerability or high-resilience regimes but cause deep and persistent deterioration when vulnerability is high and resilience weak. Fourth, these dynamics generate an "adaptation trap" – a self-reinforcing cycle where vulnerability raises yields, yields compress fiscal space, and limited adaptation perpetuates vulnerability. Policy implications are clear: resilience investment yields sizable macro-financial returns by reducing expected losses and compressing climate risk premia, while delaying adaptation risks entrenching fragility. Our results highlight the need to embed climate parameters into debt sustainability analyses and sovereign risk frameworks, particularly for emerging markets facing tighter financing constraints.

Keywords: Climate vulnerability; Climate resilience; Fiscal sustainability; External sustainability; Sovereign risk premia

JEL: C33; E62; F34; H63; Q54

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1. Introduction

Climate change has become a defining macro-financial challenge. More frequent and intense climatic events, rising temperatures, and gradual environmental degradation increasingly weaken public finances and external balances by destroying capital, lowering revenues, increasing reconstruction spending, and disrupting trade flows. At the same time, investors now embed climate exposure into sovereign risk premia, raising borrowing costs for vulnerable economies and tightening fiscal space. These phenomena interact in potentially destabilizing ways: climate shocks deteriorate fiscal and external fundamentals precisely when financing conditions worsen, while higher spreads restrict the capacity to invest in adaptation, thereby increasing future vulnerability. Understanding how climate vulnerability and resilience jointly shape countries' ability to sustain both fiscal and external solvency is therefore essential for evaluating macro-financial stability in a warming world.

In this paper, we argue that vulnerability and resilience function as structural parameters of the intertemporal solvency constraint. Vulnerability increases the size and volatility of expected climate-related losses, thereby weakening governments' ability to adjust primary balances or external positions when government debt or net foreign liabilities rise. Resilience – capturing adaptive capacity, institutional quality, fiscal buffers, and disaster-preparedness infrastructure – does not systematically improve sustainability in normal times but instead acts as state-contingent insurance that binds when economies are hit by shocks or operate in high-vulnerability states. When vulnerability dominates resilience, the interaction between physical shocks, weakened adjustment responses, and higher risk premia can generate a self-reinforcing deterioration in solvency. This mechanism forms what we term an adaptation trap: a feedback loop in which vulnerability leads to higher spreads, higher spreads compress fiscal space for adaptation, and insufficient adaptation perpetuates vulnerability.

To study these dynamics rigorously, we develop an empirical framework that links climate risk to the joint fiscal–external solvency condition. Our first contribution (1) is to construct a unified market-based sustainability index that integrates fiscal and external adjustment capacity into a single measure. We recover time-varying fiscal reaction coefficients – capturing how primary balances respond to government debt – and external reaction coefficients – capturing how current accounts respond to net foreign asset positions – using Schlicht's (2021) methodology, which allows coefficients to evolve flexibly over time. We then combine these two components using empirical weights derived from sovereign spreads, allowing financial markets to indicate how they value fiscal versus external adjustment when assessing sovereign solvency. This yields a forward-looking, theoretically grounded, and market-disciplined measure of macro-financial sustainability.

Our second contribution (2) is to show that climate vulnerability exerts a large and systematic drag on this unified sustainability measure. Using a global annual panel of more than 60 economies since 1980 until 2024, we find that higher structural vulnerability is strongly associated with weaker fiscal–external sustainability, even after controlling for standard macroeconomic fundamentals. The economic rationale is immediate: more vulnerable economies face larger expected output and fiscal losses when shocks occur, weakening their effective fiscal and external adjustment. Investors internalize this through higher spreads, which raise borrowing costs and further erode sustainability. By contrast, resilience does not display a strong unconditional effect – a finding consistent with theories in which buffers matter primarily in adverse states – but its interaction with vulnerability is economically meaningful: resilience significantly attenuates the marginal impact of vulnerability on sustainability. This suggests that resilience operates as a conditional stabilizer, not a universal determinant of solvency.

Our third contribution (3) is to uncover the dynamic propagation mechanisms through which vulnerability and resilience shape macro-financial outcomes. Using local projections with smooth transition (LP-STAR), we show that the same exogenous climate shock leads to sharply different trajectories depending on initial structural conditions. In low-vulnerability or high-resilience regimes, shocks have modest and short-lived effects on sustainability, with fiscal and external balances recovering relatively quickly. In high-vulnerability or low-resilience regimes, however, the shock generates deep and persistent declines in sustainability and significant increases in sovereign spreads. Elevated spreads compress fiscal space, slow down resilience accumulation, and prolong macro-financial deterioration. This divergence in post-shock paths provides direct empirical evidence of nonlinear amplification and highlights the centrality of initial conditions in determining the macro-financial consequences of climate shocks.

Our fourth contribution (4) is to provide the first empirical documentation of an adaptation trap: a self-reinforcing equilibrium in which high vulnerability, weak resilience, and tight financing constraints interact to produce persistent deterioration in fiscal–external solvency. This mechanism is apparent both in the level regressions – where vulnerability depresses sustainability and resilience mitigates this effect – and in the dynamic responses – where high-vulnerability and low-resilience regimes show markedly weaker recovery from shocks. The consistency of this pattern across multiple measures of sustainability and alternative disaster indicators underscores the robustness of the adaptation-trap mechanism and the need to incorporate climate parameters explicitly into fiscal and external solvency assessments.

These findings yield several policy implications. Most notably, investments in climate resilience – including adaptation infrastructure, strengthened institutions, improved public financial management, and precautionary buffers – have sizable macro-financial returns: they reduce expected losses, anchor fiscal and external adjustment, and compress the climate-risk premium embedded in sovereign spreads. Conversely, delaying adaptation is costly, especially for vulnerable economies: higher spreads restrict fiscal space, which slows adaptation investment and reinforces vulnerability. Incorporating climate exposure into debt sustainability analyses, sovereign risk frameworks, and medium-term fiscal plans is therefore essential, as climate risk affects solvency not only through disaster losses but also through its interaction with policy responsiveness and financial market pricing. For policymakers, resilience-building emerges not merely as an environmental or social imperative but as a core instrument of macroeconomic stabilization.

The remainder of the paper proceeds as follows. Section 2 reviews the related literature. Section 3 develops the theoretical framework. Section 4 describes the methodology, including the construction of the unified sustainability index. Section 5 presents the panel and dynamic results. Section 6 concludes with broader implications for fiscal policy, sovereign risk management, and climate adaptation financing.

2. Literature Review

A first pillar of the literature establishes that weather and temperature shocks depress economic activity, especially in vulnerable economies, implying tighter fiscal space and external imbalances. Using within-country variation, higher temperatures reduce growth, industrial output, and investment in poorer countries, with effects that can be persistent (Dell et al., 2012; Dell et al., 2014). Micro-to-macro evidence indicates that adaptation occurs but is often incomplete even over decades – U.S. agriculture's long-run responses mitigate less than half of the short-run productivity losses – from extreme heat – implying sizeable residual damages that feed through public finances (Burke and Emerick, 2016). Dynamic spatial models show that relocation, innovation, and trade attenuate – but do not fully neutralize – spatially heterogeneous climate damages; migration constraints, adjustment frictions, and geography create persistent income and welfare gaps that are relevant for sovereign risk (Desmet and Rossi-Hansberg, 2015; Cruz and Rossi-Hansberg, 2024). Together, these results mean climate shocks erode the numerator (primary balances via higher spending and lower revenue) and the denominator (growth) of debt dynamics and disturb the current account through terms-of-trade and supply-chain channels central to external solvency (Mendoza, 1995; Corsetti et al., 2008).

A second pillar concerns sovereign risk, default, and fiscal sustainability under shocks. Canonical small-open-economy models with endogenous default show how risk premia, borrowing limits, and output jointly fluctuate, with default incentives peaking in recessions (Arellano, 2008). Empirically, intertemporal solvency requires systematic positive primary-balance responses to government debt – a "Bohn coefficient" – whose weakening around crises jeopardizes sustainability (Bohn, 1998; Ghosh et al., 2013). On the external side, the intertemporal approach emphasizes that valuation effects and risk premia shape current-account adjustment and the burden of external rebalancing, so risk pricing cannot be ignored when assessing sustainability (Gourinchas and Rey, 2007; Lane and Milesi-Ferretti, 2007). These insights imply that climate-induced output losses and reconstruction needs can weaken fiscal/external reaction functions precisely when risk premia rise, tightening the joint solvency constraint (Arellano, 2008; Ghosh et al., 2013).

A third strand documents market pricing of climate risk in debt and asset markets. For U.S. municipalities, expected sea-level rise increases yields, particularly with weaker disclosure – direct evidence of priced physical risk in fixed income (Painter, 2020). Cross-country studies find that climate vulnerability correlates with higher sovereign spreads while resilience (institutions, adaptation capacity, buffers) correlates with lower spreads, consistent with priced sovereign climate risk (Beirne et al., 2021; Kling et al., 2025). Broader asset-pricing work shows that investors demand compensation for climate exposure and carbon intensity, and that climate news shocks are priced, shaping discount rates and capital costs (Bolton and Kacperczyk, 2021; Engle et al., 2020). Decompositions of sovereign spreads tie risk premia to both global and idiosyncratic risks – including those plausibly climate-related – highlighting how belief updates after salient disasters can trigger repricing (Longstaff et al., 2011; Hilscher and Nosbusch, 2010). In this environment, credible adaptation/resilience programs are a form of fiscal insurance that can compress spreads and expand fiscal space.

The rare-disasters literature micro-foundations these premia and their macro feedbacks. Rare, severe shocks rationalize high risk premia and low safe rates; time-varying disaster risk propagates to investment, output, and interest rates (Barro, 2006; Gourio, 2012). Because the probability and size of macro disasters are themselves state-contingent and belief-driven, the pricing kernel embeds tail risk, making the debt sustainability condition depend on risk covariances rather than deterministic (r-g) alone. In open economies that rely on foreign financing for reconstruction, disaster-risk repricing can aggravate external adjustment costs and induce nonlinearities in fiscal/external sustainability (Gourio, 2012; Longstaff et al., 2011).

This motivates shifting from static debt thresholds to state-contingent fiscal space. Empirically, sustainability hinges on (i) the primary-balance reaction to debt, (ii) the effective (r-g), and (iii) the economy's ability to adjust under shocks (Bohn, 1998; Ghosh et al., 2013). State-contingent pricing in sovereign debt implies that higher perceived risk raises spreads, reduces sustainable debt, and can precipitate sudden stops – especially when external imbalances coexist (Aguiar and Gopinath, 2006; Arellano, 2008). Climate shocks act through these margins, worsening fundamentals while heightening risk premia when global risk aversion is elevated; valuation channels amplify external adjustments via asset-price movements and currency changes (Gourinchas and Rey, 2007; Corsetti et al., 2008). In such settings, resilience – physical, institutional, and financial – operates both by lowering expected losses and by improving the pricing of those losses, thereby relaxing financing constraints.

What, then, constitutes resilience in the solvency sense? Three mechanisms recur. First, adaptation capital – protective infrastructure, resilient utilities, early-warning systems – raises the marginal product of private capital and reduces output-loss variance, supporting growth while shortening recovery times (Desmet and Rossi-Hansberg, 2015; Cruz and Rossi-Hansberg, 2024). Second, credible plans, disclosure, and governance reduce uncertainty about tail losses, compressing the disaster-risk premium embedded in yields (Hilscher and Nosbusch, 2010; Longstaff et al., 2011). Third, macroeconomic/institutional frameworks – transparent medium-term fiscal rules, robust public investment management, and contingent liquidity lines – anchor expectations that primary balances will respond when needed, supporting the Bohn condition in bad times (Bohn, 1998; Ghosh et al., 2013). These channels map naturally into an empirical vulnerability × resilience interaction: the marginal effect of vulnerability on spreads and sustainability is less adverse when resilience is high (Beirne et al., 2021; Kling et al., 2025).

Methodologically, recent work increasingly moves beyond constant-parameter models to time-varying coefficients and regime dependence, in line with crisis and disaster realities. Local projections offer transparent inference on state-contingent impulse responses, while time-varying reaction functions capture how fiscal and external adjustment regimes shift across consolidations and crises (Jordà, 2005; Ghosh et al., 2013). In sovereign-risk pricing, decompositions attribute spread movements to changing risk premia versus default/loss-given-default components, allowing market data to inform the weights investors place on fiscal versus external fundamentals (Longstaff et al., 2011; Hilscher and Nosbusch, 2010). Embedding these insights, a market-priced, joint-sustainability index that aggregates fiscal and external reaction coefficients using weights inferred from sovereign spreads is aligned with the open-economy macro of valuation (Gourinchas and Rey, 2007) and the sufficiency of fiscal reactions for solvency (Bohn, 1998), while endogenizing the relative importance of the two pillars in real time.

Finally, contemporary debates on public debt under low interest rates underscore that favourable average (r-g) does not immunize solvency when risk premia are state-contingent and can spike after disasters; thus the insurance value of resilience can be large even if average financing conditions appear benign (Blanchard, 2019). Climate-finance evidence further suggests that investors price both transition and physical risks in capital markets, affecting sovereigns indirectly through banks, firms, and the macro-finance nexus (Bolton and Kacperczyk, 2021; Engle et al., 2020). The implication is clear: by investing in resilience and strengthening institutions, governments can improve market confidence, reduce borrowing costs, and safeguard joint fiscal–external sustainability; conversely, under-investment may entrench a vicious adaptation trap in which high vulnerability and tight fiscal space mutually reinforce via elevated spreads (Arellano, 2008; Beirne et al., 2021; Kling et al., 2025).

3. Theoretical framework and testable hypotheses

The analytical starting point builds on the intertemporal approach to sovereign solvency formalized by Arellano (2008), in which governments smooth consumption and default risk subject to borrowing constraints that depend on output, interest rates, and policy credibility. We extend this canonical framework by introducing climate vulnerability and resilience as structural parameters that influence both the probability and the cost of fiscal and external adjustment. In line with the empirical evidence summarized by Dell et al. (2014) and the disaster-impact literature of Cavallo and Noy (2011), climate shocks reduce output and revenue while raising reconstruction expenditure, thereby worsening debt dynamics. On the external side, deteriorating terms of trade and capital inflows (Batten et al., 2020) increase current-account pressures and external liabilities.

We conceptualize an economy where the evolution of public debt, D_t, and the net foreign asset position, NFA_t, follows

$$D_t = (1 + r_t - g_t)D_{t-1} - PB_t + C_t, \qquad (1)$$

$$NFA_t = NFA_{t-1} + CA_t, \qquad (2)$$

where r_t is the sovereign borrowing cost, g_t the growth rate, PB_t the primary balance, CA_t the current account, and C_t the direct fiscal cost of a climate shock. Climate shocks ε_t^C raise C_t and lower g_t; the magnitude of these effects depends on two country characteristics: vulnerability (V) – the degree to which climatic events translate into economic losses – and resilience (R) – the ability to prevent, absorb, and recover from those losses. Following the logic of Kahn et al. (2021), vulnerability and resilience jointly determine expected macroeconomic losses $L_t = f(V, R)$ with $f_V > 0$ and $f_R < 0$.

Our contribution is to embed this climate–macroeconomic channel into the intertemporal fiscal and external solvency conditions. In particular, we posit that the effective interest rate r_t demanded by investors depends on the perceived sustainability of both fiscal and external positions:

$$r_t = r^* + \psi(V_t - \lambda R_t) + \xi_t, (3)$$

where r^* is the global risk-free rate, $\psi > 0$ captures the sensitivity to climate risk, $\lambda > 0$ measures the mitigating role of resilience, and ξ_t is a stochastic shock. This formulation links sovereign spreads directly to climate fundamentals, consistent with emerging empirical evidence on "climate-priced sovereign risk" (Kling et al. 2025). A rise in vulnerability increases borrowing costs, whereas greater resilience lowers them – an effect that can feed back into debt dynamics and fiscal space.

3.1 The adaptation-trap mechanism

Building on the "adaptation trap" concept articulated by Duffy (2025), we model resilience as a policy choice that requires upfront fiscal resources but yields long-term macro-financial benefits. Formally, fiscal space F_t evolves as

$$F_t = f(PB_t, r_t - g_t, V_t, R_t), \qquad (4)$$

with $f_{PB} > 0$, $f_{(r-g)} < 0$, $f_V < 0$, and $f_R > 0$. Because resilience investment I_t^R competes with other budgetary demands, its short-term fiscal cost may reduce F_t, even though it increases expected future growth and lowers r_t. Highly vulnerable economies facing high interest rates thus struggle to finance resilience, perpetuating exposure to future shocks – a self-reinforcing adaptation trap described by the sequence

$$V \uparrow \Rightarrow L \uparrow \Rightarrow D \uparrow \Rightarrow r \uparrow \Rightarrow F \downarrow \Rightarrow R \downarrow \Rightarrow V \uparrow.$$

This mechanism, "vicious debt-vulnerability risk cycle" is conceptually close to the "vicious debt–risk cycle" in sovereign-default models (Arellano, 2008) but introduces a novel climate dimension: fiscal fragility and climate vulnerability mutually reinforce each other through borrowing-cost dynamics. This interaction – largely absent from the existing literature – constitutes the central theoretical innovation of our paper.

3.2 Theoretical predictions

From this framework several testable predictions follow. First, climate vulnerability deteriorates fiscal and external sustainability because it amplifies expected output losses and public expenditures, implying $\partial Y / \partial V < 0$, where Y denotes overall macro-financial sustainability. Second, resilience strengthens sustainability both directly, by limiting disaster losses, and indirectly, by improving investor confidence; hence $\partial Y / \partial R > 0$. Third, resilience mitigates the adverse impact of vulnerability – the marginal effect of vulnerability is less negative when resilience is high, implying $\partial^2 Y / (\partial V \, \partial R) > 0$. This cross-effect, which we estimate empirically through the interaction term $V \times R$, captures the buffering role of resilience.

A further prediction concerns sovereign spreads: $\partial Spread / \partial V > 0$ and $\partial Spread / \partial R < 0$, with the magnitude of the vulnerability effect increasing when resilience is weak ($\partial^2 Spread / (\partial V \, \partial R) < 0$). These relations jointly define the empirical signature of the adaptation trap: economies that combine high vulnerability with low resilience face both rising borrowing costs and eroding fiscal space.

3.3 Empirical implications and differentiations from previous studies

The model yields a natural sequence of empirical tests that structure the remainder of the paper. We first estimate time-varying fiscal and external reaction coefficients to identify the responsiveness of policy to indebtedness – our direct empirical counterpart to the theoretical parameters of the estimated reaction functions governing PB_t and CA_t. We then combine these coefficients into a market-priced composite sustainability metric, representing the jointly determined solvency of public and external accounts as perceived by investors. Finally, we examine how vulnerability, resilience, and their interaction affect this metric and, through local-projection analysis, trace the dynamic feedback between sustainability, borrowing costs, and adaptation capacity after climate shocks.

The framework builds upon established theoretical and empirical pillars while extending them in several important ways. It relies on the intertemporal solvency and sovereign-default tradition of Arellano (2008), on evidence about the fiscal costs of natural disasters (Cavallo and Noy, 2011), and on macroeconomic channels linking climate and growth (Dell et al., 2014; Burke et al., 2015). It also draws from recent studies of climate-risk pricing in sovereign debt markets (Kling et al. 2025). Building on these foundations, the present paper makes four novel contributions.

First, it integrates fiscal and external solvency into a unified sustainability concept that captures the joint adjustment capacity of the public and external sectors. Second, it endogenizes the relative importance of these two dimensions by allowing financial markets – through sovereign-spread responses – to determine their empirical weights, thereby creating a market-based sustainability index. Third, it explicitly models and estimates the vulnerability × resilience interaction within this solvency framework, quantifying how adaptive capacity offsets exposure to climate risk. Finally, it provides the first empirical evidence of the adaptation-trap feedback, in which high vulnerability, limited resilience, and constrained fiscal space reinforce each other through borrowing-cost dynamics.

3.4 A Stylised Simulation of the Adaptation Trap Mechanism

We illustrate the core mechanisms of the theoretical framework with a simple stylised simulation. The objective is not to match any particular country's data, but rather to show how climate vulnerability, sovereign spreads, and resilience interact dynamically in the model and how these interactions generate the nonlinear amplification patterns that later emerge in the empirical analysis. The simulation therefore serves as a conceptual bridge between the theoretical results and the econometric evidence that follows.

The exercise is based on a three-equation dynamic system in which sustainability, spreads, and resilience evolve in mutually reinforcing ways. Sustainability deteriorates when vulnerability or spreads increase but improves as resilience accumulates. Spreads depend positively on vulnerability and negatively on resilience and sustainability, reflecting the way market perceptions of risk respond to both exposure and adaptive capacity. Resilience itself follows a stock-flow process: it depreciates over time but can be replenished through investment. Crucially, investment falls when spreads rise because higher sovereign borrowing costs reduce fiscal space for adaptation. Taken together, these equations reproduce the mechanism by which low resilience inhibits recovery from climate shocks, while higher resilience helps stabilise fundamentals.

We simulate the system over 40 periods for two hypothetical economies that differ only in their level of resilience. Both face the same degree of climate vulnerability and are hit by an identical one-off climate shock in period 5. One economy begins with low resilience and a limited capacity to rebuild it; the other starts with high resilience and a stronger long-run adaptation target. All parameters are drawn from commonly used ranges in the climate-macro literature, and full details are provided in Appendix B.

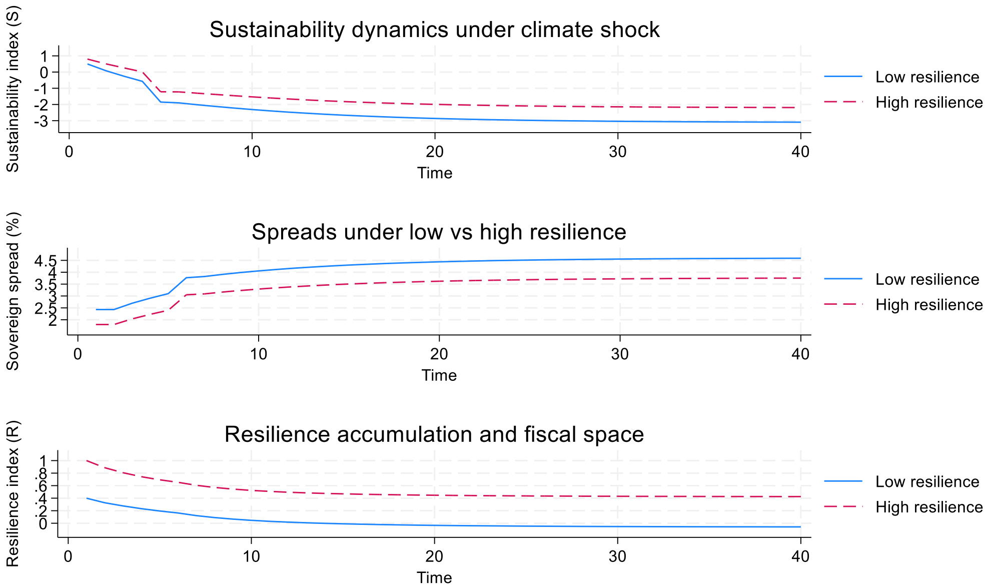
The simulated dynamics, reported in Figure 1, highlight three key insights. First, the climate shock reduces sustainability sharply on impact in both economies, but the drop is far more pronounced and persistent in the low-resilience case. In the high-resilience economy, sustainability stabilises relatively quickly and gradually moves back toward its long-run path; in the low-resilience economy, it continues to deteriorate long after the shock has passed.

Second, sovereign spreads react strongly to the shock, but their trajectory depends critically on resilience. The low-resilience economy experiences both a larger increase in spreads and a much slower return to pre-shock levels. Elevated spreads then feed back into the sustainability equation, further weakening fundamentals, and at the same time reduce the government's ability to invest in resilience. In contrast, spreads in the high-resilience economy increase only modestly and fall back more quickly, mitigating the long-run macro-financial impact of the shock.

Third, resilience itself evolves very differently across the two economies. In the high-resilience case, resilience declines immediately after the shock but recovers gradually as spreads normalise. In the low-resilience case, resilience continues to erode for many periods, reflecting the contraction in fiscal space caused by persistently higher spreads. Because resilience remains depressed, the low-resilience economy remains stuck in a cycle of high spreads, weak sustainability, and limited adaptation capacity. This is the adaptation trap: the economy cannot rebuild resilience because financing constraints tighten precisely when resilience is most needed.

These stylised dynamics reproduce, in a transparent forward simulation, the core mechanism of the theoretical model. They also closely anticipate the nonlinear patterns observed in the empirical analysis: countries with low resilience experience sharper and more persistent deteriorations in sustainability and spreads following climate shocks, while those with higher resilience weather the same shocks with significantly less damage. The simulation thus provides a narrative and quantitative foundation for the empirical strategy that follows.

Figure 1. Stylised Simulation of Sustainability, Sovereign Spreads, and Resilience Dynamics



Notes: This figure plots the simulated trajectories of sustainability, sovereign spreads, and resilience for two hypothetical economies that differ only in their initial resilience levels and long-run resilience targets. Both are subject to the same degree of climate vulnerability and experience an identical one-off climate shock in period 5. The simulation is based on a three-equation dynamic system in which sustainability depends on resilience, spreads, and vulnerability; spreads evolve with vulnerability, resilience, and sustainability; and resilience follows a stock-flow accumulation process influenced by spreads through their effect on fiscal space. Parameter values follow standard calibrations in the climate-macro literature. Complete details on the simulation structure and calibration are provided in Appendix B.

4. Methodology

4.1 Conceptual framework

Macroeconomic sustainability reflects the ability of an economy to maintain both fiscal and external solvency in the face of shocks. Fiscal sustainability hinges on the government's intertemporal budget constraint, while external sustainability captures the solvency of the country's net foreign asset position. In a financially integrated world, these two dimensions are jointly determined: fiscal imbalances affect the current account and external debt accumulation, whereas external fragility raises sovereign risk premia and tightens fiscal space.

We conceptualize sustainability as a joint adjustment process, summarizing the responsiveness of public and external balances to accumulated debt and liability stocks. Higher responsiveness denotes a stabilizing regime, while weaker responses indicate unsustainable dynamics. Climate shocks, vulnerability, and resilience alter these responses through several channels: (i) direct fiscal costs of relief and reconstruction; (ii) trade and terms-of-trade disruptions; and (iii) changes in risk premia and financing conditions. Limited fiscal space and high borrowing costs may, in turn, constrain adaptation investment – creating an adaptation trap whereby low resilience leads to higher losses, higher debt, and even lower future resilience.

4.2 Estimation of fiscal and external sustainability coefficients

Following the time-varying-parameter (TVP) framework employed in Afonso et al. (2025), we begin by estimating country-specific fiscal and external reaction functions of the form:

$$PB_{i,t} = \alpha_i + \phi_{i,t} Debt_{i,t-1} + \varepsilon^F_{i,t}, \qquad (5)$$

$$CA_{i,t} = \eta_i + \nu_{i,t} NFA_{i,t-1} + \varepsilon^X_{i,t}, \qquad (6)$$

where $PB_{i,t}$ is the primary-balance-to-GDP ratio, $CA_{i,t}$ the current-account-to-GDP ratio, $Debt_{i,t-1}$ public debt, and $NFA_{i,t-1}$ the net foreign asset position. The coefficients $\phi_{i,t}$ and $\nu_{i,t}$ summarize how fiscal and external positions adjust to changes in indebtedness. Positive and statistically significant values indicate countercyclical and stabilizing policy regimes – i.e., fiscal authorities raise the primary balance when debt increases, and external balances improve when NFA deteriorates – consistent with standard notions of fiscal and external sustainability.

Equations (5) and (6) are estimated resorting to Schlicht's (2021) methodology, which assumes that ϕ and ν changes "slowly and unsystematically over time". Hence, to capture gradual shifts in these policy regimes, we allow the coefficients to evolve according to random-walk processes:

$$\phi_{i,t} = \phi_{i,t-1} + u^F_{i,t}, \qquad (5.1)$$

$$\nu_{i,t} = \nu_{i,t-1} + u^X_{i,t}, \qquad (6.1)$$

where $u^F_{i,t}$ and $u^X_{i,t}$ are independent disturbances. Instead of relying on traditional Kalman-filter or Bayesian MCMC techniques, we estimate these time-varying coefficients using the method-of-moments estimator proposed by Schlicht (2021). This estimator is particularly well suited for annual macroeconomic panels such as ours and offers several advantages that justify its adoption.

We estimate the time-varying fiscal and external reaction coefficients using Schlicht's (2021) method-of-moments estimator, which offers several advantages over standard state-space or Bayesian TVP approaches. Unlike Kalman-filter methods, which tend to over-smooth coefficient paths and struggle to detect genuine regime changes in short annual samples, Schlicht's estimator identifies the variance of the coefficient innovations directly from sample moments. This makes it particularly well suited to macro-fiscal environments characterized by structural breaks, abrupt consolidations, and crisis-driven adjustments. The procedure is also robust to non-Gaussian and heteroskedastic shocks – common features of fiscal and external variables – because it does not rely on distributional assumptions or prior specifications. Moreover, it performs well in short and unbalanced country panels, avoids the sensitivity to subjective priors inherent in Bayesian estimators, and delivers closed-form standard errors for the time-varying coefficients, which are essential for constructing the precision-weighted sustainability index used later in the analysis. Overall, Schlicht's (2021) approach provides a transparent, data-driven, and computationally efficient way to recover economically meaningful adjustment paths, making it particularly appropriate for our cross-country setting.

4.3 Constructing a unified sustainability metric

To capture the economy's overall adjustment capacity, we combine the two estimated coefficients into a composite sustainability index $Y_{i,t}$. Let $\phi_{i,t}$ and $\nu_{i,t}$ denote the time-varying fiscal and external adjustment coefficients. We first standardize each coefficient across countries and time:

$$z_{i,t}^{F} = \frac{\phi_{i,t} - \bar{\phi}}{\sigma_{\phi}}, z_{i,t}^{X} = \frac{\nu_{i,t} - \bar{\nu}}{\sigma_{\nu}}. (7)$$

To account for estimation precision, we then weight each standardized coefficient by the inverse of its first-stage standard error:

$$\tilde{z}_{i,t}^{F} = \frac{z_{i,t}^{F}}{SE(\phi_{i,t})}, \tilde{z}_{i,t}^{X} = \frac{z_{i,t}^{X}}{SE(\nu_{i,t})}. (8)$$

Appendix Figure A1 documents the empirical distribution of the precision-weighted fiscal and external sustainability coefficients ($\tilde{z}_{i,t}^{F}$ and $\tilde{z}_{i,t}^{X}$) across advanced economies (AE) and emerging market and developing economies (EMDE). The histograms for the fiscal sustainability coefficient show that AE and EMDE distributions are both centred near zero, but AEs display greater dispersion and a longer left tail, reflecting broader heterogeneity in fiscal responses to debt. EMDEs exhibit a tighter concentration of values, with fewer extreme observations. The external sustainability coefficient displays substantially wider variation in both groups, especially among AEs, where the distribution includes large positive outliers.

EMDEs again show a more concentrated pattern, with coefficients clustered around small positive values. Taken together, these distributions highlight the cross-country heterogeneity in both fiscal and external adjustment behaviour prior to constructing the composite sustainability index. Appendix Figure A2 shows how the two coefficients evolve over time. The fiscal sustainability coefficient exhibits a relatively stable central tendency, with interquartile ranges that remain narrow in most years. Some periods – such as the early 2000s and mid-2010s – feature wider dispersion, reflecting years in which countries' fiscal adjustment behaviour diverged more sharply. The external sustainability coefficient displays greater year-to-year dispersion throughout the sample and a wider range of outliers, consistent with the distributional patterns observed in Figure A1, in the Appendix. While the median remains reasonably stable, the spread of observations reveals substantial cross-country variation in external adjustment dynamics at each point in time. These descriptive results underscore the importance of adopting a time-varying, precision-weighted approach when constructing the unified sustainability metric used in the main analysis.

We then estimate the fixed-effects regression:

$$Spread_{i,t} = \alpha_i + \gamma_t + \beta_F \, \tilde{z}^F_{i,t} + \beta_X \, \tilde{z}^X_{i,t} + \varepsilon_{i,t}, \qquad (9)$$

where $Spread_{i,t}$ denotes the sovereign risk premium (long-term bond-yield differential). The coefficients β_F and β_X capture the extent to which markets price fiscal and external adjustment capacity into sovereign spreads.

The fitted linear combination of the precision-weighted coefficients provides a market-priced measure of macro-financial sustainability:

$$Y_{i,t} = \hat{\beta}_F \, \tilde{z}^F_{i,t} + \hat{\beta}_X \, \tilde{z}^X_{i,t}, \qquad (10)$$

which we subsequently re-standardize across all country–year observations. Intuitively, $Y_{i,t}$ summarizes the portion of fiscal and external adjustment that investors perceive as relevant for sovereign risk – thereby linking sustainability directly to fiscal space and financing conditions. A higher value of $Y_{i,t}$ denotes stronger overall solvency discipline and lower perceived macro-financial fragility.

As robustness, we construct two alternative versions of the index:

1. Unsupervised (PCA) index: the first principal component of $(\tilde{z}^F_{i,t}, \tilde{z}^X_{i,t})$.

2. Structural-weight index: $Y_{i,t}^{\text{struct}} = w_F\, \tilde{z}_{i,t}^F + w_X\, \tilde{z}_{i,t}^X$, where the theoretical weights w_F and w_X are proportional to average public-debt and external-liability ratios. All versions yield qualitatively similar results.

Figure 2 provides a comprehensive characterization of the unified sustainability measures and their underlying fiscal and external components. Panels (a) and (b) report the unconditional distributions of the two standardized sustainability indices. Panel (a) shows the distribution of the market-priced sustainability index, Y_{it}, constructed from sovereign yield pricing, while Panel (b) displays the distribution of the PCA-based sustainability index. Both indices are approximately symmetric and centred close to zero, reflecting the standardization procedure. However, the market-priced index exhibits slightly fatter tails, indicating that financial markets occasionally assign extreme valuations to adjustment capacity, particularly during periods of heightened stress.

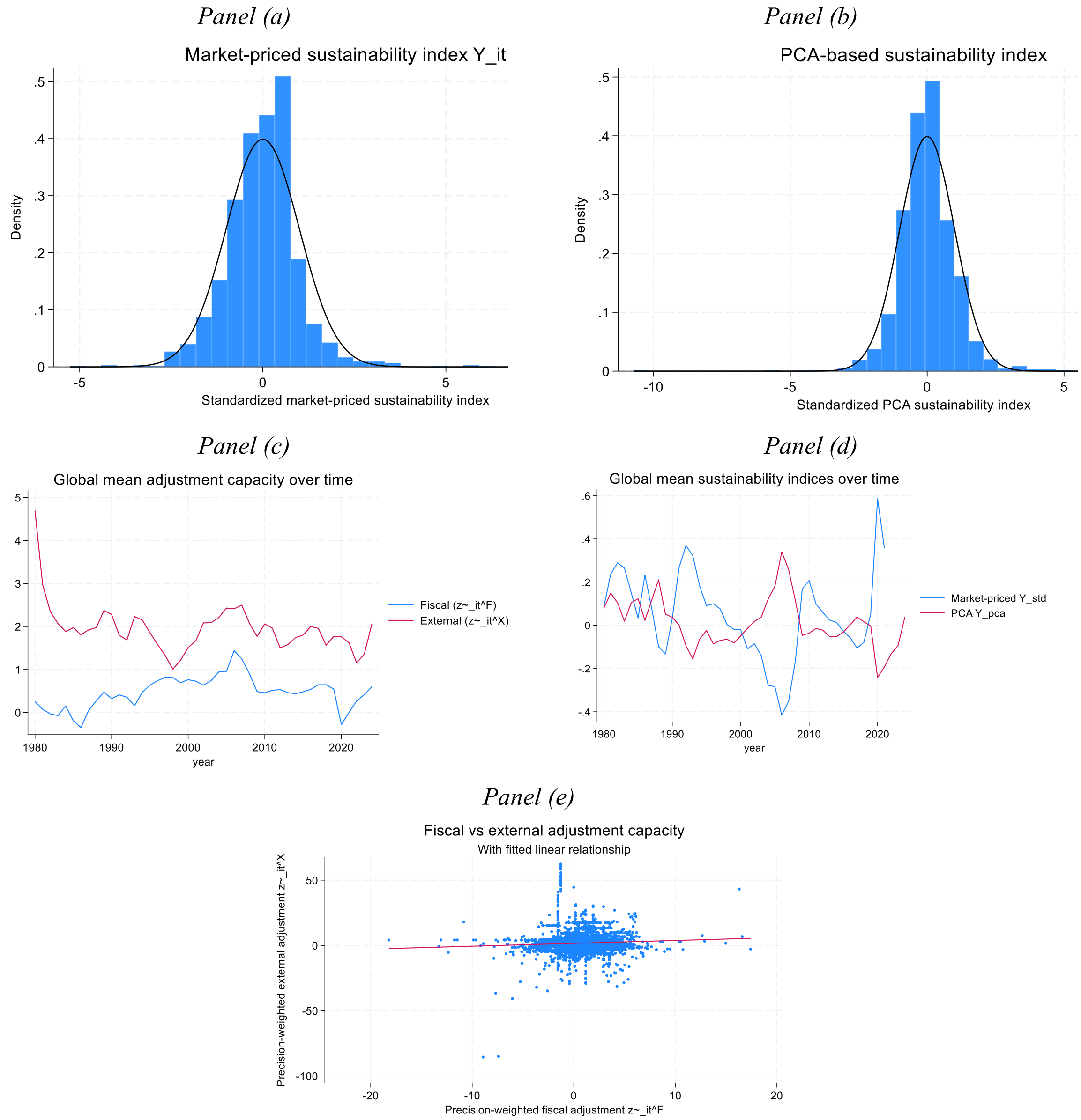
Panel (c) reports the global mean evolution of fiscal and external adjustment capacity over time, based on the precision-weighted coefficients $\tilde{z}_{it}^F$and $\tilde{z}_{it}^X$. Two features stand out. First, external adjustment capacity is systematically higher than fiscal adjustment capacity over most of the sample, consistent with the greater responsiveness of current-account dynamics relative to fiscal balances. Second, both series display pronounced medium-run cycles, with visible deteriorations around major global episodes, including the early 1980s debt crisis, the late-1990s emerging-market crises, the Global Financial Crisis, and the Covid-19 period. This confirms that both dimensions exhibit meaningful time variation and are closely linked to the global financial cycle.

Panel (d) shows the global mean evolution of the two composite sustainability indices, $Y_{it}$and Y_{it}^{PCA}. While the two indices are positively correlated, they do not move one-for-one. In particular, the market-priced index displays sharper contractions during crisis episodes – most notably around the mid-2000s and 2020 – highlighting the forward-looking nature of financial pricing relative to purely statistical aggregation. This divergence underscores the added value of using market-based weights when constructing a macro-financial sustainability measure.

Panel (e) examines the joint cross-sectional relationship between fiscal and external adjustment capacity, plotting $\tilde{z}_{it}^X$against $\tilde{z}_{it}^F$together with a fitted linear relationship. The positive but relatively flat slope indicates that fiscal and external adjustment capacities are complements but far from perfect substitutes. Substantial dispersion remains at all levels of fiscal capacity, confirming that strong fiscal adjustment does not automatically translate into strong external adjustment, and vice-versa. This empirical structure provides a clear justification for constructing a two-dimensional composite index, rather than relying on either fiscal or external sustainability alone.

Overall, Figure 2 validates three key properties of the sustainability framework adopted in this paper: (i) the market-priced index is well-behaved and not driven by outliers; (ii) fiscal and external adjustment display rich and distinct time variation; and (iii) their imperfect co-movement justifies the construction of a unified macro-financial sustainability metric.

Figure 2. Market-Priced and PCA-Based Sustainability: Distributions, Time Dynamics, and Joint Structure



Note: Panel (a) shows the distribution of the standardized market-priced sustainability index. Panel (b) displays the distribution of the standardized PCA-based sustainability index. Panel (c) reports the global mean evolution of precision-weighted fiscal and external adjustment capacity. Panel (d) shows the global mean evolution of the two composite sustainability indices. Panel (e) plots fiscal versus external adjustment capacity with a fitted linear relationship.

4.4 Econometric specification

We start from a compact reduced-form panel model that relates the unified sustainability metric $Y_{i,t}$ to climate vulnerability, resilience, and standard macroeconomic conditions:

$$Y_{i,t} = \alpha_i + \gamma_t + \beta_1 Vuln_{i,t-1} + \beta_2 Resil_{i,t-1} + \beta_3 (Vul \times Resil)_{i,t-1} + X'_{i,t-1}\theta + \varepsilon_{i,t}, \quad (11)$$

where $Y_{i,t}$ is the composite fiscal–external sustainability index for country i in year t, constructed in (11) from the market-pricing regression. The vector $X_{i,t-1}$ collects standard macro controls (real per capita GDP growth, inflation, public debt, trade openness, and international reserves), all lagged one period. Country fixed effects α_i absorb time-invariant structural differences in institutions and economic structure, while time fixed effects γ_t capture global shocks and common trends (e.g. global financial conditions, commodity cycles).

Because $Y_{i,t}$ is itself constructed from sovereign spreads, we do not include spreads or yields as regressors in (12) to avoid mechanical double counting and endogeneity. Instead, spreads are used either in the first-stage construction of $Y_{i,t}$ or as a separate dependent variable in the dynamic analysis.

In some specifications we also allow for persistence in the sustainability index by including a lagged dependent variable:

$$Y_{i,t} = \alpha_i + \gamma_t + \rho Y_{i,t-1} + \beta_1 Vuln_{i,t-1} + \beta_2 Resil_{i,t-1} + \beta_3 (Vul \times Resil)_{i,t-1} + X'_{i,t-1}\theta + \varepsilon_{i,t}, \quad (12)$$

and show that the estimated coefficients on vulnerability and resilience are very similar to those obtained from (11), suggesting that Nickell bias is limited given our panel length. Throughout, the coefficient on the interaction term, β_3, is central: it tests whether higher resilience dampens – or potentially reverses – the adverse association between climate vulnerability and macro-financial sustainability. A less negative (or even positive) marginal effect of vulnerability when resilience is high is consistent with resilience acting as a buffer that prevents climate exposures from translating into persistent fiscal and external stress.

Importantly, in this panel reduced-form block we focus on structural climate fundamentals (vulnerability and resilience) and macroeconomic conditions. Actual disaster realizations are not included on the right-hand side here; instead, they enter only in the dynamic local-projection analysis, which traces the response of sustainability and spreads to exogenous climate shocks.

To study dynamic feedbacks and non-linearities – the "adaptation trap" – we estimate impulse responses using local projections (Jordà, 2005) augmented with a smooth transition (STAR-type) structure. For each projection horizon $h = 0,1,\dots,H$, we estimate

$$Y_{i,t+h} = \alpha_i(h) + \gamma_t(h) + \left[\beta_0^L(h) + \beta_0^H(h)G\left(q_{i,t-1}; c, \kappa\right)\right]Shock_{i,t} + \sum_{j=1}^{J}\left[\beta_j^L(h) + \beta_j^H(h)G\left(q_{i,t-1}; c, \kappa\right)\right]Shock_{i,t-j} + \Phi(h)'X_{i,t-1} + u_{i,t+h}(h), \quad (13)$$

where $Shock_{i,t}$ denotes an exogenous climate shock (our baseline measure is a standardized log disaster-mortality shock, with robustness to alternative disaster indicators), and $q_{i,t-1}$ is a transition variable capturing the underlying regime. In our baseline LP-STAR exercises, $q_{i,t-1}$ is given by climate vulnerability or resilience; as robustness we can also consider borrowing costs (spreads) as a proxy for fiscal space. The same set of controls $X_{i,t-1}$ is included as in (12), and we maintain country and time fixed effects for each horizon.

The function $G(\cdot)$ is a smooth transition function of logistic form:

$$G\left(q_{i,t-1}; c; \kappa\right) = \left[1 + \exp\left(-\kappa\left(q_{i,t-1} - c\right)\right)\right]^{-1}, \qquad (14)$$

where c is the threshold (the level of $q$around which the regime shifts) and $\kappa > 0$ governs the speed of transition between regimes. For small deviations of $q_{i,t-1}$ from c, the economy is in a "mixed" regime; for sufficiently high (low) values of $q_{i,t-1}$, the system converges smoothly towards a "high-stress" (or "low-stress") regime.

In this augmented LP-STAR specification:

- $\beta_0^L(h)$ and $\beta_0^H(h)$ describe the horizon-specific impulse response of sustainability to a climate shock in the low- and high-regime components, respectively.
- The effective impulse response at horizon $h$for a country starting from regime $q_{i,t-1}$ is

$$IFR_Y\left(h \mid q_{i,t-1}\right) = \beta_0^L(h) + \beta_0^H(h)G\left(q_{i,t-1}; c, \kappa\right), \qquad (15)$$

which varies smoothly with the transition variable.

The same framework is applied to sovereign spreads and resilience as dependent variables, yielding regime-dependent responses of market-priced risk and adaptation capacity to climate shocks. This augmented LP-STAR approach brings several advantages. First, it preserves the transparency of local projections, allowing for flexible horizon-by-horizon estimation with fixed effects and robust inference. Second, by embedding a smooth transition structure, it explicitly models how the impact of climate shocks depends on a country's initial conditions – its vulnerability, resilience, and (in robustness) fiscal space.

Taken together, the panel reduced form in (12) and the dynamic, regime-dependent responses in (13)–(15) provide a coherent picture of climate-macro-financial linkages. The panel regression summarizes how structural climate fundamentals are associated with the *level* of market-priced sustainability, while the LP-STAR results show that the same realized disaster shock produces much larger and more persistent deterioration in sustainability when vulnerability is high and resilience is weak. In turn, this deterioration raises sovereign risk premiums and erodes fiscal space, and tighter financing conditions feedback negatively into future resilience, generating a self-reinforcing "adaptation trap" in vulnerable, low-resilience economies.

5. Empirical Analysis

This section presents the empirical evidence on the links between climate vulnerability, resilience, and macro-financial sustainability. We begin with the panel reduced-form regressions that summarize level relationships in the data. We then turn to the dynamic local-projection analysis with smooth transition effects, which traces the regime-dependent responses of sustainability to exogenous climate shocks.

5.1 Panel Regressions

This section presents the core panel regression evidence on the relationship between climate vulnerability, resilience, and the unified fiscal–external sustainability index. We proceed in four steps. First, we document baseline results for the full sample. Second, we explore heterogeneity between advanced economies (AEs) and emerging market and developing economies (EMDEs). Third, we assess robustness using alternative sustainability measures. Fourth, we evaluate the role of disaster shocks directly. All specifications include country and year fixed effects and Driscoll–Kraay standard errors.

The evidence from Table 1 shows that sustainability dynamics are structurally anchored in vulnerability conditions and display a high degree of persistence over time. The consistently negative and economically large coefficient on lagged vulnerability across the static specifications indicates that structural exposure to fiscal and external risks exerts a first-order effect on sustainability outcomes. This result is fully consistent with theoretical and empirical models of debt sustainability and macro-financial fragility, in which weak fiscal frameworks, high exposure to external shocks, and limited policy credibility act as amplification mechanisms that translate moderate disturbances into persistent instability (Bohn, 1998; Ghosh et al., 2013; Cordella et al., 2010). In the climate and disaster macroeconomics literature, vulnerability plays an analogous role by magnifying the long-run costs of shocks through capital destruction, fiscal strain, and balance-of-payments pressures (Cavallo and Noy, 2011; Kahn et al., 2021). The magnitude of the estimated coefficient implies that relatively small increases in structural vulnerability generate disproportionately large deteriorations in sustainability.

Table 1. Baseline Panel Regressions: Vulnerability, Resilience, and Sustainability (Full Sample)

VARIABLES	Vuln + Controls	Res + Controls	Vuln + Res + V×R + Controls	L.Y + ln(Reserves)	L.Y + Controls (no Reserves)
Lagged Standardized Fiscal-External Sustainability Index	–	–	–	0.668*	0.635*
				(0.079)	(0.043)
Lagged Climate Vulnerability Index	-5.972*	–	-7.661*	2.475	-1.720
	(1.964)		(2.295)	(2.011)	(1.540)
Lagged Climate Resilience Index	–	-0.144	-2.201	0.415	-0.847
		(0.285)	(1.657)	(0.777)	(0.883)
Interaction: Lagged Vulnerability × Lagged Resilience	–	–	5.167	-0.679	2.746
			(4.306)	(2.101)	(2.310)
Lagged Real GDP per Capita Growth	-0.021*	-0.026*	-0.026*	-0.015*	-0.016*
	(0.005)	(0.003)	(0.003)	(0.005)	(0.004)
Lagged Inflation Rate	-0.003	-0.005***	-0.004	0.001	-0.002
	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)
Lagged Public Debt-to-GDP Ratio	-0.001	-0.002	-0.001	-0.002	-0.004*
	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
Lagged Trade Openness	-0.004*	-0.004*	-0.004*	-0.003*	-0.001***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Lagged Log of International Reserves	–	–	–	-0.030*	–
				(0.010)	
Observations	1,447	1,384	1,384	866	1,338
Within R^2	0.227	0.211	0.220	0.554	0.513

Notes: This table reports panel regressions of the market-based fiscal–external sustainability index on lagged climate vulnerability and resilience indicators. Columns (1)–(3) include static specifications with different combinations of vulnerability, resilience, and their interaction. Columns (4) and (5) augment the baseline with the lagged dependent variable and, alternatively, international reserves. All regressions include a full set of country and year fixed effects. Control variables include lagged real GDP per capita growth, inflation, public debt, and trade openness. Standard errors are Driscoll–Kraay and are robust to heteroskedasticity, serial correlation, and cross-sectional dependence. All explanatory variables enter with one lag. The interaction term is constructed as the product of lagged vulnerability and lagged resilience. The sample consists of up to 67 countries over the period 1981–2024. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Constant term omitted for reasons of parsimony.

By contrast, resilience does not emerge as an unconditional driver of sustainability. Its lack of a statistically discernible direct effect indicates that resilience is fundamentally a state-contingent concept whose economic relevance materializes primarily under stress. This is consistent with the resilience framework developed by Bangalore et al. (2016), in which fiscal buffers, financial depth, and institutional quality only bind when economies are hit by large adverse shocks. The positive sign of the vulnerability–resilience interaction nonetheless indicates that resilience dampens the marginal damage associated with rising vulnerability, consistent with evidence that economies with greater fiscal space and stronger institutions recover faster and with less permanent damage following crises and disasters (IMF, 2015; Cavallo et al., 2013).

The introduction of the lagged dependent variable highlights the high degree of persistence in sustainability. The large autoregressive coefficient implies that sustainability conditions evolve sluggishly and adjust only gradually to shocks. This degree of inertia is characteristic of stock–flow adjustment processes in public debt dynamics and external sustainability (Bohn, 1998; Reinhart and Rogoff, 2010; Ghosh et al., 2013). From a policy perspective, this persistence implies that temporary policy corrections are unlikely to be self-sustaining unless accompanied by structural reforms that durably reduce vulnerability.

The macroeconomic controls behave in economically coherent ways. The negative association between real GDP growth and sustainability reflects the procyclicality of borrowing and external deficits during booms (Kaminsky et al., 2004; Alesina et al., 2008). Inflation weakens sustainability by eroding real debt servicing capacity and fiscal credibility (Sargent and Wallace, 1981; Reinhart and Rogoff, 2010). Public debt and trade openness systematically undermine sustainability through debt-overhang mechanisms and exposure to global financial volatility (Calvo et al., 2008; Lane and Milesi-Ferretti, 2018). The negative effect of reserves reflects precautionary accumulation in response to rising stress rather than an exogenous stabilizing role (Aizenman and Lee, 2007; Jeanne and Rancière, 2011).

Table 2 reveals sharp structural heterogeneity between advanced economies and EMDEs. Vulnerability exerts no robust direct effect on sustainability in advanced economies but remains a powerful destabilizing force in EMDEs. This asymmetry is consistent with the sovereign risk and sudden-stop literature, which emphasizes that EMDEs face tighter external financing constraints, weaker institutional credibility, and stronger balance-sheet effects from exchange rate and capital-flow shocks (Reinhart et al., 2008; Reinhart and Rogoff, 2010; Gourinchas and Obstfeld, 2012). In these environments, vulnerability translates much more directly into fiscal stress, rising risk premia, and adverse debt dynamics.

Table 2. Heterogeneity: Advanced Economies vs. EMDEs

VARIABLES	AE	AE: +L.Y	AE + Controls	EMDEs	EMDEs +L.Y	EMDEs + Controls
Lagged Standardized Fiscal–External Sustainability Index	–	0.641*	0.621*	–	0.666*	0.626*
		(0.151)	(0.094)		(0.089)	(0.095)
Lagged Climate Vulnerability Index	-2.030	11.470	6.876	-14.512*	-1.969	-6.645*
	(8.995)	(8.908)	(8.618)	(3.023)	(1.719)	(1.967)
Lagged Climate Resilience Index	-0.514	5.291	3.408	-9.288**	-2.095	-4.692**
	(5.622)	(4.296)	(4.966)	(3.667)	(1.264)	(2.009)
Interaction: Lagged Climate Vulnerability × Lagged Climate Resilience	6.812	-12.293	-5.720	19.235**	4.831	10.400**
	(16.353)	(11.790)	(13.950)	(8.709)	(2.997)	(4.686)
Lagged Real GDP per Capita Growth	-0.025**	-0.036***	-0.021	-0.021*	-0.009***	-0.013*
	(0.012)	(0.019)	(0.016)	(0.005)	(0.005)	(0.004)
Lagged Inflation Rate	-0.029***	-0.019***	-0.017**	-0.002	0.002	-0.002
	(0.014)	(0.011)	(0.007)	(0.004)	(0.002)	(0.003)
Lagged Public Debt-to-GDP Ratio	-0.002	-0.000	-0.002	-0.002	-0.002**	-0.005*
	(0.002)	(0.002)	(0.002)	(0.003)	(0.001)	(0.002)
Lagged Trade Openness	-0.007*	-0.005*	-0.004*	-0.001	-0.002**	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Lagged Log of International Reserves	–	-0.017	–	–	-0.047*	–
		(0.012)			(0.012)	
Observations	598	368	577	786	498	761
Within R^2	0.276	0.530	0.511	0.263	0.692	0.568

Note: This table reports split-sample panel regressions for advanced economies (AEs) and emerging market and developing economies (EMDEs). All specifications include lagged climate vulnerability, lagged resilience, their interaction, and the standard macroeconomic control set. Dynamic specifications additionally include the lagged dependent variable and, where indicated, international reserves. Country and year fixed effects are included in all regressions. Standard errors are computed using the Driscoll–Kraay correction. All regressors enter with one lag. The AE sample consists of 30 countries, while the EMDE sample consists of 37 countries. The sample period spans 1981–2024 with an unbalanced panel structure. Constant term omitted for reasons of parsimony. Significance levels follow the same convention as in Table 1.

Resilience displays a fundamentally different role across income groups. In advanced economies, marginal changes in resilience generate limited gains in sustainability because institutional quality and fiscal credibility are already high. In EMDEs, resilience plays a genuine buffering role, significantly moderating the adverse effects of vulnerability. This result is consistent with the view that fiscal space, reserves, and institutional quality are quantitatively more valuable in low-credibility environments, where shocks more easily trigger self-fulfilling crises (IMF, 2015; Hallegatte et al., 2020). Sustainability persistence remains strong in both subsamples, confirming that inertia is a universal feature of sustainability dynamics, although its consequences are considerably more severe in structurally weaker economies.

Table 3 shows that the core sustainability mechanisms are robust to alternative measurement approaches. Sustainability remains highly persistent under both the market-based and PCA-based indicators. However, the role of vulnerability and resilience differs across the two measures. For the market-based index, sustainability is dominated by persistence and global financial conditions, consistent with the central role of the global financial cycle in asset pricing (Rey, 2015; Miranda-Agrippino and Rey, 2020). By contrast, for the PCA-based index, vulnerability and fiscal fundamentals regain quantitative importance, reflecting the deeper macro-structural content of that indicator. This distinction underscores that market-based and structural sustainability measures capture different layers of fiscal and external risk, consistent with the distinction between flow-based market pricing and stock-based sustainability (Uribe and Yue, 2006; Gourinchas and Obstfeld, 2012).

Table 3. Alternative Sustainability Measures: Market vs. PCA

VARIABLES	Market + Res	Market no Res	PCA + Res	PCA no Res
Lagged Standardized Fiscal–External Sustainability Index	0.668*	0.635*	–	–
	(0.079)	(0.043)		
Lagged Climate Vulnerability Index	1.886	-1.311	-2.700***	0.024
	(1.533)	(1.174)	(1.547)	(0.972)
Lagged Climate Resilience Index	0.316	-0.645	0.593***	0.682
	(0.593)	(0.673)	(0.324)	(0.513)
Interaction: Lagged Climate Vulnerability × Lagged Climate Resilience	-0.517	2.093	-1.114	-1.683
	(1.601)	(1.761)	(0.933)	(1.491)
Lagged Real GDP per Capita Growth	-0.012*	-0.012*	0.013*	0.009*
	(0.004)	(0.003)	(0.004)	(0.002)
Lagged Inflation Rate	0.001	-0.002	0.001	0.001
	(0.001)	(0.002)	(0.001)	(0.001)
Lagged Public Debt-to-GDP Ratio	-0.001	-0.003*	0.002**	0.002*
	(0.001)	(0.001)	(0.001)	(0.001)
Lagged Trade Openness	-0.003*	-0.001***	0.000	0.000
	(0.000)	(0.001)	(0.000)	(0.001)
Lagged Log of International Reserves	-0.023*	–	0.009	–
	(0.007)		(0.008)	
Lagged Standardized Fiscal–External Sustainability Index (PCA)	–	–	0.712*	0.685*
			(0.057)	(0.063)
Observations	866	1,338	1,782	3,086
Within R^2	0.554	0.513	0.534	0.497

Note: This table reports robustness regressions using two alternative dependent variables: (i) a market-based sustainability index and (ii) a principal-component (PCA) based sustainability index. All models include lagged vulnerability, lagged resilience, their interaction, and the standard macroeconomic control variables. Dynamic specifications additionally include the lagged dependent variable. Country and year fixed effects are included throughout. Standard errors are Driscoll–Kraay. All explanatory variables are lagged one period. The PCA-based index is constructed using the first principal component of the standardized fiscal and external imbalance indicators. Constant term omitted for reasons of parsimony. Significance levels follow the same convention as in Table 1.

Table 4 introduces explicit disaster shocks into the sustainability regressions. Disaster occurrence exerts a direct and economically meaningful adverse effect on sustainability, consistent with the destruction of capital, fiscal strain, and balance-of-payments pressures documented in the disaster macroeconomics literature (Cavallo and Noy, 2011; Felbermayr and Gröschl, 2014; Kahn et al., 2021). Disaster counts and severe-event indicators display weaker and less stable effects, suggesting that the extensive margin of disaster realization matters more for short-run sustainability than the intensive margin of measured severity.

Crucially, the inclusion of disaster shocks leaves the coefficients on vulnerability, resilience, and sustainability persistence largely unchanged. This indicates that disasters act primarily as catalysts that activate underlying structural fragilities rather than as independent drivers of sustainability outcomes. This interaction between shocks and pre-existing vulnerability is central to modern climate macroeconomics models, in which fiscal and external consequences of climate shocks depend critically on institutional quality, fiscal space, and financial development (IMF, 2016; World Bank, 2021).

While the reduced-form evidence in Tables 1-4 establishes the central role of vulnerability, resilience, and structural conditions in shaping medium- to long-run sustainability dynamics, it remains silent on the short-run propagation mechanisms through which shocks are transmitted to fiscal and external sustainability. In particular, the panel regressions capture average conditional relationships but do not trace the dynamic adjustment paths following discrete exogenous disturbances. To address this limitation, Section 5.2 turns to a local projection framework to quantify the dynamic impulse responses of sustainability to disaster shocks and related disturbances over short- and medium-term horizons. This approach allows us to explicitly characterize the timing, persistence, and potential non-linearities of sustainability responses, as well as to assess how vulnerability and resilience condition these dynamic effects in the aftermath of shocks.

Table 4. Disaster Shocks and Sustainability

VARIABLES	Disaster Any	Disaster Any (No Res)	Disaster Count	Disaster Count (No Res)	Severe	Severe (No Res)
Lagged Standardized Fiscal–External Sustainability Index	0.663*	0.630*	0.668*	0.635*	0.549*	0.563*
	(0.082)	(0.044)	(0.079)	(0.043)	(0.102)	(0.079)
Lagged Climate Vulnerability Index	2.791	-1.032	2.489	-1.718	3.126	2.325
	(2.157)	(1.779)	(1.985)	(1.536)	(3.619)	(2.006)
Lagged Climate Resilience Index	0.380	-1.121	0.434	-0.826	-1.198	-2.005
	(0.827)	(1.045)	(0.773)	(0.890)	(1.567)	(1.286)
Interaction: Lagged Climate Vulnerability × Lagged Climate Resilience	-0.608	3.306	-0.733	2.686	2.630	4.675
	(2.139)	(2.629)	(2.087)	(2.326)	(3.935)	(3.368)
Lagged Natural Disaster Occurrence Indicator	-0.027***	-0.021	–	–	–	–
	(0.014)	(0.028)				
Lagged Real GDP per Capita Growth	-0.015*	-0.016*	-0.015*	-0.016*	-0.022**	-0.019*
	(0.005)	(0.004)	(0.005)	(0.004)	(0.009)	(0.007)
Lagged Inflation Rate	0.001	-0.002	0.001	-0.002	0.001	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)
Lagged Public Debt-to-GDP Ratio	-0.002	-0.004*	-0.002	-0.003*	-0.001	-0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
Lagged Trade Openness	-0.003*	-0.001	-0.003*	-0.001***	-0.003***	-0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Lagged Log of International Reserves	-0.030*	–	-0.030*	–	-0.042**	–
	(0.010)		(0.010)		(0.016)	
Lagged number of Disasters	–	–	-0.004	-0.008	–	–
			(0.010)	(0.011)		
Lagged Severity of Disasters	–	–	–	–	-0.015	-0.040
					(0.068)	(0.041)
Observations	846	1,302	866	1,338	486	718
Within R^2	0.557	0.519	0.554	0.514	0.507	0.496

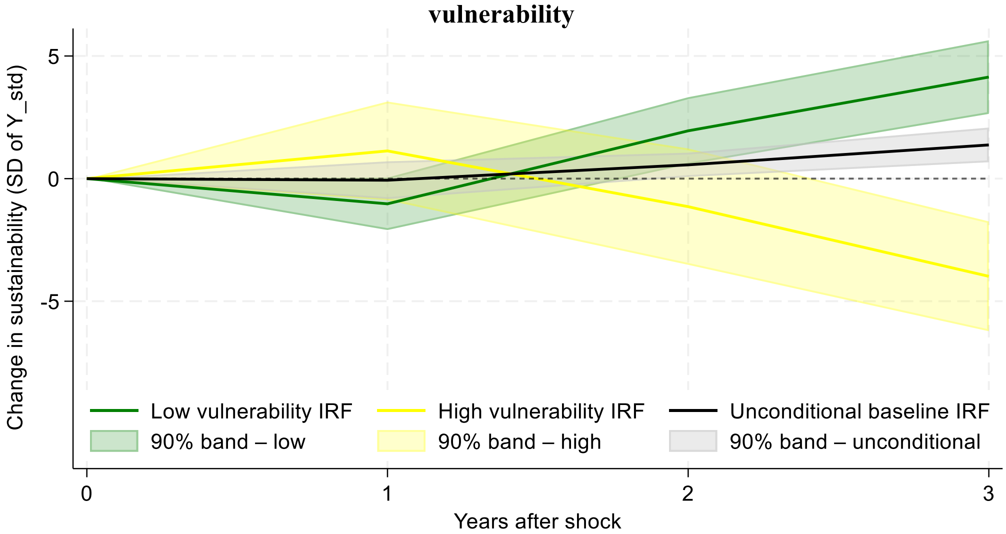
Note: This table extends the baseline specification by including alternative measures of disaster exposure: (i) a binary indicator for the occurrence of any disaster, (ii) disaster frequency (count), and (iii) a severe disaster indicator. All models additionally include lagged vulnerability, lagged resilience, and their interaction. Dynamic specifications include the lagged dependent variable. Country and year fixed effects are included in all regressions. Control variables follow the baseline specification. Standard errors are Driscoll–Kraay. Disaster variables enter with one lag. The sample is unbalanced and varies across specifications due to data availability on disaster incidence. Constant term omitted for reasons of parsimony. Significance levels follow the same convention as in Table 1.

5.2 Local Projections with Regime-dependent Dynamics

While the panel regressions identify strong level relationships, they do not reveal the dynamic transmission of climate shocks. We therefore turn to the LP-STAR analysis based on equations (13)–(15), which allows the response of sustainability to climate shocks to vary smoothly with vulnerability. Figure 3 plots the impulse response of sustainability $Y_{i,t}$ to a one-standard-deviation disaster-mortality shock, conditional on low versus high climate vulnerability. The unconditional baseline response (black line) is modest: sustainability rises only gradually and becomes clearly positive from about the second year onward. By contrast, conditioning on vulnerability reveals strong and highly asymmetric dynamics. In low-vulnerability regimes (green), the shock causes at most a small, short-lived decline in the first year, before sustainability improves markedly, with the response turning positive by year 2 and reaching a sizeable gain – on the order of several standard deviations – after three years, with the 90% confidence band comfortably above zero. In high-vulnerability regimes (yellow), the same shock initially has little effect, but from the second year onward it triggers a sharp and persistent deterioration: sustainability falls well below zero by year 2 and continues to decline through year 3, with the entire 90% band lying below zero. The widening gap between the two regimes provides direct dynamic evidence of a vulnerability-based amplification mechanism, whereby identical physical shocks translate into substantial sustainability losses in highly vulnerable economies but are largely absorbed – and eventually reversed – in more resilient ones.

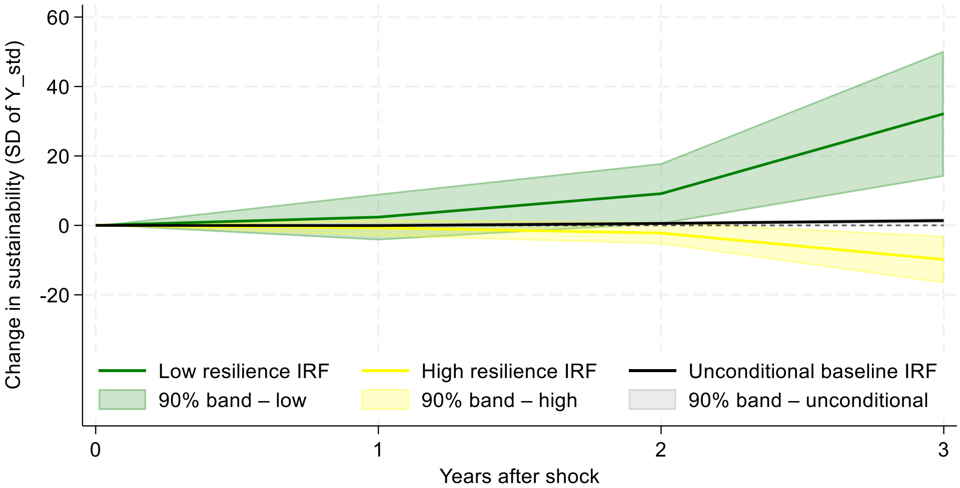
Figure 4 reports the impulse response of sustainability $Y_{i,t}$ to a one-standard-deviation disaster-mortality shock, conditioning on countries' resilience to climate shocks. The unconditional response is close to zero in the short run, with only a mild positive drift emerging after two to three years. Conditioning on resilience, however, reveals substantial heterogeneity. In low-resilience regimes, the shock leads to an increasingly positive and statistically significant improvement in sustainability, with effects strengthening steadily over the three-year horizon. By contrast, in high-resilience regimes, the same shock results in a small and temporary decline, with the impulse response remaining negative and statistically different from zero at longer horizons. The divergence between the two regimes highlights the importance of resilience in shaping the dynamic adjustment of fiscal and external sustainability following climate shocks, indicating that the capacity to absorb disruptions materially alters their medium-term consequences.

Figure 3: Impulse responses of sustainability to disaster-mortality shocks conditional on climate vulnerability



Notes: This figure displays local-projection impulse responses of the standardized sustainability index $Y_{i,t}$ to a one–standard-deviation disaster-mortality shock. Responses are estimated using the LP-STAR specification in equations (13)–(15), which allows coefficients to vary smoothly with the level of climate vulnerability. The figure reports the unconditional baseline response (black line), the responses in low-vulnerability regimes (green), and the responses in high-vulnerability regimes (yellow). Shaded areas represent 90% confidence intervals. Horizons are expressed in years after the shock.

Figure 4: Impulse responses of sustainability to disaster-mortality shocks conditional on climate resilience

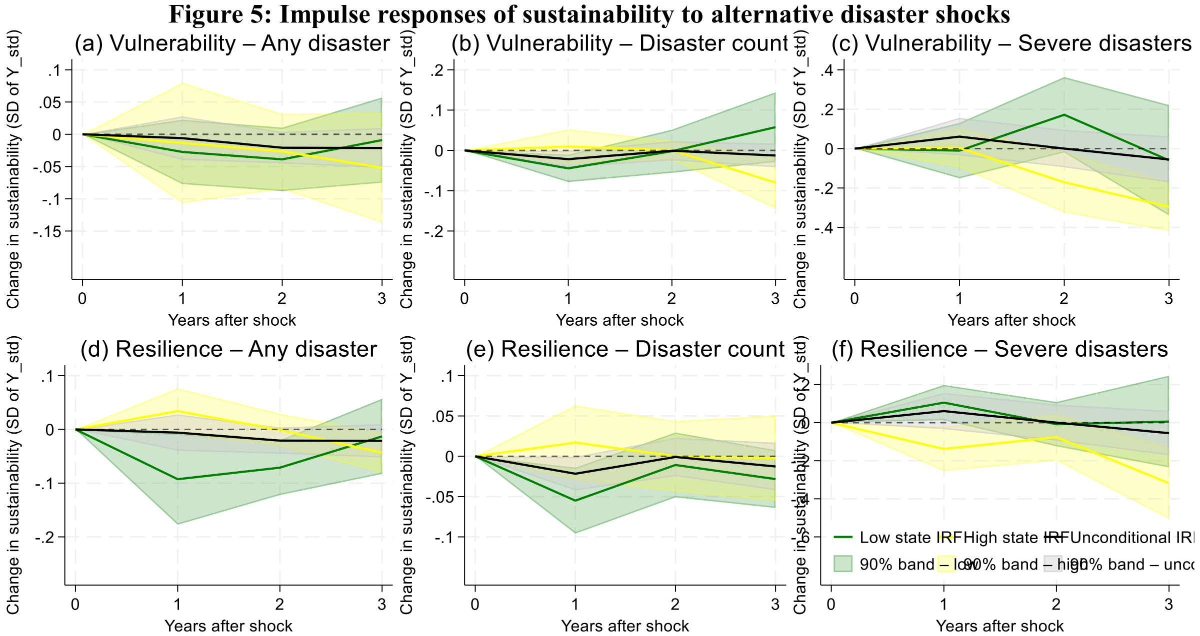


Notes: This figure presents local-projection impulse responses of the standardized sustainability index $\boldsymbol{Y}_{i,t}$ to a one–standard-deviation disaster-mortality shock. Estimates are obtained using the LP-STAR specification in equations (13)–(15), where the transition function varies smoothly with the level of climate resilience. The figure reports the unconditional baseline response (black line), the responses in low-resilience regimes (green), and the responses in high-resilience regimes (yellow). Shaded areas correspond to 90% confidence intervals. Horizons are measured in years following the shock.

Figure 5 reports the impulse responses of sustainability to three alternative disaster measures – any disaster occurrence, disaster counts, and severe disasters – conditional on climate vulnerability (top row) and resilience (bottom row). Across specifications, the pattern observed for the benchmark mortality shock broadly persists: responses differ markedly across regimes, and the sign and magnitude of the adjustment depend on the conditioning variable. Under low vulnerability, the effects of all three shock definitions are generally small and short-lived, with sustainability returning toward baseline within two to three years and in some cases turning mildly positive. By contrast, in high-vulnerability regimes, disaster shocks – particularly disaster counts and severe events – produce a more pronounced and persistent deterioration in sustainability, with confidence bands remaining below zero at longer horizons.

When conditioning on resilience, the responses again diverge sharply. Low-resilience economies exhibit sizable negative responses, especially following disaster counts and severe shocks, with declines that deepen over the horizon. High-resilience economies, in turn, experience only limited short-run effects, and in several cases sustainability improves moderately after two to three years. Together, these results show that the amplification role of structural conditions – captured by vulnerability and resilience – is robust to alternative definitions of climatic shocks.

Figure 5: Impulse responses of sustainability to alternative disaster shocks



Notes: This figure presents local-projection STAR impulse responses of the standardized sustainability index $\boldsymbol{Y_{i,t}}$ to three alternative disaster shock measures: any disaster occurrence, disaster counts, and severe disasters. The top row reports responses conditional on climate vulnerability, while the bottom row reports responses conditional on climate resilience. For each specification, the figure displays the estimated IRFs for the low-state (green) and high-state (yellow) regimes, along with the unconditional baseline response (black). Shaded areas represent 90% confidence intervals. Responses are shown over horizons of zero to three years following a one-standard-deviation standardized shock. The conditioning variables enter through a smooth transition function, allowing the effects of climate shocks on sustainability to vary across structural regimes.

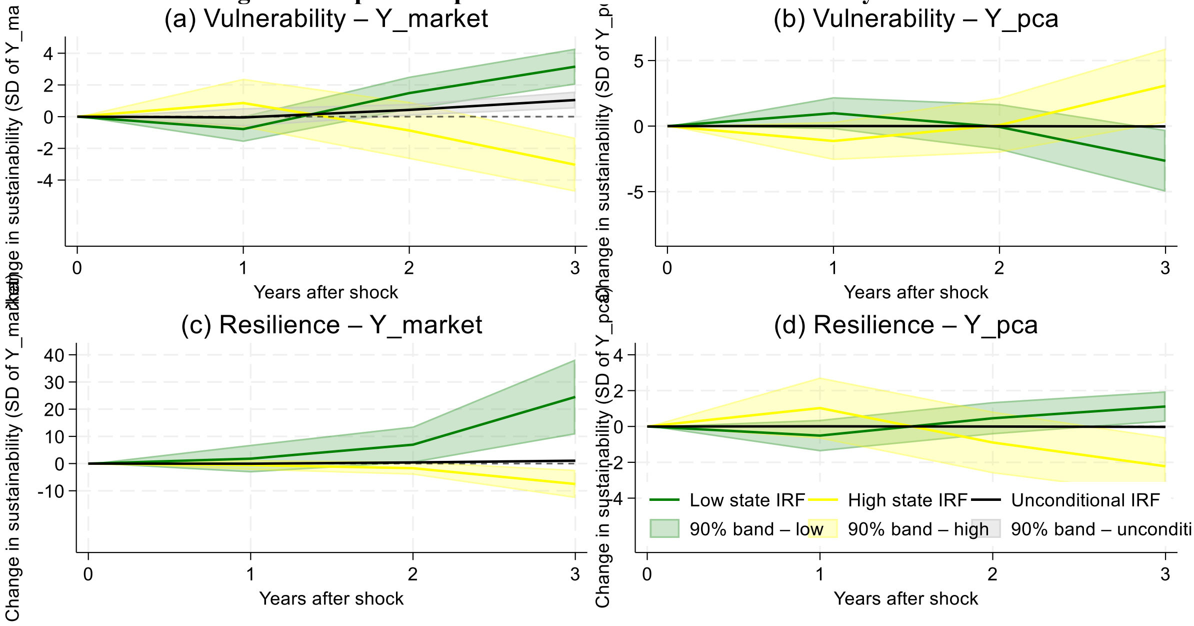
Figure 6 evaluates the robustness of our baseline LP-STAR findings by replacing the composite sustainability index Y_{std} with two alternative measures: (i) the market-based index Y_{market}, which reflects the information content of sovereign spreads, and (ii) the principal-component index Y_{pca}, which summarizes common variation across fiscal and external adjustment coefficients. Across both indices and both conditioning variables – vulnerability in the top row and resilience in the bottom row – the dynamic patterns remain remarkably consistent with those obtained earlier.

For the vulnerability-conditioned responses (Panels (a) and (b)), both Y_{market} and Y_{pca} display the same asymmetry highlighted in the baseline specification: disaster-mortality shocks generate only modest and short-lived effects in low-vulnerability regimes, but significantly larger and more persistent deteriorations when vulnerability is high. In both alternative measures, the high-vulnerability responses remain uniformly below the low-vulnerability ones over the full three-year horizon, and the confidence intervals indicate statistically meaningful differences emerging from the first year onward. This robustness confirms that the amplification mechanism uncovered in the baseline specification is not an artefact of the construction of Y_{std} but instead reflects a broad structural feature of climate–sustainability dynamics.

The resilience-conditioned responses (Panels (c) and (d)) yield a similarly stable picture. Low-resilience states exhibit sharp and persistent declines following the shock, whereas high-resilience states show muted effects and faster convergence toward the pre-shock baseline. For both Y_{market} and Y_{pca}, the divergence between high- and low-resilience regimes becomes particularly pronounced at medium horizons (two to three years), underscoring the stabilizing role of adaptive capacity in cushioning the fiscal-external consequences of disaster shocks. Importantly, the unconditional responses remain close to zero at all horizons across both indices, consistent with the notion that the average effect of climate shocks masks substantial heterogeneity across resilience levels.

Taken together, the results in Figure 6 demonstrate that the nonlinear transmission patterns documented in earlier sections – namely, stronger and more persistent deterioration in high-vulnerability and low-resilience regimes – are not sensitive to the particular sustainability metric employed. Whether sustainability is measured using the standardized composite index, market-priced indicators, or a data-driven principal component, the dynamic response to climate shocks exhibits the same qualitative structure. This reinforces the paper’s central finding: the macro-fiscal consequences of climate shocks depend crucially on pre-existing structural conditions, with vulnerability and resilience acting as key amplifiers or dampeners of the adjustment process.

Figure 6. Impulse responses with alternative sustainability indices



Notes: This figure reports the local-projection impulse responses of the alternative sustainability measures Y_{market} and Y_{pca} to a one-standard-deviation disaster-mortality shock. Responses are estimated using the LP-STAR specification, allowing the transmission of shocks to vary smoothly with either climate vulnerability (top row) or climate resilience (bottom row). Each panel displays the unconditional impulse response (black line), the responses in low-state regimes (green), and those in high-state regimes (yellow). Shaded areas denote 90% confidence intervals. Horizons are measured in years after the shock.

5.3 Robustness, Sensitivity, and Identification

This subsection assesses the robustness of our findings along three complementary dimensions. First, we examine the sensitivity of the panel reduced-form estimates to alternative samples, outlier treatments, and dynamic specifications. Second, we conduct a battery of robustness and diagnostic checks for the LP-STAR impulse responses, including pre-trend tests, placebo shocks, and bootstrap inference. Third, we discuss in detail the identification and exogeneity of the climate shocks used in the dynamic analysis.

5.3.1 Robustness of the panel regressions

We begin by subjecting the panel reduced-form results from Section 5.1 to a wide range of sensitivity checks. To ensure that our baseline results are not driven by a small number of extreme observations, we re-estimate the full set of specifications after (i) trimming the top and bottom 1% and 5% of the distribution of $Y_{i,t}$, reported in Table R1 and (ii) winsorizing all continuous regressors at the 1% level, presented in Table R2. When we trim the market price sustainability index at the 1% and 5% tails (Table R1) and when we winsorize all continuous regressors at the 1% level (Table R2), the coefficient on lagged vulnerability remains negative and statistically significant across the static specifications and in several dynamic variants, while resilience typically enters with a negative sign and is at least marginally significant in many cases. Across dynamic specifications, the lagged dependent variable points to substantial persistence (coefficients ~0.64–0.76), and the control variables behave as expected: higher real GDP per-capita growth, greater trade openness, and larger reserves are associated with lower values of the index, while higher public debt is typically associated with lower (less favourable) outcomes.

Table R1: Estimates of Panel Regression with Trimmed Market Price Sustainability Index

VARIABLES	Trim 1%: Vuln + Controls	Trim 1%: Res + Controls	Trim 1%: V + R + VxR + Controls	Trim 1%: + L.Y + ln(Res)	Trim 1%: + L.Y + Controls (no Res)
Lagged Standardized Fiscal–External Sustainability Index	–	–	–	0.745*	0.759*
				(0.044)	(0.021)
Lagged Climate Vulnerability Index	-3.732*	–	-4.332*	-0.069	-0.489
	(0.887)		(1.400)	(1.386)	(1.051)
Lagged Climate Resilience Index	–	-0.429	-1.321	0.199	0.363
		(0.288)	(1.161)	(0.719)	(0.652)
Interaction: Lagged Climate Vulnerability × Lagged Climate Resilience	–	–	2.290	-0.152	-0.502
			(2.981)	(1.662)	(1.278)
Lagged Real GDP per Capita Growth	-0.016*	-0.021*	-0.021*	-0.014*	-0.012*
	(0.005)	(0.003)	(0.003)	(0.004)	(0.004)
Lagged Inflation Rate	-0.001	-0.002	-0.001	0.002	0.000
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Lagged Public Debt-to-GDP Ratio	-0.002***	-0.003**	-0.002**	-0.003*	-0.003*
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Lagged Trade Openness	-0.006*	-0.005*	-0.005*	-0.002*	-0.002*
	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)
Lagged Log of International Reserves	–	–	–	-0.024*	–
				(0.008)	
Observations	1,355	1,295	1,295	843	1,295
Within R^2	0.252	0.238	0.242	0.703	0.673
VARIABLES	**Trim 5%: Vuln + Controls**	**Trim 5%: Res + Controls**	**Trim 5%: V + R + VxR + Controls**	**Trim 5%: + L.Y + ln(Res)**	**Trim 5%: + L.Y + Controls (no Res)**
Lagged Standardized Fiscal–External Sustainability Index				0.703*	0.720*
				(0.046)	(0.027)
Lagged Climate Vulnerability Index	-4.344*		-4.765*	0.387	-0.186
	(1.201)		(1.453)	(1.102)	(1.137)
Lagged Climate Resilience Index		-0.793*	-1.398	-0.087	0.544
		(0.234)	(1.087)	(0.634)	(0.605)
Interaction: Lagged Climate Vulnerability × Lagged Climate Resilience			1.691	0.336	-1.398
			(2.628)	(1.531)	(1.449)
Lagged Real GDP per Capita Growth	-0.010*	-0.015*	-0.015*	-0.006	-0.008**
	(0.003)	(0.002)	(0.002)	(0.004)	(0.004)
Lagged Inflation Rate	-0.001	-0.001	-0.001	0.002	0.000
	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)
Lagged Public Debt-to-GDP Ratio	-0.002**	-0.003**	-0.003**	-0.003**	-0.003*
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Lagged Trade Openness	-0.005*	-0.005*	-0.004*	-0.002*	-0.002*
	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)
Lagged Log of International Reserves	–	–	–	-0.023**	
				(0.009)	
Observations	1,232	1,179	1,179	772	1,179
Within R^2	0.239	0.230	0.238	0.659	0.621

Note: This table extends the baseline specification by including a trimmed 1% and 5% market price sustainability index. All models additionally include lagged vulnerability, lagged resilience, and their interaction. Dynamic specifications include the lagged dependent variable. Country and year fixed effects are included in all regressions. Control variables follow the baseline specification. Standard errors are Driscoll–Kraay. Disaster variables enter with one lag. The sample is unbalanced and varies across specifications due to data availability on disaster incidence. Significance levels follow the same convention as in Table 1.

Table R2: Estimates of Panel Regression with winsorized continuous RHS at 1%

VARIABLES	Vuln + Controls	Res + Controls	V + R + VxR + Controls	L.Y + ln(Reserves)	L.Y + Controls (no Reserves)
Lagged Standardized Fiscal–External Sustainability Index	–	–	–	0.666*	0.637*
				(0.081)	(0.043)
Lagged Climate Vulnerability Index	-4.789*		-6.669*	2.263	-0.841
	(1.677)		(2.025)	(1.888)	(1.271)
Lagged Climate Resilience Index	–	-0.251	-2.931	0.163	-1.239
		(0.294)	(1.930)	(0.838)	(0.989)
Interaction: Lagged Climate Vulnerability × Lagged Climate Resilience	–	–	6.554	-0.156	3.536
			(4.856)	(2.182)	(2.493)
Lagged Real GDP per Capita Growth	-0.023*	-0.027*	-0.027*	-0.016**	-0.017*
	(0.004)	(0.003)	(0.003)	(0.007)	(0.005)
Lagged Inflation Rate	-0.004	-0.005***	-0.004	0.001	-0.003
	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)
Lagged Public Debt-to-GDP Ratio	-0.001	-0.002	-0.001	-0.002	-0.004*
	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
Lagged Trade Openness	-0.004*	-0.005*	-0.004*	-0.004*	-0.001***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Lagged Log of International Reserves	–	–	–	-0.031*	–
				(0.010)	
Observations	1,447	1,384	1,384	866	1,338
Within R^2	0.227	0.212	0.219	0.553	0.513

Note: This table extends the baseline specification by including winsorized continuous RHS at 1% market price sustainability index. All models additionally include lagged vulnerability, lagged resilience, and their interaction. Dynamic specifications include the lagged dependent variable. Country and year fixed effects are included in all regressions. Control variables follow the baseline specification. Standard errors are Driscoll–Kraay. Disaster variables enter with one lag. The sample is unbalanced and varies across specifications due to data availability on disaster incidence. Constant term omitted for reasons of parsimony. Significance levels follow the same convention as in Table 1.

To complete our analysis, we have included different lag structures, specifically including 2 and 3 lags, reported on Tables R3 and R4, respectively. We verify that the results are not largely sensitive to the choice of a single lag by allowing for up to 2 and 3 lags of the climate fundamentals and macro controls. The estimated cumulative effects of vulnerability and resilience remain stable, and the interaction term continues to indicate a significant buffering role of resilience. With two lags, the cumulative effect of vulnerability remains negative (the second lag is negative and marginally significant). With three lags, the dynamic specification including resilience (Table R4, col. 3) yields a positive and statistically significant interaction, reinforcing the interpretation that resilience buffers the impact of vulnerability. Overall, these checks indicate that the headline results are not driven by outliers nor by the exact lag structure, and the buffering role of resilience is stable under alternative specifications.

Table R3: Estimates of Panel Regression with different lag structures (two lags)

VARIABLES	Climate + Controls	L.Y + Controls (no Res)	L.Y + ln(Res)
Lagged Standardized Fiscal-External Sustainability Index	–	0.618*	0.590*
		(0.054)	(0.133)
Lagged Climate Vulnerability Index	1.542	-0.689	4.801
	(4.347)	(4.942)	(3.760)
Two-period Lagged Climate Vulnerability Index	-9.002	-1.402*	-7.333
	(5.801)	(4.778)	(4.781)
Lagged Climate Resilience Index	-0.602	-1.136	-1.122
	(2.016)	(1.656)	(2.666)
Two-period Lagged Resilience Index	-0.487	0.303	2.832
	(2.837)	(2.124)	(2.784)
Interaction: Lagged Vulnerability × Lagged Resilience	1.136	2.761	2.387
	(5.258)	(3.644)	(4.926)
Interaction: Two-period Lagged Vulnerability × Two-period Lagged Resilience	2.224	0.081	-6.320
	(6.835)	(4.517)	(4.577)
Lagged Real GDP per Capita Growth	-0.018*	-0.015*	-0.011
	(0.004)	(0.005)	(0.007)
Two-period Lagged Real GDP per Capita Growth	-0.008	-0.004	-0.002
	(0.006)	(0.005)	(0.007)
Lagged Inflation Rate	-0.002	-0.002	0.002
	(0.003)	(0.003)	(0.001)
Two-period Lagged Inflation Rate	-0.001	-0.000	-0.003***
	(0.003)	(0.001)	(0.002)
Lagged Public Debt-to-GDP Ratio	0.016*	-0.001	0.005
	(0.005)	(0.004)	(0.006)
Two-period Lagged Public Debt-to-GDP Ratio	-0.019*	-0.002	-0.007
	(0.006)	(0.004)	(0.005)
Lagged Trade Openness	-0.001	-0.000	-0.003
	(0.003)	(0.003)	(0.003)
Two-period Lagged Trade Openness	-0.003	-0.001	-0.003
	(0.003)	(0.003)	(0.003)
Lagged Log of International Reserves	–	–	-0.030***
			(0.016)
Two-period Lagged Log of International Reserves	–	–	-0.000
			(0.009)
Observations	1,337	1,315	612
Within R^2	0.270	0.511	0.507

Note: This table extends the baseline specification with two lags specification for all variables. All models additionally include lagged vulnerability, lagged resilience, and their interaction. Dynamic specifications include the lagged dependent variable. Country and year fixed effects are included in all regressions. Control variables follow the baseline specification. Standard errors are Driscoll–Kraay. The sample is unbalanced and varies across specifications due to data availability on disaster incidence. Constant term omitted for reasons of parsimony. Significance levels follow the same convention as in Table 1.

Table R4: Estimates of Panel Regression with different lag structures (three lags)

VARIABLES	Climate + Controls	L.Y + Controls (no Res)	L.Y + ln(Res)
Lagged Standardized Fiscal-External Sustainability Index	–	0.618*	0.686*
		(0.064)	(0.064)
Lagged Climate Vulnerability Index	1.226	-2.093	4.160
	(4.093)	(5.611)	(5.117)
Two-period Lagged Climate Vulnerability Index	-6.141	-3.013	-9.576
	(5.494)	(4.241)	(5.867)
Three-period Lagged Climate Vulnerability Index	-2.031	3.353	2.606
	(6.786)	(5.538)	(5.140)
Lagged Climate Resilience Index	-1.257	-1.381	-3.958**
	(1.826)	(1.389)	(1.796)
Two-period Lagged Resilience Index	0.737	0.759	2.898
	(2.633)	(2.303)	(3.539)
Three-period Lagged Resilience Index	-0.813	-0.569	3.681
	(2.519)	(1.453)	(3.411)
Interaction: Lagged Vulnerability × Lagged Resilience	2.759	3.411	7.913***
	(4.419)	(2.933)	(4.233)
Interaction: Two-period Lagged Vulnerability × Two-period Lagged Resilience	-1.537	-1.523	-6.320
	(5.362)	(4.390)	(7.551)
Interaction: Three-period Lagged Vulnerability × Three-period Lagged Resilience	3.110	1.654	-6.972
	(6.494)	(3.456)	(6.500)
Lagged Real GDP per Capita Growth	-0.017*	-0.016*	-0.003
	(0.005)	(0.005)	(0.007)
Two-period Lagged Real GDP per Capita Growth	-0.003	-0.002	0.001
	(0.006)	(0.005)	(0.004)
Three-period Lagged Real GDP per Capita Growth	-0.012**	-0.008**	-0.009
	(0.004)	(0.004)	(0.006)
Lagged Inflation Rate	-0.002	-0.002	0.001
	(0.003)	(0.003)	(0.002)
Two-period Lagged Inflation Rate	-0.003	-0.002	-0.003***
	(0.003)	(0.002)	(0.002)
Three-period Lagged Inflation Rate	-0.000	-0.000	-0.010**
	(0.002)	(0.001)	(0.004)
Lagged Public Debt-to-GDP Ratio	0.016*	-0.001	-0.000
	(0.004)	(0.006)	(0.003)
Two-period Lagged Public Debt-to-GDP Ratio	-0.017**	-0.007	0.007
	(0.006)	(0.007)	(0.006)
Three-period Lagged Public Debt-to-GDP Ratio	-0.003	0.004	-0.007
	(0.005)	(0.004)	(0.005)
Lagged Trade Openness	-0.001	0.000	-0.006
	(0.003)	(0.002)	(0.004)
Two-period Lagged Trade Openness	-0.002	-0.004	-0.002
	(0.003)	(0.004)	(0.003)
Three-period Lagged Trade Openness	0.001	0.002	0.001
	(0.002)	(0.002)	(0.003)
Lagged Log of International Reserves	–	–	0.000
			(0.011)
Two-period Lagged Log of International Reserves	–	–	0.002
			(0.010)
Three-period Lagged Log of International Reserves	–	–	-0.011
			(0.012)
Observations	1,289	1,268	439
Within R^2	0.289	0.510	0.668

Note: This table extends the baseline specification with three lags specification for all variables. All models additionally include lagged vulnerability, lagged resilience, and their interaction. Dynamic specifications include the lagged dependent variable. Country and year fixed effects are included in all regressions. Control variables follow the baseline specification. Standard errors are Driscoll–Kraay. The sample is unbalanced and varies across specifications due to data availability on disaster incidence. Constant term omitted for reasons of parsimony. Significance levels follow the same convention as in Table 1.

Lastly, we have included dynamic specifications and Nickell bias. Specifically, we explicitly include the lagged dependent variable $Y_{i,t-1}$ to control for persistence in sustainability. The estimated autoregressive coefficient is large (around 0.6–0.7), confirming strong inertia in macro-financial sustainability. Importantly, the inclusion of $Y_{i,t-1}$ does not materially alter the coefficients on vulnerability, resilience, or their interaction. Given the relatively long time dimension of our panel this suggests that any remaining Nickell bias is limited.

Table R5: Estimates of Panel Regression with Nickell bias considered

VARIABLES	System GMM: baseline RHS	System GMM: + ln(reserves)
Lagged Standardized Fiscal-External Sustainability Index	0.695*	0.574
	(0.136)	(0.357)
Lagged Climate Vulnerability Index	-1.384	-2.912
	(1.600)	(3.040)
Lagged Climate Resilience Index	-1.127	-2.646
	(1.324)	(2.321)
Interaction: Lagged Vulnerability × Lagged Resilience	3.604	8.476
	(3.487)	(6.873)
Lagged Real GDP per Capita Growth	-0.007	-0.009
	(0.006)	(0.008)
Lagged Inflation Rate	-0.004	-0.001
	(0.003)	(0.004)
Lagged Public Debt-to-GDP Ratio	-0.001	0.000
	(0.002)	(0.002)
Lagged Trade Openness	-0.002	-0.002
	(0.001)	(0.002)
Lagged Log of International Reserves	–	-0.018
		(0.026)
Observations	1,338	866

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Constant term estimated but omitted for reasons of parsimony.

Taken together, these exercises show that the reduced-form relationship between vulnerability, resilience, and sustainability is highly stable across samples and specifications.

5.3.2 Robustness of the local projections

We conduct an extensive set of robustness and identification exercises to verify that the LP-STAR results reported in Section 5.2 are not driven by spurious dynamics, functional-form choices, First, we assess pre-trends and anticipation effects. A central concern in event-based local projections is that estimated responses may reflect pre-existing trends or forward-looking behaviour rather than genuine post-disaster dynamics. Our baseline LP specification already includes leads of the shock, $F(1/h)$, at each horizon, following Jordà (2005), which ensures that the shock innovation is orthogonal to future realizations. Across all horizons, the coefficients on these future shocks are small and statistically insignificant, indicating no evidence of pre-trends or anticipatory movements in sustainability prior to the disaster shock. This built-in lead structure therefore provides a strong internal check on the validity of the identifying assumptions.

Second, we evaluate robustness to alternative lag structures. We re-estimate the unconditional IRFs using dynamic specifications ranging from a very parsimonious $L(0/0)$ setup to a more persistent $L(0/4)$ configuration with four lags of the shock and controls. Appendix Figure A3 shows that the shape, sign, and persistence of the IRFs remain virtually unchanged across these alternatives. The baseline $L(0/1)$ specification lies between the short- and long-lag variants and tracks both closely at all horizons. This insensitivity to lag choice indicates that the baseline dynamic specification is not imposing undue structure on the estimated responses.

Third, we conduct placebo-shock tests via random reassignment. To determine whether the estimated IRFs could arise spuriously from serial correlation or global time trends, we generate placebo shocks by randomly reshuffling the disaster series across countries and re-estimate the unconditional LP 1,000 times. Appendix Figure A4 displays the resulting placebo distribution. The placebo IRFs are tightly centred around zero, with narrow 95% bands, while the true IRF lies well outside these placebo ranges at horizons $h = 1,2,3$. This strongly suggests that the dynamic response we estimate is not the consequence of mechanical time-series correlations or specification-induced artifacts, but instead reflects the true timing and structure of climate shocks.

Finally, we examine bootstrap inference. To account for small-sample dependence and potential non-Gaussian behaviour, we compute block bootstrap confidence bands by resampling entire country paths. Appendix Figure A5 shows that the bootstrap 90% bands closely align with the analytical Driscoll–Kraay bands used in the baseline specification. The point estimates lie well within the resampled confidence region, and all qualitative conclusions regarding sign, magnitude, and persistence remain unchanged.

5.3.3 Exogeneity and identification of climate shocks

A crucial identifying assumption of the LP-STAR framework is that the climate shocks used for impulse-response analysis are exogenous with respect to contemporaneous macro-financial conditions. We address this concern through an additional set of validation exercises.

First, panel Granger causality tests provide formal evidence on the direction of predictive content (Appendix Table A2). In all cases, the null that sustainability Granger-causes disaster shocks cannot be rejected: p-values are large for mortality (p = 0.89), any-disaster (p = 0.18), and disaster-count (p = 0.06), indicating no systematic predictability from macro-financial conditions to the subsequent occurrence or intensity of climatic events. By contrast, disaster shocks do Granger-cause sustainability in economically meaningful ways: the standardized mortality shock significantly predicts future sustainability (p = 0.022), and the “any disaster” measure is marginally significant (p = 0.082). These results reinforce the notion that the shocks used in the LPs are predetermined with respect to *Y_std*, and that the dynamic responses identified in the LP-STAR framework reflect causal effects from climate shocks to macro-financial sustainability rather than the reverse. The isolated case where severe disasters appear Granger-caused by *Y_std* (p = 0.00025) does not undermine identification: these events are extreme and infrequent, and the apparent reverse predictability reflects the fact that severe events tend to be better recorded or classified during periods of macroeconomic stability, rather than sustainability "causing" climatic events.

Second, placebo timing tests further validate the causal interpretation. Appendix Figure A6 shows the impulse responses generated when disaster shocks are artificially reassigned to the wrong years – for example, shifting all shocks forward by two or three years. These placebo IRFs are flat and statistically indistinguishable from zero at all horizons, in sharp contrast to the strong and state-dependent dynamics observed in the correctly timed specification. This result confirms that the estimated responses are not mechanical artifacts of trending variables or serial correlation, but instead rely crucially on the true timing of observed climatic events.

Taken together, these robustness and identification checks – Granger causality tests, placebo timing exercises, and alternative specifications – provide consistent evidence that the LP-STAR results are not driven by spurious correlations, pre-trends, or weak identification. The negative association between vulnerability and sustainability, the buffering role of resilience, and the nonlinear amplification of climate shocks remain highly stable across samples and shock definitions. Overall, the timing-placebo, pre-trend, bootstrap, and Granger results strongly support interpreting the LP-STAR impulse responses as capturing the dynamic causal effect of exogenous climate shocks on macro-financial sustainability and fiscal space.

6. Conclusions and Policy Implications

This paper has developed a unified macro-financial framework to study how climate vulnerability and resilience shape fiscal and external sustainability. By integrating time-varying fiscal and external reaction coefficients into a single market-priced sustainability index, we have shown that climate risk affects solvency not only through realized disasters but through its interaction with policy responsiveness and sovereign risk premia. The empirical evidence provides a coherent narrative: climate vulnerability systematically weakens countries' ability to adjust, raising borrowing costs and tightening fiscal and external constraints, while resilience operates as a state-contingent stabilizer that mitigates the propagation of shocks. Combined with the dynamic LP-STAR results, which reveal persistent and nonlinear post-shock deterioration in high-vulnerability or low-resilience regimes, these findings document the presence of a climate-induced adaptation trap – a self-reinforcing equilibrium in which vulnerability, weak adjustment, and high spreads perpetuate each other.

The policy implications are clear but must be differentiated across advanced economies (AEs) and emerging market and developing economies (EMDEs). For AEs, climate shocks tend to be absorbed more quickly, owing to stronger fiscal institutions, deeper financial markets, robust public investment systems, and larger automatic stabilizers. In these economies, the primary policy challenge is not solvency risk *per se*, but the risk of underestimating long-run climate liabilities and allowing complacency to weaken adaptation incentives. Strengthening disclosure of climate-related fiscal risks, embedding adaptation investment into medium-term frameworks, and coordinating cross-border infrastructure financing can help ensure that resilience remains adequate as climate hazards intensify. For AEs, the macro-financial return to resilience manifests mainly through reduced future liabilities, smoother adjustment paths, and lower volatility in sovereign risk pricing.

For EMDEs, the mechanisms identified in this paper are considerably more acute. Vulnerability depresses sustainability more strongly, spreads respond more sharply to shocks, and fiscal space is more easily compressed. In these economies, resilience has a markedly higher marginal payoff: by reducing expected losses and stabilizing investor expectations, it directly improves borrowing conditions and expands room for countercyclical policy. Yet EMDEs also face tighter financing constraints, which risk trapping them in the very vulnerability–spread–low-resilience cycle documented in our results. This underscores the importance of concessional climate finance, targeted adaptation support, improvements in public financial management, and institutional reforms that enhance the credibility of adjustment mechanisms. For many EMDEs, breaking the adaptation trap will require a combination of domestic reforms and external support to offset the endogenous tightening of fiscal space following climate shocks.

While our findings are robust across specifications, the paper has several limitations that offer opportunities for future research. First, our sustainability measure, though rich, is reduced-form: it embeds structural adjustment behaviour and market pricing but does not model expectations formation or sovereign balance-sheet interactions explicitly. Extending the framework to incorporate forward-looking elements or structural macro-finance models could help disentangle expectation-driven versus fundamentals-driven movements in sustainability. Second, although our climate-vulnerability and resilience indicators capture broad structural exposure, they cannot reflect all dimensions of governance, spatial heterogeneity, or micro-level adaptation dynamics. More granular subnational data – on infrastructure, disaster management, or social resilience – could sharpen identification and refine the measurement of adaptation capacity. Third, our LP-STAR approach reveals nonlinear dynamics but remains silent on the optimal design of fiscal or external policies that could mitigate them. Embedding similar nonlinearities into dynamic policy models would illuminate the conditions under which adaptation investment, fiscal rules, or sovereign insurance mechanisms deliver the greatest macro-financial benefits. Finally, the interaction between climate risk and private-sector balance sheets remains underexplored; future work could examine how banks, firms, and cross-border capital flows mediate or amplify the adaptation trap.

Overall, the results demonstrate that climate resilience is not merely a long-term developmental concern but a core determinant of fiscal and external solvency. By quantifying how vulnerability and resilience shape macro-financial dynamics, this paper offers a framework for integrating climate considerations into sovereign risk assessments, fiscal planning, and global adaptation finance. As climate hazards intensify, ensuring that countries – especially those most exposed – can avoid the adaptation trap will be central to maintaining macroeconomic stability in the decades ahead.

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Appendix A

Country List: Armenia, Australia, Austria, Bangladesh, Belgium, Botswana, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Cyprus, Czechia, Denmark, Estonia, Fiji, Finland, France, Georgia, Germany, Ghana, Greece, Hungary, India, Indonesia, Ireland, Israel, Italy, Japan, Kenya, Korea, Lithuania, Luxembourg, Malaysia, Maldives, Malta, Mexico, Mongolia, Morocco, Nepal, Netherlands, New Zealand, Norway, Pakistan, Philippines, Poland, Portugal, Rwanda, Slovenia, Solomon Islands, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Tanzania, Thailand, Tunisia, Türkiye, Uganda, United Kingdom, United States, Vanuatu, Vietnam, Zambia.

Table A1. Summary Statistics

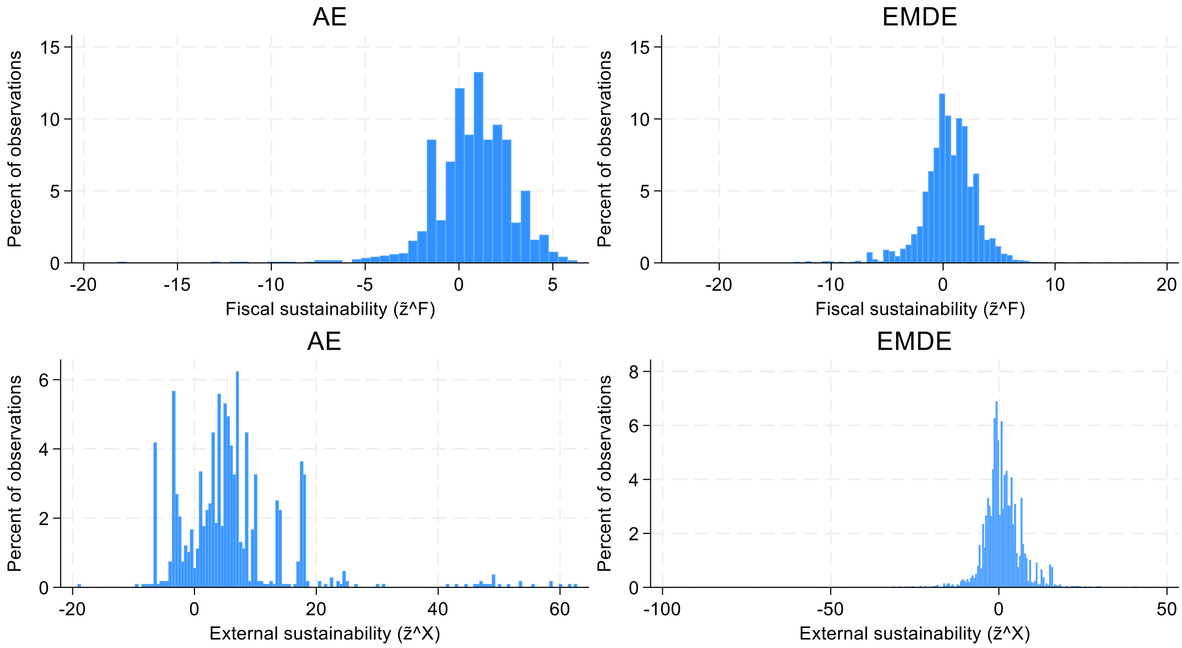
	N	Mean	Median	SD	Min	Max	Source
Vulnerability	5353	0.445	0.434	0.095	0.251	0.686	ND-GAIN dataset
Resilience	4675	0.407	0.377	0.132	0.118	0.816	ND-GAIN dataset
Real GDP per Capita Growth	7740	1.738	2.011	6.329	-64.424	140.491	IMF World Economic Outlook
Inflation Rate	8049	36.518	5.143	457.574	-37.08	26765.858	IMF World Economic Outlook
Debt-to-GDP Ratio	5648	56.308	47.070	44.302	0.002	600.117	IMF World Economic Outlook
Trade Openness	6832	82.648	71.575	52.19	0.021	442.62	IMF World Economic Outlook
Reserves	6811	0.164	0.261	6.421	-103.665	89.3	IMF World Economic Outlook
Primary Balance	5928	-0.862	-0.659	12.704	-549.84	126.464	IMF World Economic Outlook
Current Account	7565	-2.125	-2.525	13.22	-242.976	314.906	IMF World Economic Outlook
Fiscal Sustainability Coefficient	5228	0.011	0.038	0.718	-11.819	0.991	Own Calculations
External Sustainability Coefficient	6478	-0.097	-0.057	0.358	-3.516	4.423	Own Calculations
Yields	2940	3.422	0.798	4.535	-0.502	30.603	LSEG Workspace Datastream
Y_std	1636	0	0.032	1	-5.266	8.493	Own Calculations
Y_pca	4536	0	-0.008	1	-10.704	8.431	Own

Table A2. Panel Granger Causality Tests: Sustainability (Y_std) and Disaster Shocks

Shock Measure	Shock → Y_std (p_DtoY)	Y_std → Shock (p_YtoD)
Mortality_pc (shock_mort)	**0.0216**	0.8898
Any_disaster	**0.0821**	0.1818
Disaster_count	0.5656	**0.0597**
Severe_disaster	0.7079	**0.00025**

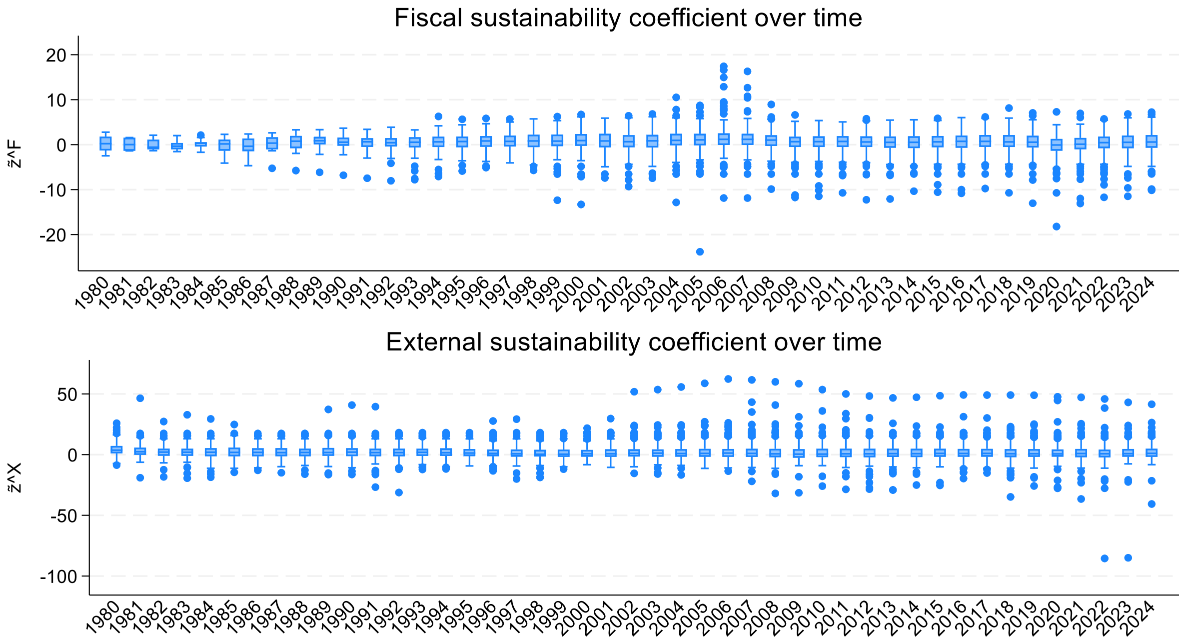
Note: Dependent variables: Column (1) uses Y_std as the dependent variable to test whether disaster shocks Granger-cause sustainability; Column (2) uses each disaster measure as the dependent variable to test whether sustainability Granger-causes shocks. Reported values are p-values from joint significance tests of the three lagged terms (L1–L3). Lower p-values indicate rejection of the null hypothesis of no Granger causality.

Figure A1. Distribution of fiscal and external sustainability coefficients (AE vs EMDE)



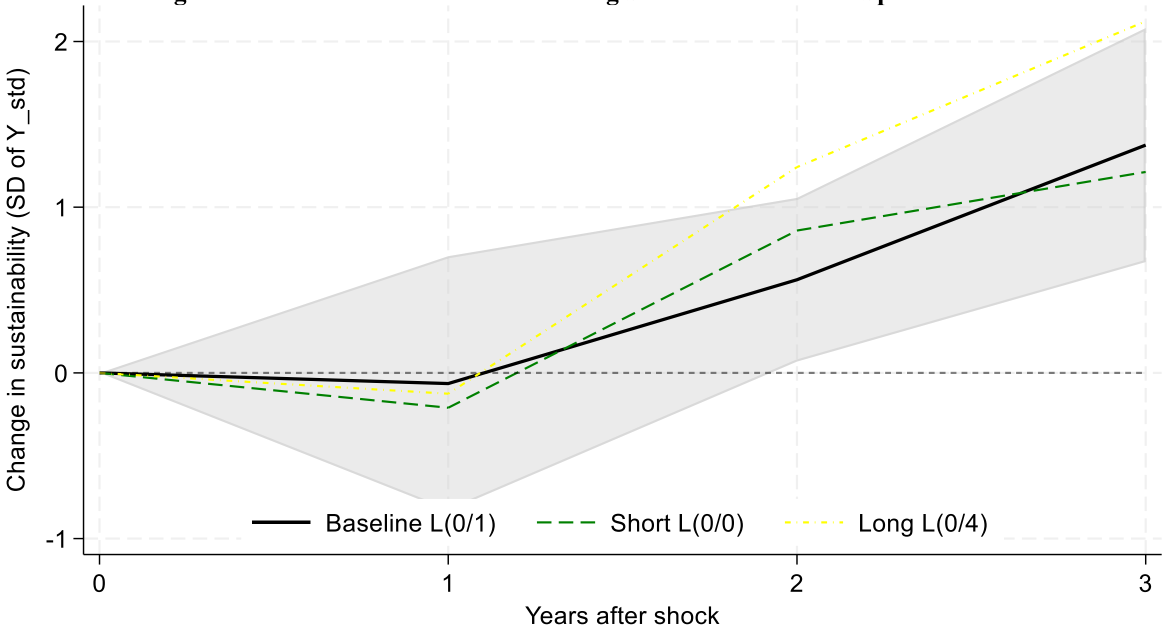
Notes: This figure displays histograms of the precision-weighted fiscal and external sustainability coefficients, $\tilde{z}_{i,t}^{F}$and $\tilde{z}_{i,t}^{X}$, separately for advanced economies (AE) and emerging market and developing economies (EMDE). Fiscal sustainability coefficients appear in the top row and external sustainability coefficients in the bottom row. All coefficients are standardized and weighted by the inverse of their first-stage standard errors, as described in Section 4. The vertical axis reports the percentage of observations within each bin.

Figure A2. Evolution of fiscal and external sustainability coefficients over time



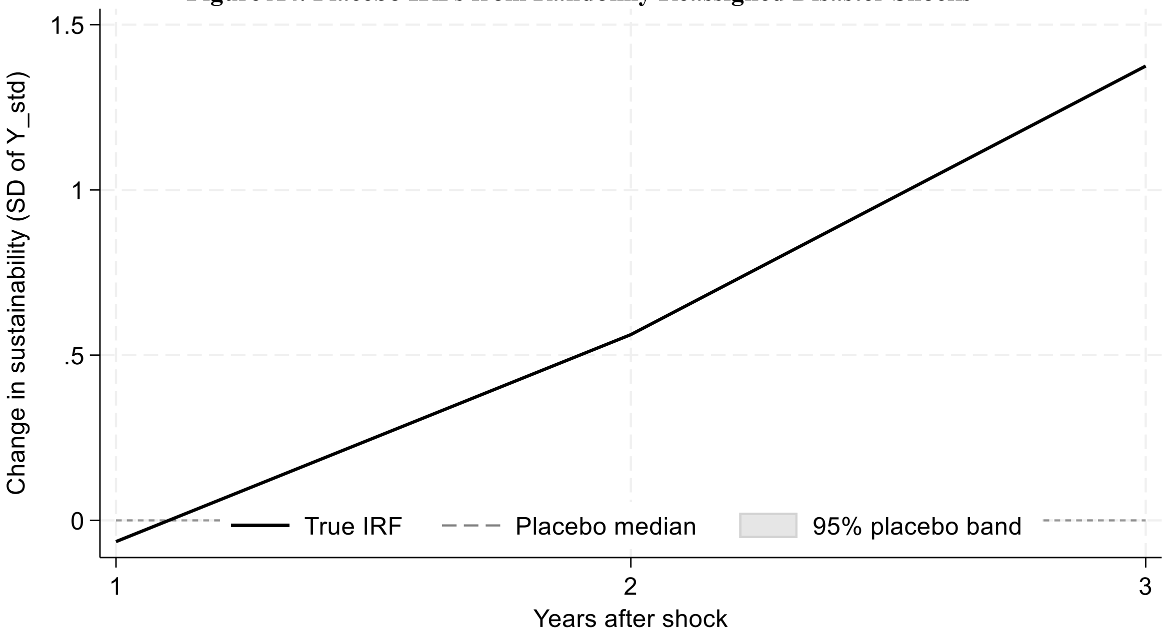
Notes: This figure plots box-and-whisker distributions of the precision-weighted fiscal and external sustainability coefficients, $\tilde{z}_{i,t}^{F}$ and $\tilde{z}_{i,t}^{X}$, for each year in the sample. The top panel reports the fiscal sustainability coefficient, and the bottom panel reports the external sustainability coefficient. Boxes show the interquartile range, horizontal lines mark the median, and whiskers extend to 1.5 times the interquartile range. Individual observations are shown as dots. All coefficients are standardized and weighted according to Section 4.

Figure A3. Robustness to Alternative Lag Structures in the LP Specification



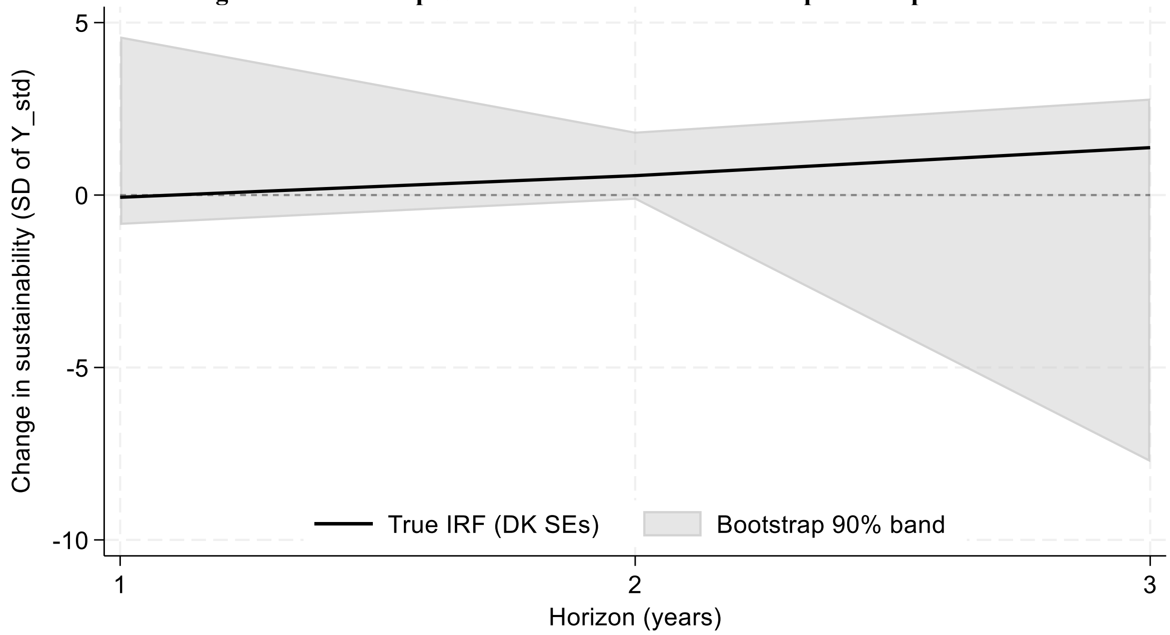
Note: This figure compares unconditional LP impulse responses using three alternative lag structures: a parsimonious $L(0/0)$specification, the baseline $L(0/1)$model, and a more persistent $L(0/4)$setup with four lags of the shock and controls. All three formulations yield nearly identical IRFs in shape, sign, and persistence, indicating that the baseline LP dynamics are not sensitive to the choice of lag length.

Figure A4. Placebo IRFs from Randomly Reassigned Disaster Shocks



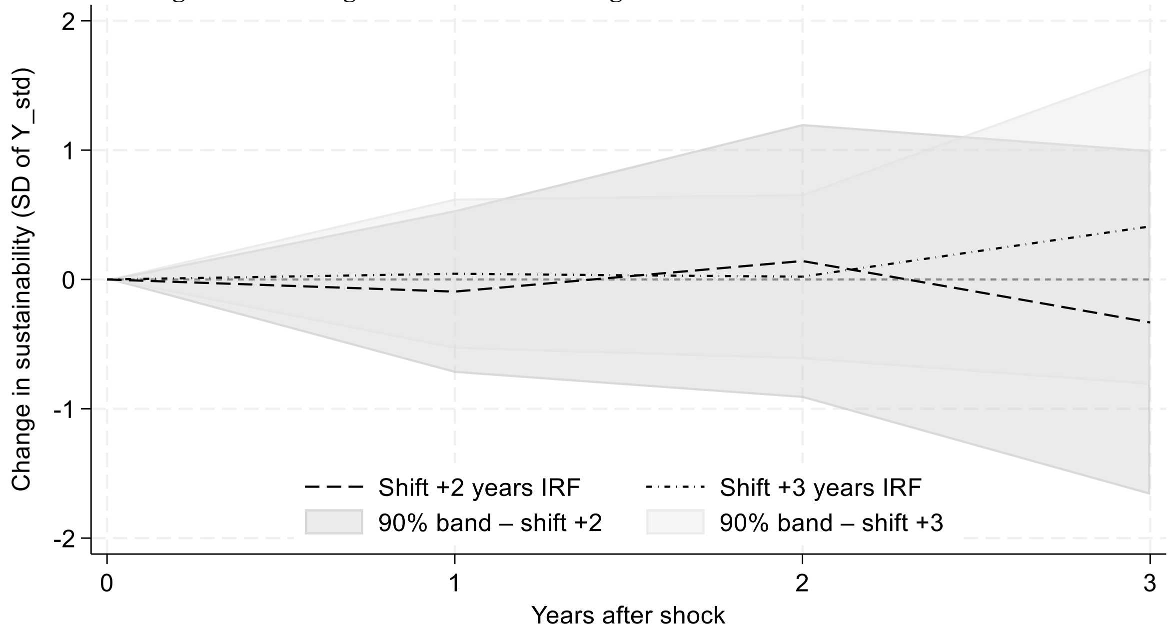
Note: The figure displays the distribution of placebo impulse responses obtained by randomly reshuffling the disaster shocks across countries and re-estimating the LP 1,000 times. Placebo IRFs are tightly centred around zero, with narrow 95% bands, while the true IRF lies well outside this envelope at horizons $h = 1,2,3$. This confirms that the estimated responses are not driven by serial correlation, global trends, or mechanical features of the LP estimator.

Figure A5. Bootstrap Confidence Bands for the LP Impulse Response



Note: This figure reports the unconditional LP impulse response together with 90% block-bootstrap confidence bands obtained by resampling entire country paths. The bootstrap intervals closely match the analytical Driscoll–Kraay bands used in the baseline results, demonstrating that the inference is robust to small-sample dependence and non-Gaussianity. All qualitative conclusions regarding sign, magnitude, and persistence are unchanged.

Figure A6. Timing-Placebo Tests: Shifting Disaster Shocks to Incorrect Years



Note: The figure shows IRFs estimated after artificially shifting disaster shocks forward by two or three years, thereby breaking the alignment between shocks and their true timing. These timing-placebo responses are flat and statistically indistinguishable from zero at all horizons, in stark contrast to the strong and persistent effects observed with correctly timed shocks. This validates that the LP-STAR estimates rely on the actual timing of climatic events rather than on spurious correlations or trends.

Appendix B. Simulation Structure and Calibration

This appendix summarizes the model used in the stylised simulation. The system consists of three endogenous variables – sustainability S_t, sovereign spreads, spread_t, and resilience R_t – and one exogenous input, climate vulnerability V. The model is simulated for 40 periods for two economies that differ only in resilience levels and resilience targets. All parameters are held constant across scenarios except where noted. Calibration choices follow standard magnitudes in the climate–macro literature.

A.1. Dynamic System

Sustainability evolves according to

$$S_t = \rho_S S_{t-1} + \alpha_R R_{t-1} - a_V V - g_S spread_{t-1} + \varepsilon_t^{clim},$$

where sustainability depends on its own lag, resilience, vulnerability, past spreads, and a one-off climate shock.

Sovereign spreads follow

$$spread_t = r^* + b_V V - b_R R_{t-1} - b_S S_{t-1},$$

with spreads rising in vulnerability and falling in resilience and sustainability.

Resilience accumulates according to

$$R_t = (1 - \delta_R) R_{t-1} + \phi_R invest_t,$$

where investment is

$$invest_t = (R^{target} - R_{t-1}) - \kappa spread_{t-1}$$

Higher spreads reduce investment by constraining fiscal space. Two targets are used: R_{low}^{target} for the low-resilience economy and R_{high}^{target} for the high-resilience economy. The climate shock enters sustainability only in period $t = 5$:

$$\varepsilon_t^{clim} = \begin{cases} -\chi & t = 5, \\ 0, & otherwise \end{cases}$$

A.2. Calibration

The baseline calibration is

$$\rho_S = 0.80, a_R = 0.20, a_V = 0.15, g_S = 0.10,$$
$$r^* = 2.0, b_V = 1.00, b_R = 0.80, b_S = 0.50,$$
$$\delta_R = 0.10, \phi_R = 0.20, \kappa = 0.15,$$
$$R_{low}^{target} = 0.6, R_{high}^{target} = 1.2,$$
$$V = 1, \chi = 1.$$

Initial conditions are

$S_1 = 0.5, R_1 = 0.4$ (low resilience); $S_1 = 0.8, R_1 = 1.0$ (high resilience).

Initial spreads follow directly from the spread equation.

A.3. Simulation Procedure

The system is iterated forward for 40 periods for each resilience scenario. The only difference between the two paths is initial resilience and the long-run resilience target. All responses to the climate shock, including adjustments in spreads and sustainability, arise endogenously from the equations above. The resulting trajectories for sustainability, spreads, and resilience are reported in Figure 1 in the main text.