# Natural Disasters, Adaptation and Default Risk

Carlos Bolivar
University of Minnesota

Federico Dueñas
Inter-American Development Bank

Oscar M. Valencia
Inter-American Development Bank

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**Abstract**

This paper studies the link between sovereign default risk and public investment in climate adaptation, which reduces the economic cost of natural disasters. We develop a sovereign default model that incorporates adaptation investment and quantify its effects on bond prices and fiscal policy. Our empirical analysis shows that countries with higher adaptation levels, measured by the ND-GAIN index, experience lower economic losses from disasters and reduced sovereign risk. We demonstrate that adaptation public investment is inefficiently low due to lack of commitment . Finally, we analyze how sovereign risk influences adaptation policy .

**Keywords: Sovereign debt, Default risk, Debt sustainability, Climate Change, Natural Disasters**

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*Not for circulation. E-mail: boliv005@umn.edu, f.duenas@uniandes.edu.co and oscarva@iadb.org

# 1 Introduction

The effect of climate change on the frequency and severity of natural disasters has been one of the most important concerns for policymakers in recent years. Beyond their environmental and social costs, these events create significant macroeconomic challenges, particularly for emerging markets, where fiscal constraints and financial vulnerabilities limit governments' ability to respond to an emergency such as a natural disaster. In this context, understanding the fiscal impact of natural disasters is an essential objective of policymakers and rating agencies. This paper focuses on the relation between default risk and public investment in *adaptation*. Adaptation is defined as an investment that reduces economic losses during a natural disaster. Such investments can be understood as changes to the infrastructure to make it more resilient to earthquakes, hurricanes, etc.

The relationship between default and adaptation is a two-way relationship. Natural disasters destroy part of the production capacity of affected countries, which reduces the government's ability to repay and increases the risk of default. Furthermore, as the risk of natural disasters increases with climate change, lenders anticipate a higher risk of default and demand higher interest rates on sovereign bonds, reducing the capacity of the government to withstand public investment in adaption. [1] In this context, investing in adaptation has two positive effects on fiscal sustainability. First, it can help the government reduce the ex post economic losses of natural disasters. Additionally, it can help decrease the ex ante costs by reducing risks and lowering the spreads on government debt. In this paper, we analyze the optimal adaptation policy of the government and their impact on default risk.

Our analysis proposes a quantitative sovereign default model with the risk of natural disasters, as in Mallucci (2020). The main innovation is to explicitly add the possibility of investing in increasing adaptation. In the model, adaptation is a technology that reduces economic losses during a natural disaster.

In the model, investment in adaptation has three positive effects. With high adaptation, the government has more resources, which relaxes the fiscal budget in the event of a natural disaster. Second, when GDP has a persistent component, a higher adaptation has an additional dynamic effect by changing the conditional distribution of future income. Finally, adaptation reduces the risk of default and positively affects bond prices.

The first contribution of the paper is to quantify those effects and get a measure of the impact of adaptation on sovereign bond prices. The lack of available data on government expenditures and the cost of adaptation is a critical shortcoming in the literature on natural disasters to study the impact of investment in adaptation. To overcome this issue, in this

[1] See Mallucci (2020) for an analysis of the effect of natural disasters on the risk of default.

paper, we first establish that some existing indicators of the level of adaptation in the economy, such as the ND-GAIN index published by Notre Dame Global, are indeed informative about the resilience of the economy to natural disasters. Second, we use model and indirect inference techniques to identify the parameters in the cost function of the adaption.

The identification strategy requires four steps. We first follow Gómez González et al. (2024), using yearly data for 36 EM, to obtain empirical evidence that countries with a high ND-GAIN index experience lower costs in terms of GDP in the event of a natural disaster. Second, we establish the empirical relation between the yield of sovereign bonds and the level of adaption. Third, we characterize the relationship between spreads and adaption in the model as a function of the cost of investment. There are key mechanisms at work in this relation. The first is the effect of adapting to the default risk that we describe before. The second is that the government's ability to finance investment in *adaptation* is affected by the risk of default and the cost of borrowing. When the risk of default is low, the government can finance the public investment in adaptation with relatively cheap debt, which gives incentives to the government to increase adaption. Also, the magnitude of this relation depends on the cost of increase adaption. Critically, in the model the relation about the strength of this second mechanism depends on the cost of adaption. Intuitively, if the cost is high, the elasticity of the investment with respect to changes in the spread is expected to be lower as the government requires to invest more resources to have an impact on risk. Finally, as a result, it is possible to use the relation between spreads and adaption to inform the model about the underlying cost of investing in adaption.

A second important result of the paper result is to establish that in the presence of long-term bonds, the investment in adaptation is inefficiently low. Following Arellano et al. (2018), we use the government's Generalized Euler Equation (GGE) to show analytically that the government does not fully internalize the effect of adaptation reducing the risk of default. The intuition is that part of the benefits of increasing adaptation and reducing future default risk go to legacy investors through realized capital gains in outstanding bonds. Also, because lenders anticipate that the government will not internalize this effect in future choices, the current price of government bonds is inefficiently low. This result is closely related to the well-known hand-in-debt inefficiency of sovereign debt models due to dilution, as shown by Hatchondo and Martinez (2009) in the case of maturity choice and Aguiar et al. (2009) and Krugman (1988) for public investment.

This result is also related to Esquivel (2024) among others who establish that investment is low in efficiency in the presence of sovereign default risk. However, our result is different in two critical ways. First, in our model, investment in adaptation not only increases the expected output as the canonical investment but also reduces output volatility. Lower volatility reduces the risk of default and has an additional positive effect on government bond prices. Second, we focus on an analysis of public investment. Unlike private investors, the government internalizes the effect of higher investment in bond prices; however, due to a lack of commitment, it fails to internalize the full effect. We provide a new mechanism for which investment and in particular public investment is low inefficiency in models with default risk and long-term bonds.

The third contribution of the paper is to study the effect of sovereign risk on public investment on adaptation and study welfare implications. The government's access to the international market shapes the optimal investment policy in adaptation. We derive non-arbitrage conditions between investment and debt and use those non-arbitrage conditions to analyze how fluctuations in the price of government bonds impact investment in adaption. Intuitively, when the government can take debt at high prices in international markets, it can use those resources to finance investment. In doing so, the government can effectively reduce the risk associated with natural disasters without reducing consumption. However, if the risk of default is high (for example, because the initial debt stock is high), the cost of debt-financed investment is high and the government chooses to reduce investment. Moreover, when the government has no access to the international market after a default, investment in adaptation is low because the government should use domestic resources to finance investment, which makes it very costly.

**Related Literature.** Our paper belongs to the quantitative literature on sovereign default that is based on the seminal contribution of Arellano (2008) and Aguiar and Gopinath (2006). See Aguiar and Amador (2021) for a recent review of the literature.

Our paper also belongs to the literature on natural disasters. The literature identifies two types of response to climate shocks: ex ante adaptation and ex post adaptation. Ex-ante adaptation includes preventive investments, such as climate-resilient infrastructure, insurance strategies, and contingent financing mechanisms. In contrast, ex-post adaptation refers to emergency responses and post-disaster reconstruction, including international aid and multilateral financing (Shklovski et al. (2010); Dell et al. (2012)). Empirical evidence suggests that countries with lower ex ante adaptation capacity experience greater economic losses, which worsens fiscal sustainability and increases sovereign risk. However, the literature has yet to fully integrate adaptation investment into sovereign risk models, particularly in long-term debt markets.

Although adaptation can mitigate economic losses, its benefits are not without cost. Hsiang and Narita (2012) find that adaptive capacity can be expensive, with declining marginal benefits. This is particularly relevant for tropical cyclones, where adaptation efforts show limited returns. In addition, the magnitude and persistence of climate shocks play a crucial role in determining their impact on government finances and sovereign borrowing conditions.

A growing body of work explores the link between climate risk and sovereign borrowing costs. Cevik and Jalles (2022) find that countries with greater climate resilience face lower spreads of sovereign debt, while those more vulnerable pay a higher risk premium. Similarly, Boitan and Marchewka-Bartkowiak (2022) document that countries with weaker climate management capacity in Europe face significantly higher borrowing costs, particularly in southern and southeastern regions. Beirne et al. (2024) emphasize the role of political stability and financial development as mitigating factors in fiscal space. Finally, Gómez González et al. (2024) highlight the asymmetric nature of climate risk in sovereign financing costs, showing that countries with higher debt spreads experience more pronounced effects.

Despite these findings, the literature largely treats adaptation as an exogenous factor rather than a strategic decision by governments. Existing models emphasize the adverse effects of climate shocks on sovereign risk, but do not examine how adaptation investment could alter fiscal outcomes and default probabilities.

Our paper builds on recent general equilibrium models linking sovereign risk and climate change. Mallucci (2020) extends a sovereign default model with long-term bonds, incorporating the risk of natural disasters and showing that increased climate shocks increase borrowing costs and constrain financial market access. However, Mallucci (2020) does not model adaptation as an endogenous policy tool, assuming instead that governments passively absorb climate shocks. Phan and Schwartzman (2023) expand on this by incorporating capital accumulation and financial frictions, finding that climate shocks have persistent effects on economic growth and fiscal stability, causing recovery to delay for more than two decades. However, like Mallucci (2020), their model does not account for how governments might mitigate these risks through adaptation investment.

We address this gap by explicitly incorporating adaptation investment into a sovereign default model. Unlike Mallucci (2020), which focuses on the negative effects of climate risk on sovereign debt, our study models adaptation as a technology that reduces economic losses and the probability of default. Similarly, while Phan and Schwartzman (2023) analyze the long-term growth implications of climate shocks, they do not examine how adaptation affects sovereign risk and fiscal stability over time.

However, we find that adaptation investment is inefficiently low under a long-term bond framework. This occurs because the benefits of reduced sovereign risk are transferred to legacy bondholders, reducing government incentives to invest in climate resilience. We propose an innovative financial mechanism to address this inefficiency: sovereign bonds linked to adaptation investment. Unlike traditional climate financing tools, these bonds explicitly align government incentives with financial markets, ensuring that adaptation efforts translate into improved credit ratings and lower borrowing costs.

Our paper demonstrates that climate change amplifies the risk of sovereign default and reshapes optimal fiscal policy and debt management strategies. Although prior literature has primarily documented the negative fiscal effects of climate shocks, our work introduces explicit adaptation strategies within sovereign risk models, opening a new avenue for studying how governments can proactively manage these risks through financial innovation and sovereign debt market regulation.

On the other hand, our paper relates to sovereign debt literature that analyzes the interaction of default risk and investment. Some important examples of this literature are Arellano et al. (2018), Esquivel (2024) and Esquivel and Samano (2023). While those papers focus on private investment and establish that in the presence of default risk the investment is inefficiently low, our paper focuses on public investment and establish that even public investment which is made by a government that internalizes the effect of investment on bond prices the investment is inefficiently low due to lack of commitment.

**Outline.** The remainder of the paper is organized as follows. Section 2 describes the empirical motivation of the article. Section 3 describes the model. In Section 4, we characterize the optimal policy of the government. In Section 5, we discuss the calibration strategy. In Section 6 we present the quantitative results, and in Section 7 we conclude.

# 2 Empirical Motivation

In this section, we study the performance of existing indicators in adaptation to predict the capacity of governments to reduce economic losses in the event of natural disasters. We present evidence that the main indicator used in the literature, ND-GAIN, is informative when measuring the benefits of adaptation to reduce the cost of natural disasters. In the quantitative analysis, we use this result to implement a direct inference approach to inform the model about the cost of investing in Adoption.

## 2.1 Measurement

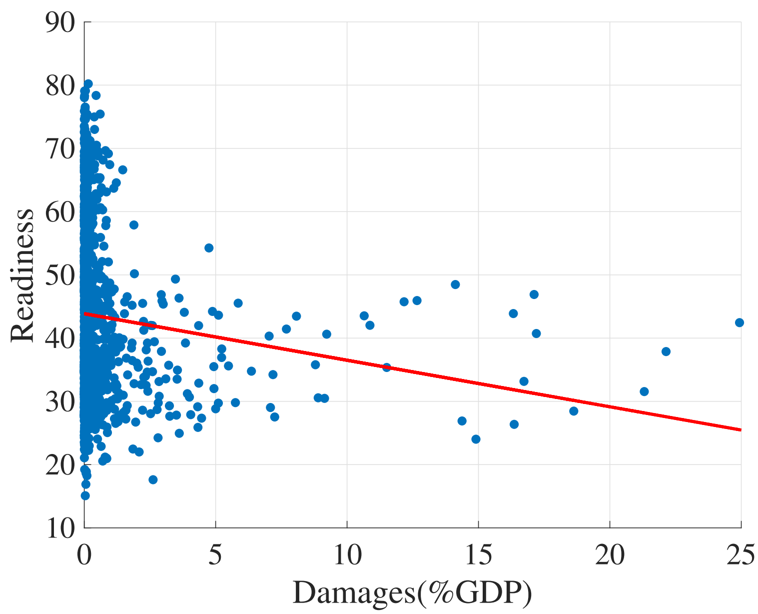
We use the ND-GAIN index provided by the Notre Dame Global Adaptation Initiative to measure exposure to natural disasters. In particular, we will use three indicators of the index that evaluate how prepared the government is to adapt in the event of a natural disaster. Those indicators measure the ability to adapt to the economy, government, and community. We use an index called readiness, which is constructed as a combination of the three indicators with the same weight.

In addition, we use information from EM-DATA, which reports an estimate of economic damage after a series of natural disasters.

## 2.2 Readiness and Cost of Natural Disasters

Using a sample of 36 countries between 1995 and 2023, in Figure 1, we illustrate this correlation for the readiness index.

Figure 1: Damage and Vulnerability to Natural Disasters




We can see in Figure 1 that countries with a higher readiness experience an average loss lower than countries with a low index. Furthermore, in Table 4, we present the descriptive statistics of the readiness index categories, including their correlation with damages from natural disasters.

Table 1: Descriptive Statistics

| Variable | Mean | St dev. | Min. | Correlation |
|---|---|---|---|---|
| Readiness | 40.44 | 13.27 | 11.48 | −0.0083 |
| Economic | 41.64 | 13.49 | 0 | 0.0086 |
| Government | 49.21 | 18.04 | 0.13 | 0.0077 |
| Social | 30.29 | 15.58 | 8.14 | −0.0373 |

We can see that there is a small positive correlation with two components of the index, economics and government. However, there is a negative correlation in the overall index driven by the social component. We study this relation more formally, using the following panel regression.

$$Damages_{it} = \omega_0 + \omega_R Readiness_{it} + \omega_S Size_{it} + \omega_X X_{i,t} + \epsilon_i \tag{1}$$

Equation (1) relates the economic damages during a natural disaster to the size of the natural disaster ($Size_{it}$), the level of adaptation of the country at the time of the natural disaster ($Readiness_{it}$) and the set of controls which includes fixed effects. In table 2 we present the results of the estimation of (1).

Table 2: Cost of Natural Disasters and Readiness

| | $\omega_R$ | $\omega_s$ |
|---|---|---|
| Coefficient | −0.0144 | 0.0743 |
| | (0.089) | (0.035) |
| Observations | 438 | |

*Notes:* P-values in parentheses

After controlling for the size of the natural disaster and the effects of the country-fix, there is a negative correlation between readiness and the cost of the natural disaster. This negative correlation suggests that when countries invest in increasing adaption, which is reflected in higher readiness, they tend to experience a lower economic cost in case of natural disasters. The main focus of this paper is to analyze how governments can use this tool to reduce the default risk and how it has positive effects on welfare.

# 3 Model

We study a small open economy in which the government takes debt in the international market. As in Eaton and Gersovitz (1981), the government lacks commitment, and each period decides whether to default on the debt. Following Mallucci (2020), we assume that the economy experiences natural disasters that affect the output with an exogenous probability. The main innovation of the model is that the government has access to technology for adaptation, which reduces the impact of natural disasters.

## 3.1 Endowment

In each period, the government receives a stochastic endowment of tradable goods $y_t$. The government's income follows an $AR(1)$ process subject to two shocks. A standard endowment shock $\epsilon_t$ captures business cycle fluctuations, and an event disaster shock $\gamma_t$ captures the possibility of facing a natural disaster.

In a disaster, the economy has a cost in terms of output $h_t$. The cost depends on the size of the natural disaster, which is captured by $\gamma_t$, and also depends on the level of adaptation of the economy, which we denote by $a_t$. In particular, the endowment cost in the event of a natural disaster is:

$$h(a_t, \gamma_t) = \gamma_t(1 - a_t) \tag{2}$$

where $a_t \in [0, 1]$. If the economy is fully prepared to adapt and overcome any effect of a natural disaster, $a_t = 1$, and the cost in terms of income for the government is zero, regardless of the natural disaster. On the other hand, if the economy is not prepared to reduce any of the effects of a natural disaster $a_t = 0$, the government should assume the total cost of any natural disaster. For a given level of adaptation, income follows the following process.

$$y_t = \rho y_{t-1} - \xi_t h(a_t, \gamma_t) + \epsilon_t \tag{3}$$

Where $\xi_t \in \{0, 1\}$ is an indicator variable that takes the value of one if the economy is faced with a natural disaster and zero otherwise. We assume that $\xi_t$ follows a Bernoulli distribution with a success probability of $\pi$. Note that $\xi_t$ captures the risk of getting a natural disaster while $\gamma_t$ captures the intensity of the natural disaster.

## 3.2 Government

The government has time-separable preferences over consumption given by:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t [u(c_t) - d_t \nu_t] \tag{4}$$

Here $d_t$ stands for an indicator function that takes the value of one if the government defaults and zero otherwise. When the government defaults, we assume that it has a utility cost $\nu_t$ with a p.d.f. independent of debt $f(\nu)$.

During each period in which the government has access to international markets, it decides whether to default on its debt. When it chooses to repay, the government determines the new level of borrowing. However, in each period, the government chooses the level of investment in adaptation for the next period.

The government takes debts using long-term bonds denoted by $b_t$. Long-term bonds are introduced following Hatchondo and Martinez (2009), Chatterjee and Eyigungor (2012), and Arellano and Ramanarayanan (2012). Specifically, a bond in period t promises to pay $\delta(1-\delta)^{j-1}$ units of the tradable good in period $t+j$, for all $j \geq 1$. Denoting by $b_t$ the initial face value of the debt and $i_t$ the new issuance, we have the following.

$$b_{t+1} = b_t(1-\delta) + i_t \tag{5}$$

The investment cost of adaptation for the government is $f(a_t)$, which is a convex cost function of $a_t$. The budget constraint of the government is given by:

$$c_t + f(a_{t+1}) = y_t + (1-d_t)[b_t\delta - q_t(b_{t+1} - (1-\delta)b_t)] \tag{6}$$

Here, $q_t$ stands for the price of sovereign bonds. In case of default, all debt is forgiven and the government receives a utility and an output cost. Following Chatterjee and Eyigungor (2012), we assume that the output cost of default is a nonlinear function of the income. Then, at default, the endowment of the economy is:

$$y_t^D = y_t - \max\{0, \eta_1 y_t + \eta_2 y_t^2\} \tag{7}$$

In addition, in the event of default, the government is out of the financial market for several periods. When the government is out of the market with a probability $\theta$, it gains access to the financial markets.

### 3.3 International Investors.

Similarly to Eaton and Gersovitz (1981), there is a continuum of identical lenders that are risk neutral. They have access to a risk-free asset with a gross interest rate of $R$. We also assume that they collectively have enough resources to buy any arbitrary number of government bonds. The asset pricing condition for government bonds is therefore

$$q_t = \mathbb{E}\left[\frac{(1-d_t)[\delta + (1-\delta)q_{t+1}]}{R}\right]. \tag{8}$$

### 3.4 Competitive Equilibrium.

We define the competitive equilibrium of the small open economy.

**Definition 1.** (Competitive Equilibrium) Given an initial condition $\{b_0, a_0\}$, an equilibrium consists of a sequence of prices $\{q_t\}$, government policies $\{b_t, a_t, d_t\}$ such that

(i) Given prices, $\{b_t, a_t, d_t\}$ solves the government problem (4) subject to (6);

(ii) Given government policies, $q_t$ satisfies the break even condition of investors (17);

## 4 Optimal Policy

The government lacks commitment, so we will focus on the Markov Equilibrium. The relevant state for the government is the initial level of debt $b$, the level of adaptation $a$, the cost of default $\nu$, and the income $y$. We summarize the state with $s = \{b, a, y, \nu\}$. The problem of government is

$$V(s) = \max_{d \in \{0,1\}} (1-d)V^R(b, y) + d[V^D(y, \nu)]. \tag{9}$$

Here $V^R(b, y)$ and $V^D(y, \nu)$ are the values of the payment and the default, respectively. The value of repayment is defined as:

$$V^R(b, y) = \max_{a', b'} u(c^R) + \beta \mathbb{E}[V(s')] \tag{10}$$

subject to

$$c^R = y + \delta b - f(a') + q(b', a', y)(b' - (1-\delta)b)$$

$$y'(y,a',\gamma') = \rho y - \xi' h(a',\gamma') + \epsilon'$$

Note that the government induces a distribution over the endowment in the next period by choosing $a'$. In particular, it chooses the economic exposure to a natural disaster, which is equivalent to choose a conditional distribution of the endowment. The value under default is defined as:

$$V^D(y,\nu) = \max_{i'} u(c^D) - \nu + \beta \mathbb{E}[\theta V^R(0,a',y') + (1-\theta)[V^D(a',y')]] \tag{11}$$

subject to

$$c^D = y^D - f(a')$$

$$y'(y,a',\gamma') = \rho y - \xi' h(a',\gamma') + \epsilon'$$

We characterize the default decision of the government by defining the following threshold.

$$V^D(y.\hat{\nu}(b,y)) = V^R(b,y) \tag{12}$$

That is, the cost of default that makes the government indifferent between default and repayment. Using this threshold, the default function of the government is :

$$d_t(s) = \begin{cases} 1 & \text{if} \quad \hat{\nu}(b,y) > \nu_t, \\ 0 & \text{otherwise.} \end{cases} \tag{13}$$

Furthermore, the conditional probability of default for a given endowment and debt is as follows.

$$F(\hat{\nu}(b,y)) = \int_{\underline{\nu}}^{\hat{\nu}(b,y)} f(\nu) d\nu. \tag{14}$$

A higher level of adaptation decreases incentives to default because it increases the endowment of states with natural disasters. We formalize this result in the following lemma:

**Lemma 1.** *Default incentives are stronger when the level of adaptation is lower. In the event of a natural disaster, and for a given size of the economic and disaster shocks $\gamma, \epsilon$; for any $a_L < a_H$:*

$$\textit{If} \;\; V^R(b, \rho y_{t-1} + \xi h(a_L,\gamma) + \epsilon) \geq V^D(\rho y_{t-1} + \xi h(a_L,\gamma) + \epsilon, \nu) \tag{15}$$

$$\textit{then} \quad V^R(b, \rho y_{t-1} + \xi h(a_H, \gamma) + \epsilon) > V^D(\rho y_{t-1} + \xi h(a_H, \gamma) + \epsilon, \nu) \tag{16}$$

*Proof.* In Appendix B.1 □

The lemma 1 is closely related to the result in Arellano (2008), which shows that the government's incentives to default are higher when the endowment is low. In contrast, we show in Lemma 1 that a government with a lower level of adaptation has a lower endowment when faced with a natural disaster and consequently has higher incentives to default.

The lemma 1 establishes the first relation between adaptation and sovereign risk. Countries with low levels of adaptation face higher risks and, consequently, will face lower bond prices. In the next section, we study the other side of this relation. High-risk counties have fewer resources to invest in adaptation.

Using the break-even condition of international investors and the probability of default, we define the price function.

$$q(y, B', a') = \mathbb{E}\left[\frac{(1 - d(s))[\delta + (1 - \delta)q(y', B'', a'')]}{R}\right]. \tag{17}$$

We close the model description by defining equilibrium. Then a Markov perfect equilibrium is defined as follows.

**Definition 2.** (Markov Equilibrium) A Markov perfect equilibrium is defined by a set of strategies $\{\mathcal{B}, \mathcal{M}, \mathcal{D}\}$, value function of the government $\{V\}$, and a price $q(y, B', a')$ such that

i given the price, $\{\mathcal{B}, \mathcal{M}, \mathcal{D}\}$ solves the problem of the government at every state, and $V$ attains the maximum;

ii $q(y, B', a')$ satisfies the break-even condition of foreign investors

## 4.1 Optimal Investment in Adaptation

This section presents our main analytical results regarding how the level of debt and the government's access to international markets shape the optimal investment in Adaptation against natural disasters.

### 4.1.1 Adaptation under Repayment

When the government is in good standing and has access to the international market, we obtain the following necessary conditions for optimality[2]:

$$u(c^R)[q_{B'}(B' - (1-\delta)B) + q] = \beta\mathbb{E}[(1-d(s))u'(c^{R'})(1+(1-\delta)q')] \tag{18}$$

$$u'(c^R)[f'(a') - q_{a'}(B' - (1-\delta)B)] = \beta\pi\mathbb{E}[\gamma'([1-d(s)]u'(c^{R'}) + d(s)u'(c^{D'})] \tag{19}$$

Equation (18) is the usual Euler equation of debt that equates the marginal benefit of increasing current consumption and the marginal cost of repaying the debt in the next period.

On the other hand, equation (19) is the Euler equation of investment in adaptation. The left-hand side represents the cost of increasing investment in adaptation. When the government increases the level of adaptation, the budget constraint is tightened because the government has to pay for the investment in advance; this effect is captured by $f'(a')$. In addition, as the government increases the adaptation, according to Lemma 1, the default risk decreases for the next period. Consequently, the price of government bonds increases. The effect on prices is captured by $q_{a'} > 0$. The net cost of increasing adaptation over current consumption is the difference between these two effects.

The right-hand side of equation (19) is the benefit of the government to have higher adaptation in the next period. The benefit depends on the probability that the natural disaster will occur ($\pi$) and the expected cost of the disaster.

Interestingly, the benefits of adaptation also depend on the probability of default. When the probability of default is low, the government anticipates that it will reduce consumption to deleverage the debt, so the government's marginal utility is high, and the benefit of adaptation is higher. Next, we will solve the effect on prices of increasing investment to complete the derivation of the Generalized Euler Equation (GEE).

**The Generalized Euler Equation (GEE)** Let us re-write the price function of government bonds as follows:

$$q(y, B', a') = \mathbb{E}\left[\frac{(1-d(y', B', a'))[\delta + (1-\delta)q(y, \mathcal{B}(B', a'), \mathcal{A}(B', a'))]}{R}\right]. \tag{20}$$

[2] Aguiar and Amador (2019) show that the objective function is differentiable when there is a utility shock to the default cost, as $\nu_t$.

Where $B'' = \mathcal{B}(B', a')$ and $a'' = \mathcal{A}(B', a')$ are the optimal policies of the government iterated a period forward. We take the derivative of the price function regarding the future level of adaptation and use the related envelope conditions to have the following.

$$q_{a'} = \mathbb{E}_{y,\gamma}\left[\frac{-f(\hat{V})\gamma'[u'(c^{D'}) - u'(c^{R'})][\delta + (1-\delta)q] + (1 - F(\hat{V}))(1-\delta)[q'_{B'}\mathcal{B}_m + q'_{a'}\mathcal{A}_m]}{R}\right] \quad (21)$$

In equation (21), we highlight two effects. The first term is the change in the probability of default due to the higher investment in adaptation. During a natural disaster, with adaptation, the government has more resources, which changes the threshold of the default cost at which the government defaults, reducing the risk and increasing prices. The second part of the derivative captures the effect of prices on future policies. Higher current investment in adaptation implies that the government would take less future debt and choose higher adaptation. Both effects increase current prices because debt is long-term.

The derivative of the price function depends on the future derivative of the price with respect to adaptation, those derivatives configure a recursive function that we have to solve. To do so, we follow Arellano et al. (2023). First, it is possible to use (18) and (19), solve for $q_{B'}$ and $q_{a'}$ respectively, and define the following functions[3]:

$$H_{B'}(B', a') = \frac{\beta\mathbb{E}[(1-d(s))u'(c^{R'})(1+(1-\delta)q')]}{u(c^R)(B' - (1-\delta)B)} - \frac{q}{(B' - (1-\delta)B)} \quad (22)$$

$$H_{a'}(B', a') = \frac{f'(a')}{(B' - (1-\delta)B)} - \frac{\beta\pi\mathbb{E}[\gamma'([1-d(s)]u'(c^{R'}) + d(s)u'(c^{D'})]}{u'(c^R)(B' - (1-\delta)B)} \quad (23)$$

Now we can replace those functions with (21) to get:

$$q_{a'} = \mathbb{E}_{y,\gamma}\left[\frac{-f(\hat{V})\gamma'(u'(c^{D'}) - u'(c^{R'}))[\delta + (1-\delta)q] + (1 - F(\hat{V}))(1-\delta)[H_{B'}\mathcal{B}_m + H_{a'}\mathcal{M}_m]}{R}\right] \quad (24)$$

As shown by Arellano et al. (2023), we can express the derivatives of the price function in terms of independent functions (22) and (23). Finally, we combine (19) and (24) to derive the Generalized Euler Equation (GEE) of adaptation as follows:

[3] See Mateos-Planas and Ríos-Rull (2015) for a general discussion of the GEE in sovereign debt models.

$$\left[f'(a') - \mathbb{E}\left[\frac{-f(\hat{V})\gamma'[u'(c^{D'}) - u'(c^{R'})][\delta + (1-\delta)q] + (1-F(\hat{V}))(1-\delta)[H_{B'}\mathcal{B}_m + H_{a'}\mathcal{A}_m]}{R}\right]\right.$$
$$\left.(B' - (1-\delta)B)\right] u'(c^R) = \beta\pi\mathbb{E}[\gamma'([1-d(s)]u'(c^{R'}) + d(s)u'(c^{D'})] \quad (25)$$

This Euler equation accounts for the cost of the lack of commitment of the government in future policies. Because the government lacks commitment it takes as a given the future policies of the government $\mathcal{A}_m$ and $\mathcal{B}_m$. In turn, future choices of borrowing and adaptation affect the current response of prices to the government's policies. The GEE accounts for the cost to the government of having a given policy in the future that is not optimal from the perspective of the current government.

Formally, because the future policy is suboptimal, the envelope conditions of future borrowing of investment and adaptation fail to hold. As a result, there is a wedge in the GEE conditions that accounts for how costly it is for the government to have suboptimal adaptation and debt policies in the future.

The GGE (25) underscores one of the central insights of the model. The investment in adaptation is inefficiently low when debt is issued using long-term bonds. If the government has the technology to commit to a future level of investment in adaptation, it will choose $a''$ and $B''$ so that (22) and (23) are zero for every period. Under commitment, we could use the envelope theorem to cancel out the effect of future policies in the GGE. Instead, because future governments will deviate from the optimal policy, the generalized Euler equation accounts for the impact of current investment on future policies.

This result is closely related to the dilution problem described in Hatchondo and Martinez (2009). Intuition works as follows. A higher level of adaptation reduces the probability of default in the future and increases the price of current bonds. Part of this increase is reflected in capital gains for legacy lenders. Because the government does not internalize the positive effect of investment in adaptation on those legacy lenders, it chooses a lower level of adaptation. However, lenders anticipate that the government will underinvest and the price of the bonds will be inefficiently low.

## 4.2 Debt-financed Adaptation

To further inspect the trade-off behind the optimal choices of the government, let us analyze a policy in which the government keeps constant consumption and increases the level of debt to finance investments in adaptation. Starting from a set of initial states $\{b, y\}$, the government sets a certain level of consumption $\bar{c}$. We denote "candidate policies" as the pairs of $B', a'$ that are consistent with that consumption:

$$\bar{c} = y + B - f(a') + q(y, B', a')(B' - (1-\delta)B) \tag{26}$$

Given the policies from the next period onward, $\mathbb{E}V(B', y')$ is the expected continuation value. Because consumption is fixed in the current period, the differences in utility are completely driven by differences in the continuation values. In optimal policy, the government equates the net marginal benefit of adaptation to debt finance with zero. If we totally differentiate $\mathbb{E}V(B', y')$, use the associates envelop conditions from (10) and (11), and totally differentiate (26), we have[4]:

$$\begin{aligned}
&\mathbb{E}\left[(1-d(s))u'\left(c^{R'}\right)\right]\left[\frac{q_{B'}(B'-(1-\delta)B)'+q}{f'(a')-q_{a'}(B'-(1-\delta)B)}\right] = \\
&\qquad \pi\left(\mathbb{E}[\gamma']\mathbb{E}\left[u'\left(c^{R'}\right)\right]+\mathbb{COV}\left(u'\left(c^{R'}\right),\gamma'\right)\right)+ \\
&\pi\mathbb{E}\left[\left(u'\left(c^{D'}\right)-u'\left(c^{R'}\right)\right)\left(\mathbb{E}\gamma'\mathbb{E}d(s)+\mathbb{COV}(\gamma',d)\right)\right]+\mathbb{COV}\left(u'\left(c^{D'}\right)-u'\left(c^{R'}\right)\right),\gamma'd\right)
\end{aligned} \tag{27}$$

The left-hand side of (27) represents the marginal utility cost of debt-financed adaptation. The first term is the expected marginal cost of having one additional unit of debt in the future. The second term in brackets is the increase in debt that would allow the government to have a constant current consumption for each additional unit of adaptation. They combined represent the expected marginal cost of increasing debt to finance one unit of adaptation. This cost depends on how prices change with respect to debt and adaptation because price changes shape the ratio at which the government should increase debt to finance adaptation. In particular, if the price were to increase with an increase in both the investment in adaptation and the debt, the new borrowing needed to finance that investment would be lower. This mechanism is related to Esquivel and Samano (2023), which studies a model with capital accumulation in which the government can implement fiscal expansion and reduce debt simultaneously by increasing investment.

We decompose the benefits of debt-financed adaptation on the right-hand side of (27). Adaptation has two positive effects on the future. The first term captures the positive effect in terms of government income, which depends on the expected size of the losses in the

[4]For expositional purposes we keep the notation $q_{B'}$ and $q_{a'}$ for the derivatives of the price function. One could use the analysis in the previous subsection to derive the analytical conditions.

event of a natural disaster $\gamma'$ and also depends on the correlation of the marginal utility of consumption and the size of the losses. In an economy where losses from natural disasters are negatively correlated with the economic cycle, the government has more incentives to invest in adaptation because the cost of assuming those losses in terms of utility is higher. The intuition is that for the government is less costly in utility units to cover losses from natural disasters when the economy is in a boom compared to when the economy is in a recession.

The second term captures the insurance component of the default and how it correlates with the cost of the natural disaster. Suppose that the cost of natural disasters is positively correlated with default episodes. In that case, the government has fewer incentives to increase adaptation because during a default episode consumption is higher, so the utility cost of the disaster is lower. Finally, the last term accounts for the effect of adaptation in increasing the differences between the marginal utility of consumption under repayment and default.

## 4.3 Adaptation Under Default

We conclude this section by analyzing the optimal investment in Adaptation when the government cannot access the international market. In this case, the first-order condition of the adaptation is the following.

$$u'(c^D)f'(a') = \beta\pi\left(\theta\mathbb{E}\left[\gamma' u'\left(c^{R'}\right)\right] + (1-\theta)\mathbb{E}\left[\gamma' u'\left(c^{D'}\right)\right]\right) \tag{28}$$

When the government is in autarky, the option of debt-financed investments is not available. In this case, the cost of increasing adaptation should be financed by lowering consumption as shown by the left-hand side of (28). In addition, there are no benefits to bond prices.

However, the marginal deficit of the government depends on the probability of having access to international markets in the next period. If the likelihood of regaining access is higher, the government expects a high future consumption because it could borrow again. It reduces the marginal utility of consumption in the next period and reduces the incentives to invest in adaptation. As a result the longer the government expect to be excluded from the market, the more incentives it would have to increase adaptation.

**Take away** In summary, we show that investment in adaptation positively affects the prices of government bonds. We also show that there is underinvestment in adaptation because the government has long-term bonds. We also show that the price effect of adaptation and the possibility of financing it with debt increase the incentives of the government to invest.

# 5 Calibration

In this section, we describe the calibration of the quantitative model. The baseline calibration follows Mallucci (2020) to facilitate comparability. The analysis focuses on the parameters we calibrate internally: the damages during a natural disaster and the parameters in the cost function of adaptation.

## 5.1 Quantitative Strategy

Let us begin by describing the strategy that we follow to calibrate the model. The first part of the identification is to assess the effect of increasing adaptation on the economic cost of natural disasters.

**Cost of Natural Disasters** The first step in calibration is to discipline the cost of a natural disaster before investing in adaptation, which in the model is controlled by $\gamma$.

To do that, we need to construct an empirical contrafactual of the economic losses when there is no investment. The key assumption to identify the distribution of $\gamma$ is the following.

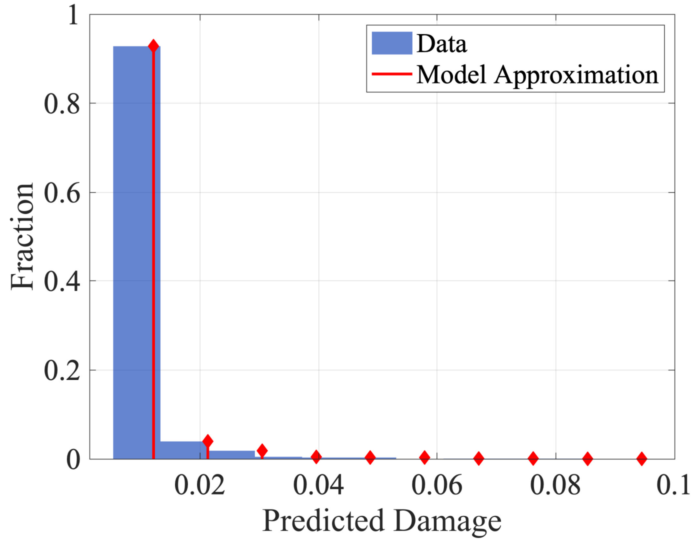
**Assumption 1.** *The country with the lowest adaptation (Readiness Index = Min value) made zero investment in increasing adaptation.*

Given this assumption, we construct a contractual distribution of the cost of a natural disaster with zero investment ($\hat{Damages_i}$) using:

$$\overline{\gamma} = \omega_0 + \omega_R Readiness_{Min} + \omega_S Size_i + \omega_X X_{i,t} + \epsilon_i \tag{29}$$

In Figure 2 we plot the empirical distribution of $\overline{\gamma}$, and compare it with the discretized approximation $\gamma$ that we use in the numerical exercise to approximate the empirical distribution.

Figure 2: Damages probability distribution




**Cost of adaption** The second key parameter that we need to distinguish is the cost of adaptation. We assume that the cost of the investment in adaptation has the quadratic form as follows.

$$f(a') = \iota(a')^2 \tag{30}$$

To discipline the value of $\iota$, we will use the relation between adaptation and the spreads of sovereign bonds. We first compute the cost of the natural disaster as a function of the investment in adaptation in the data using the following.

$$h_i(Readi\hat{n}ess, Size) = \hat{\omega_0} + \hat{\omega_R} Readiness_i + \hat{\omega_S} Size_i \tag{31}$$

Next, we use the following auxiliary regression.

$$\psi_i = \varphi_0 + \varphi_{Dam} h_i(Readi\hat{n}ess, Size) + \epsilon_i \tag{32}$$

where $\psi_i$ is the spread of government bonds over the risk-free bond. In addition, $h_i$ represents the expected damages of a natural disaster given the investment in adaptation. In the data, we measure $h_i$ by using (31), while in the model we have a direct observation of the function $h$.

The idea of identification is to use indirect inference to inform the model about the cost of investing in adaptation ($\iota$). In particular, with the auxiliary regression (32), we match the following moment:

$$\frac{\text{Cov}(\psi_i, h(a,\gamma))}{\text{Var}(h(a,\gamma))} \tag{33}$$

Empirically, we construct country spreads as 10-year sovereign yields minus 10-year US Treasuries, estimate a panel-fixed-effects model of climate damage on ND-GAIN controls, and take the fitted values ("predicted damages"). In the model, we simulate the bond prices $q_t$, compute the simulated spreads as $(1/q_t - \delta - R_t)$, and measure the damage of the disaster as $h(a_t, \gamma_t) = \gamma_t(1 - a_t)$.

In table 3 we present the results of the estimation of $\beta_D$ in the data and in the model in our baseline calibration.

Table 3: The Adaptation-Spread Relation

| | Data | Model |
|---|---|---|
| Estimation | 0.99 | 0.96 |
| | (0.286) | (0.420) |
| Observations | 160 | 1000 |

*Notes:* P-values in parentheses.

# 6 Quantitative Analysis

In this section, we describe the solution and calibration of the quantitative model and explore the implications of investing in adaptation. The key focus is how we use the available data on adaptation to discipline the model's parameters. Next, we present quantitative results.

## 6.1 Parameters

All parameter values used in the baseline calibration are in Table 4. We set a series of parameters to predetermined values, common in the literature, while other parameters are calibrated to match moments of interest in the Antigua and Barbuda economy.

Table 4: Calibration

| | Value | Source |
|---|---|---|
| Interest rate | $R = 1.0451$ | Arellano (2008) |
| Risk aversion | $\sigma = 2$ | Arellano (2008) |
| Income Persistence | $\rho = 0.92$ | GDP Antigua and Barbuda |
| Mean of discount factor | $\beta = 0.915$ | Arellano (2008) |
| Probability of Regaining Access | $\theta = 0.33$ | Arellano (2022) |
| Output Loss linear | $\eta_1 = -0.2$ | Mean Spread Antigua and Barbuda |
| Output Loss quadratic | $\eta_2 = 0.445$ | Mean Spread Antigua and Barbuda |
| Probability of Hurracane. | $\pi = 0.103$ | Malluci (2022) |
| Mean Hurricane Cost | $\gamma = 0.78$ | Mean of a Panel Sample |
| Investment Cost | $\iota = 0.0053$ | - |

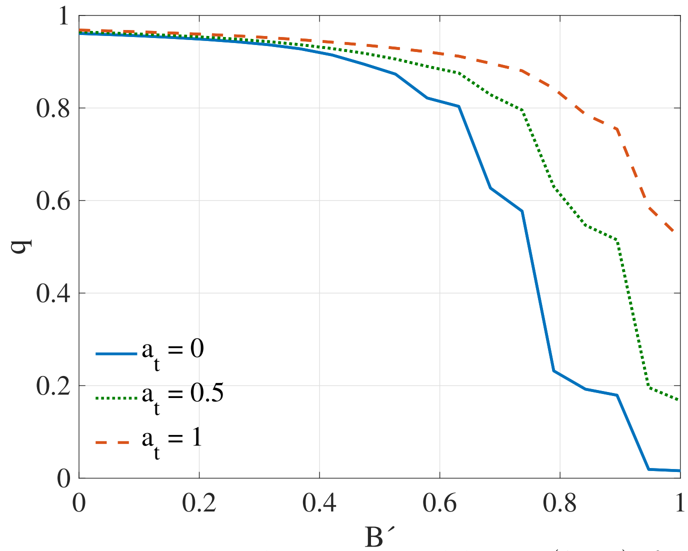
The predetermined parameters are the coefficient of relative risk aversion, which we set to $\sigma = 2$, the international interest rate $R = 1.017$, and the probability of regaining access to the global market after a default $\gamma = 0.282$.

We assume that the endowment of tradable goods follows a log-normal AR(1) process with persistence $\rho = 0.92$ to match the Antigua and Barbuda GDP as in Mallucci (2020). On the other hand, we assume that the default cost parameter is $\eta = 0.96$. We set $\beta = 0.915$ to match the average position of net foreign assets to GDP. In addition, we assume that the probability of a natural disaster $\pi = 0.103$ is equal to the probability of the occurrence of a hurricane in Antigua and Barbuda. Finally, in the case of a hurricane, we assume that the mean cost of a hurricane is $\gamma = 0.78$.

## 6.2 Price Function

We begin the analysis of the numerical results by analyzing the price function of government bonds. In Figure 3, we plot the price of government bonds as a function of new borrowing for different levels of adaptation.

Figure 3: Price Function




*Note:* This figure is computed assuming that there is a Natural disaster ($\xi = 1$) of high intensity ($\gamma = 0.094$) and the endowment is at the mean ($y = 1.0260$)

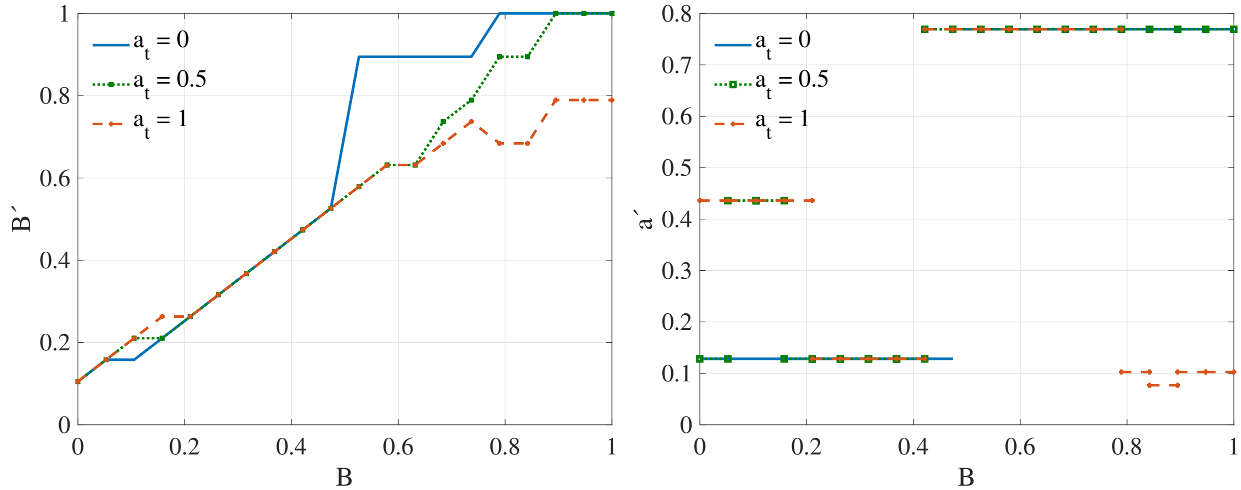
We can see that higher initial adaption leads to higher prices. However, the differences are greater when new borrowing is high of debt. The intuition is that when the government issues low debt, the risk is low, so getting insurance through adaptation has a negligible impact on prices. On the other hand, when the government issues large amounts of debt, the risk is high, so the investment in adaptation significantly impacts prices.

## 6.3 Optimal Policy

Next, we will analyze optimal policies for investment and debt. In panel 9a, we plot the policy function of debt for a country where the economy cycle is at its mean and the country is facing a strong natural disaster. We plot the optimal policy for three different initial adaptation levels.

We observe high differences when the initial level of debt is high. In particular, for high levels of initial debt, the government would deleverage is the initial level of adaption is high because in those states the government has more available resources. However, the government would increase the debt further if the initial level of adaptation is low. It increases the risk of default, but the government is willing to increase the risk because consumption would be very low if the government tries to reduce debt while facing a natural disaster with low adaptation.

Figure 4: Optimal Policy




(a) Debt (b) Investment in Adaption

*Note:* This figure is computed assuming that there is a Natural disaster ($\xi = 1$) of high intensity ($\gamma = 0.094$) and the endowment is at the mean ($y = 1.0260$)

In panel 9b, we plot the policy function of investment for a high endowment and a strong natural disaster. The nonmonotonic shape of the policy function of debt has some interesting results on the policy function of investment.

For low levels of debt, the policy function of the government does not change with the initial level of adaptation. However, for high debt levels, investment is close to zero when adaptation is high, while it is close to 0.8 when initial adaptation is low. This result illustrates a key relationship between default risk and investment in the model. When the initial level of debt is high and the economy is in a boom, because a high initial adaptation helped the country mitigate the consequences of a natural disaster, the government has incentives to reduce debt and avoid costly default. As a result, it chooses to reduce the investment in new adaptations to reduce the impact on the consumption of deleverage. One could think of this case as one in which the government is borrowing contained, so it chooses investment to be close to zero and uses all the resources to consume and reduce debt.

## 6.4 Welfare Analysis

Now, let us measure the welfare benefits of adaptation. For every initial state where adaptation is zero, we compute the percentage increase in consumption in all possible future histories that the household would require to be indifferent between living in an economy with the possibility of investing in adaptation and an economy where it is not possible. Due to the homotheticity of the utility function, the welfare gain $\gamma$ in state $s$ is given by:

$$(1+\gamma(s))^{(1-\sigma)}V(B,g,s) = V^{NA}(s)$$

Here $V^{NA}(s)$ is the value of the government when there is no possibility of adaptation. Figure 5 shows the welfare benefits of adaption as a function of current debt. In panel 5a, we show the benefit for a low endowment (1 std. dev. below mean). Panel 5b shows similar welfare costs but for the case of a high endowment (1 std. dev. above mean). We can see that the greatest impact of adaptation is for intermediate levels of debt, when the endowment of the government is low, and when the country faces natural disasters. Intuitively, these are the states where it is more valuable for the government to have adapation because it mitigates economic losses in a state where the risk of default is high. When the level of debt is very high, the government will default, so part of the befits of adaption associated with the increase in prices disappear, so the impact in welfare is lower.

When the endowment is high, the benefit of having adaptation in increasing the level of debt for the full region of debt is that the government will repay because the cost of default is high. In this case, the impact of welfare increases as the risk of default increases.

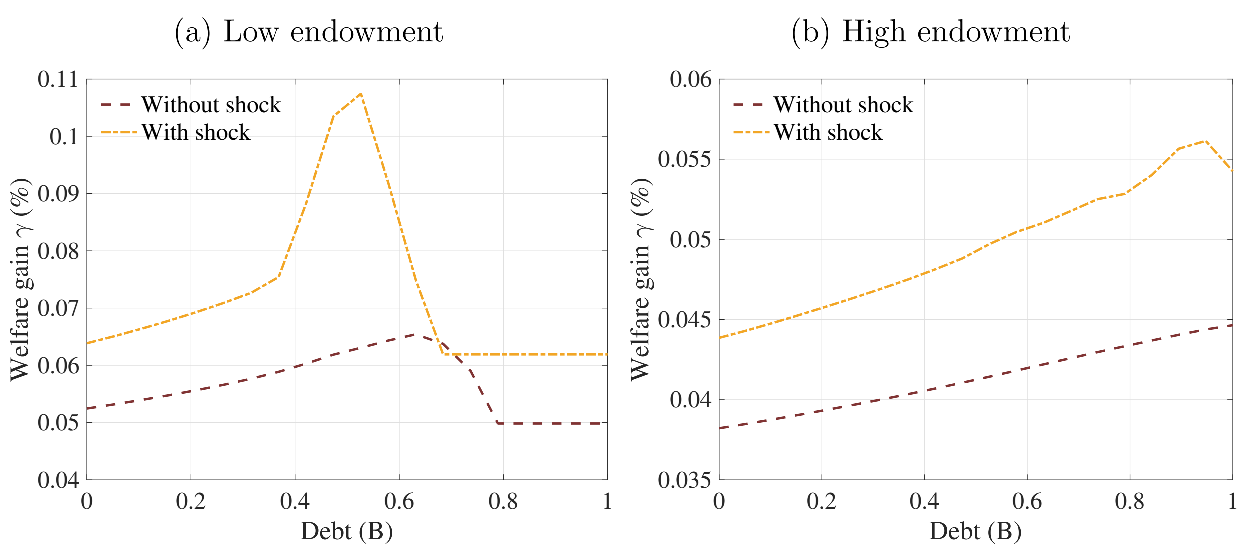



Figure 5: Welfare Losses of Political Frictions

*Note:* This figure is computed assuming the impatience of the households is at the mean $\beta = 0.904$ for both a low endowment level ($y_L = 0.90$) and a high endowment level ($y_H = 1.168$).

On average, a household would require an increase in consumption of 0.06% to be indifferent between living in an economy where the government does not invest in adaptation and moving where it does.

# 7 Conclusion

This paper examines the relationship between sovereign default risk and public investment in adaptation to natural disasters. By developing a sovereign default model that incorporates adaptation as a policy tool, we quantify its effects on fiscal sustainability and bond prices. Our findings highlight that adaptation investment mitigates the economic impact of disasters, reduces sovereign risk, and improves borrowing conditions. However, in the presence of long-term bonds, governments fail to fully internalize these benefits, leading to inefficiently low investment. This inefficiency arises when the government lacks commitment with respect to public investment policy.

Empirically, we establish that countries with higher adaptation levels, measured by the ND-GAIN index, suffer lower economic losses from natural disasters and face lower borrowing costs. Our identification strategy combines cross-country data with a structural model to assess the effect of adaptation on sovereign bond yields. We also show that access to international credit markets plays a crucial role in determining the optimal adaptation policy. When sovereign risk is high, governments face borrowing restrictions that limit investment, reinforcing the cycle of vulnerability to disasters. These results underscore the need for policy interventions, such as financial instruments tied to adaptation investment, to improve governments' ability to finance climate resilience while maintaining fiscal stability.

We find that investing in adaptation is an additional tool to reduce the impact of natural disasters on sustained risk that complements other policies such as the financial instruments studied by Mallucci (2020) and Phan and Schwartzman (2023).

# References


Aguiar, M. and Amador, M. (2019). A contraction for sovereign debt models. *Journal of Economic Theory*, 183:842–875.

Aguiar, M. and Amador, M. (2021). *The economics of sovereign debt and default*. Princeton University Press.

Aguiar, M., Amador, M., and Gopinath, G. (2009). Investment cycles and sovereign debt overhang. *The Review of economic studies*, 76(1):1–31.

Aguiar, M. and Gopinath, G. (2006). Defaultable debt, interest rates and the current account. *Journal of International Economics*, 69(1):64–83.

Arellano, C. (2008). Default Risk and Income Fluctuations in Emerging Economies. *American Economic Review*, 98(3):690–712.

Arellano, C., Bai, Y., and Mihalache, G. (2018). Default risk, sectoral reallocation, and persistent recessions. *Journal of International Economics*, 112:182–199.

Arellano, C., Mateos-Planas, X., and Ríos-Rull, J.-V. (2023). Partial default. *Journal of Political Economy*, 131(6):000–000.

Arellano, C. and Ramanarayanan, A. (2012). Default and the maturity structure in sovereign bonds. *Journal of Political Economy*, 120(2):187–232.

Beirne, J., Park, D., Saadaoui, J., and Uddin, G. S. (2024). Impact of climate risk on fiscal space: Do political stability and financial development matter?

Boitan, I. A. and Marchewka-Bartkowiak, K. (2022). Climate change and the pricing of sovereign debt: Insights from european markets. *Research in International Business and Finance*, 62:101685.

Cevik, S. and Jalles, J. T. (2022). This changes everything: Climate shocks and sovereign bonds∗. *Energy Economics*, 107:105856.

Chatterjee, S. and Eyigungor, B. (2012). Maturity, indebtedness, and default risk. *American Economic Review*, 102(6):2674–2699.

Dell, M., Jones, B. F., and Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 4(3):66–95.

Eaton, J. and Gersovitz, M. (1981). Debt with Potential Repudiation: Theoretical and Empirical Analysis. *Review of Economic Studies*, 48(2):289–309.

Esquivel, C. (2024). Underinvestment and capital misallocation under sovereign risk. *Journal of International Economics*, 151:103973.

Esquivel, C. and Samano, A. (2023). Expansionary fiscal consolidation under sovereign risk.

Gómez González, J. E., Uribe, J., and Valencia, O. M. (2024). Asymmetric sovereign risk: Implications for climate change preparation. Technical report, IDB Working Paper Series.

Hatchondo, J. C. and Martinez, L. (2009). Long-duration bonds and sovereign defaults. *Journal of international Economics*, 79(1):117–125.

Hsiang, S. M. and Narita, D. (2012). Adaptation to cyclone risk: Evidence from the global cross-section. *Climate Change Economics*, 3(02):1250011.

Krugman, P. (1988). Financing vs. forgiving a debt overhang. *Journal of development Economics*, 29(3):253–268.

Mallucci, E. (2020). Natural disasters, climate change, and sovereign risk. *FRB International Finance Discussion Paper*, (1291).

Mateos-Planas, X. and Ríos-Rull, J.-V. (2015). The generalized euler equation and the bankruptcy–sovereign default problem. *URL http://www. sas. upenn. edu/˜ vr0j/slides/vvucl. pdf. Slides, Department of Economics, University of Pennsylvania.*

Phan, T. and Schwartzman, F. F. (2023). Climate defaults and financial adaptation.

Sánchez, J. M., Sapriza, H., and Yurdagul, E. (2018). Sovereign default and maturity choice. *Journal of Monetary Economics*, 95:72–85.

Shklovski, I., Burke, M., Kiesler, S., and Kraut, R. (2010). Technology adoption and use in the aftermath of hurricane katrina in new orleans. *American Behavioral Scientist*, 53(8):1228–1246.

# A Algorithm

**1.** Construct a grid for $b'$ of $1 \times n_B$, $a'$ of $1 \times n_a$, and the shocks of $1 \times (n_y + n_\gamma)$.

**2.** Guess the value function $V$ of $(n_y + n_\gamma) \times (n_B + n_a)$ and compute the expected value function $\mathbb{E}V$.

**3.** Given $a'$, update $b'$ using formulas in Sánchez et al. (2018) :

$$b' = \arg\max_{b'} u(c) + \beta \mathbb{E}V(y', b')$$

subject to the budget constraint:

$$c = y - \kappa b + q(y, b, i)(b' - (1 - \delta)b) - \gamma(1 - a) - \iota a^2.$$

**4.** Given new $b'$, for each state $b, a, \gamma, y$, construct:

$$\mathbb{E}V_{b'} = \mathbb{E}V(s_{b'} : s_{b'} + n_a, s_y),$$

where $s_y$ is the position of the exogenous state $(\gamma, y)$, and $s_{b'}$ is the position for $b'$, with $a' = 0$.

**5.** Perform grid search over $a'$ by modifying $f(a')$ and update:

$$\mathbb{E}V_{b'} = \mathbb{E}V(s_{b'} : s_{a'}, s_y),$$

where $s_{a'} = s_{b'} + x_a$, with $x_a$ being the index of $a'$.

**6.** Solve for the default decision using the value function:

$$V^D(y, b) = \max_{a'} u(y - \gamma(1 - a')) + \beta \mathbb{E}V(y', 0).$$

The country defaults if:

$$V^D(y, b) > V(y, b).$$

**7.** Compute the price function $q(y, b, i)$ using the bond pricing equation:

$$q(y, b, i) = \mathbb{E}\left[\frac{1 - d(y', b')}{R}\right],$$

where $d(y', b')$ is the default decision.

**8.** Update the value function $V$ and expected value function $\mathbb{E}V$:

$$V(y, b) = \max_{b'} u(c) + \beta \mathbb{E}V(y', b').$$

**9.** Update prices by solving the bond market equilibrium condition:

$$q(y, b, i) = R^{-1} \sum_{y'} \mathbb{E}\left[(1 - d(y', b'))q(y', b', i)\right].$$

**10.** Check convergence. If not converged, return to step 2 and iterate until equilibrium is reached.

# B Proofs

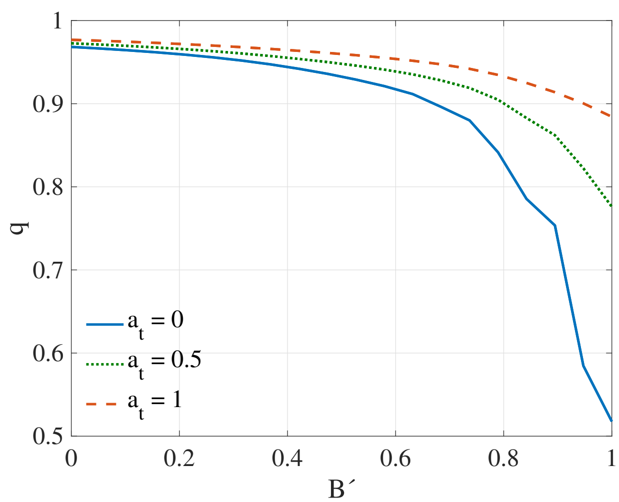
## B.1 Lemma 1

The proof has two steps; first we follow Arellano (2008) to show that default is more likely when the endowment is lower, and second we show that that the endowment is lower with lower adaptation.

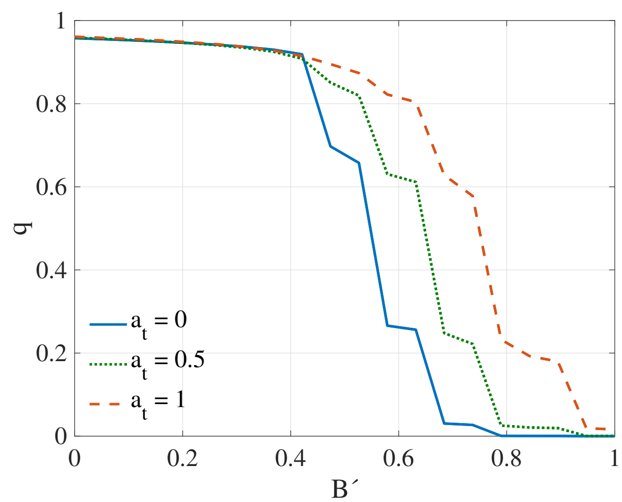
# C Addtional Plots

**Price Function.** Figure 6 plots the bond-price schedule $q(y, B')$ against new borrowing $B'$ under a high-intensity disaster state ($\xi = 1$, high $\gamma$). Panel (a) fixes income at a high endowment and panel (b) fixes income at a low endowment. Within each panel, we compare three adaptation levels $a_t \in \{0, 0.5, 1\}$. Prices are decreasing in $B'$ and are uniformly higher for larger $x$, with the price gaps widening at higher $B'$. This reflects that greater adaptation lowers default risk, and thus raises bond prices.

Figure 6: Price Function




(a) High income - strong shock

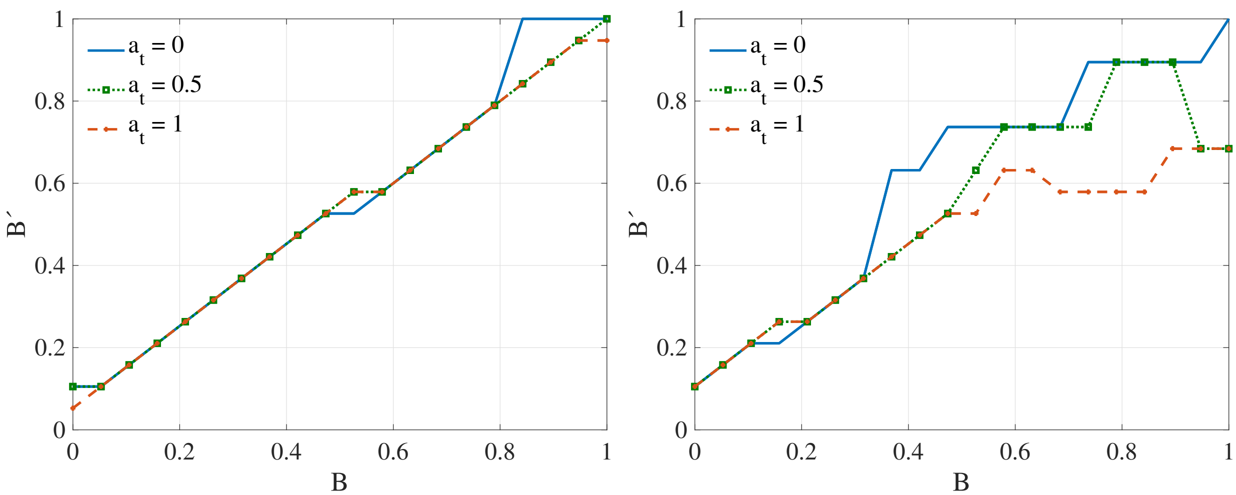



(b) Low income - strong shock

*Note:* This figure is computed assuming that there is a Natural disaster ($\xi = 1$) of high intensity ($\gamma = 0.094$) for both a low endowment level ($y_L = 0.90$) and a high endowment level ($y_H = 1.168$).

**Debt Function** Figure 7 plots the optimal debt policy function $B'(B)$ under a high-intensity disaster state ($\xi = 1$, high $\gamma$). Panel (a) fixes income at a high endowment and panel (b) fixes income at a low endowment. Within each panel, we compare three adaptation levels $a_t \in \{0,\ 0.5,\ 1\}$. For low initial debt, the policy is similar across $a$ and close to the 45° line, but differences widen as $B$ rises. Higher adaptation (larger $a$) is associated with lower issuance (smaller $B'$), while low adaptation induces higher issuance (larger $B'$), especially at high $B$. This reflects that adaptation relaxes disaster-time resources and reduces default risk, making debt reduction optimal when leverage is elevated, whereas low adaptation pushes borrowing to smooth consumption despite higher risk.

Figure 7: Debt Function



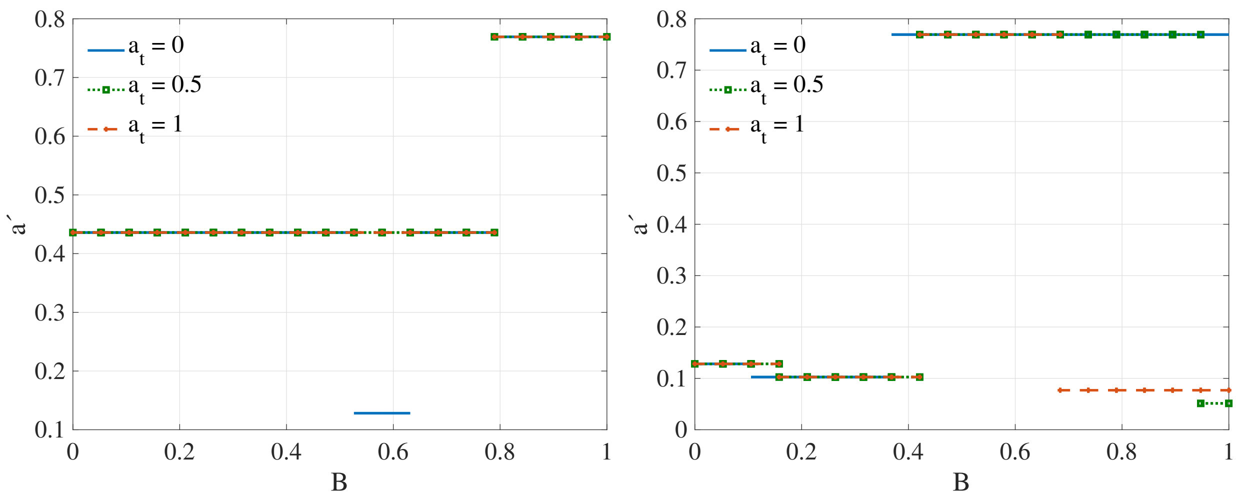

(a) High income - strong shock

(b) Low income - strong shock

*Note:* This figure is computed assuming that there is a Natural disaster ($\xi = 1$) of high intensity ($\gamma = 0.094$) for both a low endowment level ($y_L = 0.90$) and a high endowment level ($y_H = 1.168$).

**Adaptation Function** Figure 8 plots the adaptation policy function $a'(B)$ under a high-intensity disaster state ($\xi = 1$, high $\gamma$). Panel (a) fixes income at a high endowment and panel (b) fixes income at a low endowment . Within each panel, we compare three current adaptation levels $a_t \in \{0, 0.5, 1\}$. For low initial debt, policies are similar across $a$, but differences widen as $B$ increases: when current adaptation is low ($a = 0$), the government invests aggressively (high $a'$); when current adaptation is high ($a = 1$), it invests little (low $a'$). This pattern reflects the insurance value of adaptation: investment is prioritized when the economy is poorly prepared, while at high debt levels well-adapted economies reallocate resources away from new adaptation toward debt reduction.

Figure 8: Mitigation Function

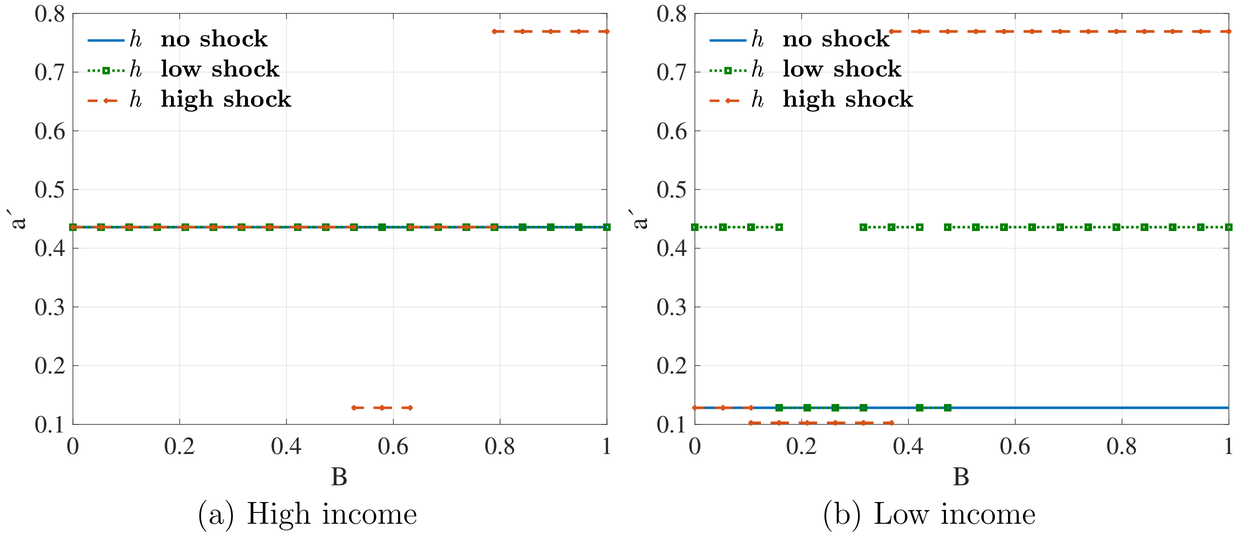



(a) High income (b) Low income

*Note:* This figure is computed assuming that there is a Natural disaster ($\xi = 1$) of high intensity ($\gamma = 0.094$) for both a low endowment level ($y_L = 0.90$) and a high endowment level ($y_H = 1.168$).

Figure 9 plots the adaptation policy function $a'(B)$ holding the current adaptation level fixed, and comparing disaster intensities. Panel (a) fixes income at a high endowment and panel (b) fixes income at a low endowment. For any given $B$, $a'$ is higher when the prospective disaster is more severe: investment is lowest under no shock and largest under a high shock, reflecting the insurance value of adaptation. Differences across $h$ widen as $B$ increases, since higher debt amplifies default risk and raises the marginal benefit of investing in adaptation.

Figure 9: Mitigation Function




*Note:* This figure is computed assuming a fixed initial adaptation level ($a = 0$) and compares different disaster intensities: no shock ($\gamma = 0$), low shock ($\gamma = 0.040$), and high shock ($\gamma = 0.0944$). Results are shown for both a low endowment level ($y_L = 0.90$) and a high endowment level ($y_H = 1.168$).

**Simulations** The simulations compare the paths of debt, default risk, and macroeconomic variables in economies with and without adaptation. With adaptation, Figure 10, shocks lead to smaller output losses, lower default probabilities, and more stable debt dynamics, as investment cushions the fiscal impact of disasters. Without adaptation, Figure 11, natural disasters trigger deeper contractions and sharper increases in borrowing costs, making defaults more frequent and debt paths more volatile. These simulations highlight the stabilizing role of adaptation in mitigating disaster risk and preserving fiscal sustainability.

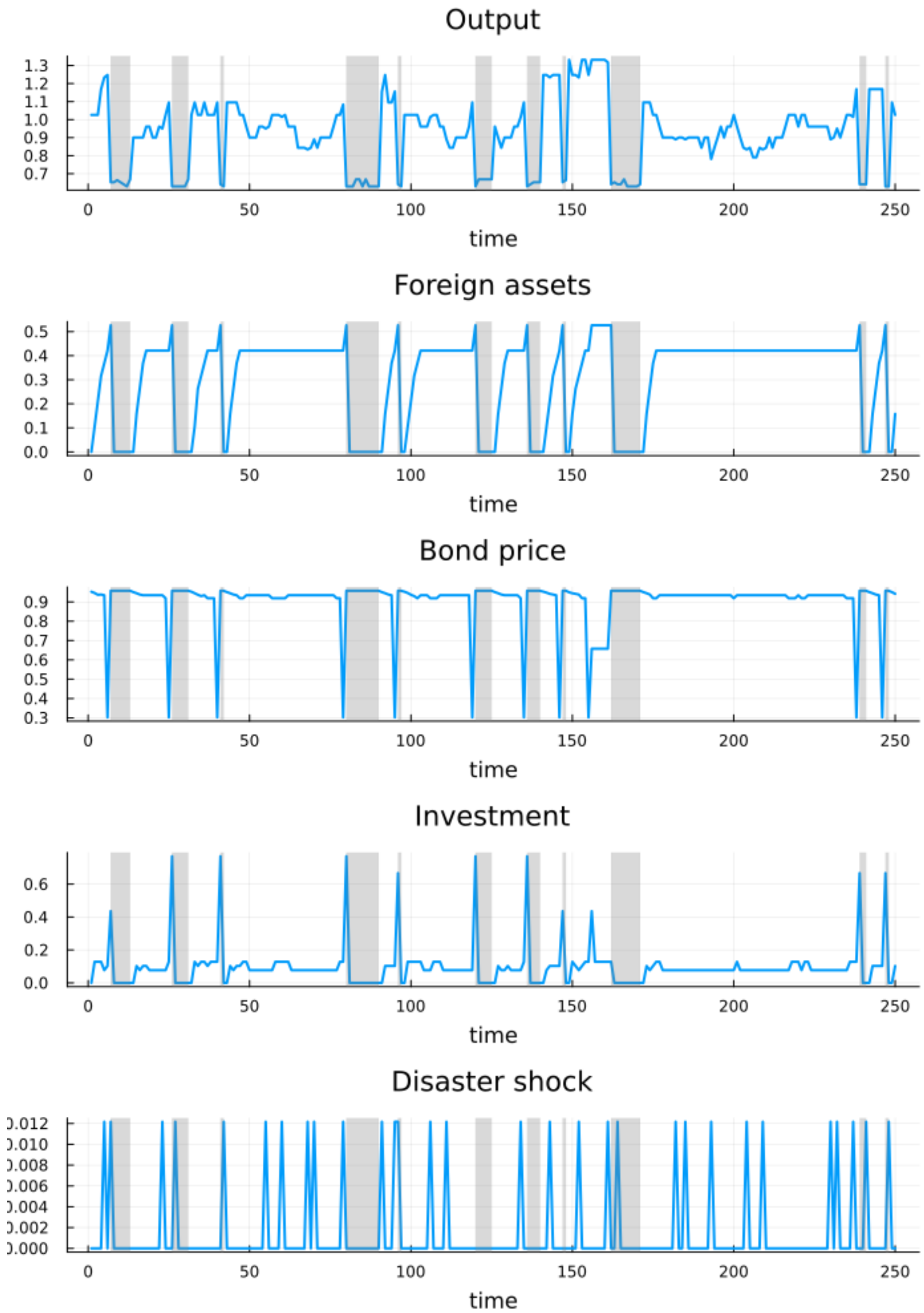



Figure 10: Simulation with Adaptation

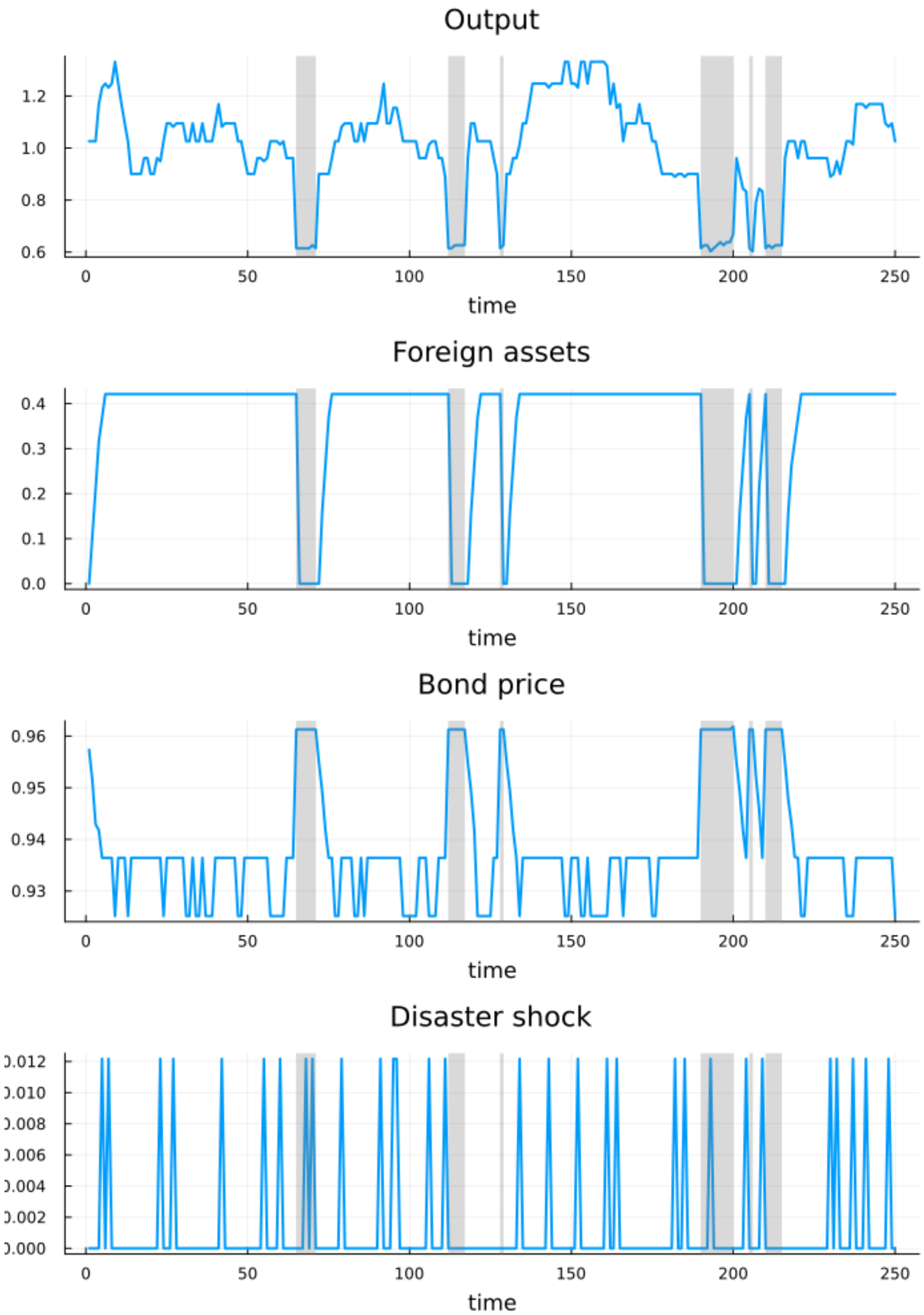



Figure 11: Simulation without Adaptation