Natural Disaster Modeling with the DSGE DIGNAD Framework: A Study of Madagascar

Josué, ANDRIANADY

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Josué Ravahiny ANDRIANADY [1]

[1] ravahiny.andrianady@dauphine.eu

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Abstract

This study utilizes the DSGE model DIGNAD to assess the economic impacts of natural disasters on Madagascar. Four distinct scenarios are analyzed: the first scenario (zero scenario) simulates the effects of a natural shock occurring in 2027. The second scenario evaluates the impact of investing 1% of GDP in resilient infrastructure over a 5-year period preceding the shock. The third scenario examines the outcomes of a similar 1% GDP investment in standard, non-resilient infrastructure before the shock. The fourth scenario considers the implications of a 2% GDP investment in resilient infrastructure aimed at enhancing the country's relatively low GDP, currently at around 31%. The findings reveal a projected contraction of approximately 6% in GDP growth in the event of the shock. Investing in resilient infrastructure significantly mitigates the decline in growth, reducing it by about 2% of GDP. Despite this benefit, the substantial financial requirements for such infrastructure present a considerable challenge for Madagascar.

Keywords: DSGE model, DIGNAD, natural disasters, economic impact, resilient infrastructure, Madagascar, GDP growth, investment scenarios.

1 Introduction

Madagascar is highly vulnerable to a range of climate-related risks, which include tropical cyclones, droughts, and floods. These natural hazards are significantly exacerbated by the ongoing effects of climate change, presenting substantial challenges for the country's economic stability and development. Historically, Madagascar experiences a tropical cyclone approximately every 0.9 years, while droughts and floods occur on average every 2.7 and 3 years, respectively [7]. The recurring nature of these disasters results in severe damage to physical infrastructure, disrupts economic activity, and induces immediate contractions in GDP. The impact of such disasters extends beyond short-term economic disruptions, leading to long-term impediments to potential growth and development.

The economic consequences of these natural disasters are multifaceted. They not only cause direct physical damage but also lead to reductions in government revenues as economic activities are curtailed and agricultural output is compromised. Additionally, the need for increased public expenditure on disaster relief and reconstruction further exacerbates fiscal deficits and contributes to rising public debt. This combination of factors strains the financial resources of the country, limiting its capacity to invest in other critical areas and hindering overall economic stability.

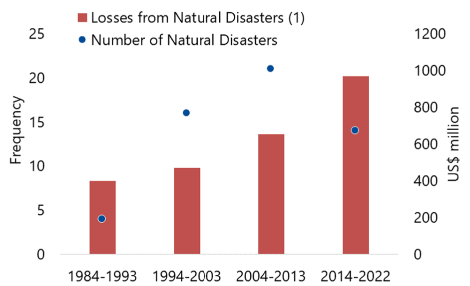
Looking ahead, the impacts of climate change are expected to intensify the frequency and severity of these natural hazards. For instance, it is projected that the intensity of tropical cyclones could increase by 18.4% by 2050 [1]. This anticipated rise in the frequency and intensity of climate-related events underscores the urgency of developing effective strategies to manage and mitigate their economic impacts.

To address these pressing concerns, this article employs the DIGNAD model, a comprehensive tool designed to simulate and analyze the economic impacts of natural disasters. By leveraging this model, we aim to provide a detailed assessment of how these climate risks affect Madagascar's economy. Our objective is to elucidate the economic repercussions of these hazards and to offer insights into policy interventions that can enhance the country's resilience. The findings from this analysis will inform strategies to improve disaster management, reduce vulnerability, and support sustainable development in the face of escalating climate risks.

2 Climate Change Risks and Impacts in Madagascar

Madagascar is exposed to a range of climate risks, including tropical cyclones, droughts, and floods, all of which are exacerbated by climate change (see fig 2 and table 1). The country historically experiences a tropical cyclone approximately every 0.9 years on average, with droughts and floods occurring every 2.7 and 3 years, respectively [7]. These natural disasters destroy physical capital and reduce GDP in the short term, while also diminishing potential growth over the medium term. They decrease revenues and create additional spending needs, thereby exacerbating deficits and increasing public debt. Although uncertainty remains regarding the future frequency of tropical cyclones, floods, and droughts, their impact is expected to escalate with rising temperature and precipitation variability. Thus, a typical tropical cyclone is projected to increase in intensity by 18.4% by 2050 [1].

Figure 1: Historical Frequency of Natural Disasters in Madagascar and the Resulting Total Losses



Source: EM-DAT,2022 [7]

2.1 Major Climate Risks

Tropical cyclones represent a substantial climatic threat to Madagascar, particularly affecting its eastern and northern regions. These cyclones are distinguished by their intense wind velocities, heavy precipitation, and storm surges, which result in considerable damage to infrastructure, residential properties, and agricultural lands.A typical tropical cyclone results in 1.8% of GDP in aggregate losses, with 57% of these losses attributed to damage to physical assets (based on assessments by authorities of the impact of tropical cyclones Ava and Enawo). [8] Madagascar is among the nations with the highest cyclone vulnerability in Africa, experiencing an average of three to four cyclones annually. The cyclone season spans from November to March, during which extensive damage can occur, including substantial crop losses, heightened incidence of disease outbreaks, degradation of coastal and marine ecosystems, disruption of essential urban services such as water and electricity, severe flooding, infrastructural damage, and occasionally, loss of life.

Droughts exert a profound impact on the southwestern and central regions of Madagascar, characterized by prolonged periods of inadequate rainfall. This phenomenon leads to critical water shortages, diminished agricultural output, and food insecurity. The scarcity of water adversely affects both livestock and human populations by reducing the availability of potable water.An average drought would reduce real growth by 0.3%, with persistent effects in subsequent years. [8] Furthermore, droughts can initiate a cycle of poverty and malnutrition, as affected communities grapple with the challenge of maintaining their livelihoods under these harsh conditions.

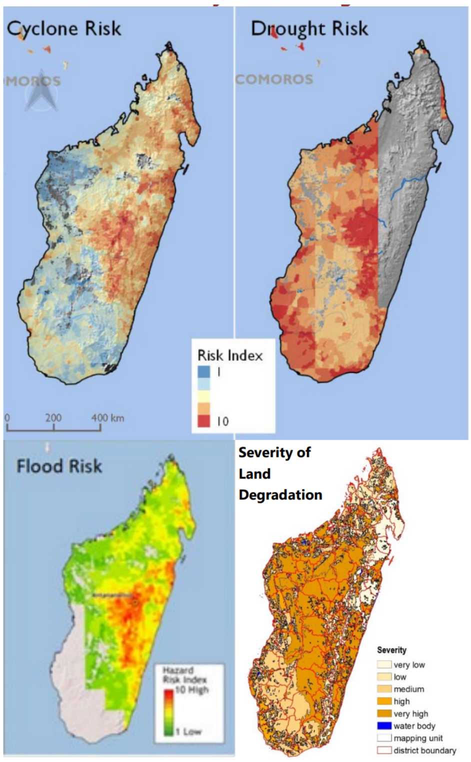
Flooding is a recurring issue in the eastern and central regions of Madagascar, particularly during the rainy season and in the aftermath of tropical cyclones. Prolonged and intense rainfall can lead to riverine overflow, resulting in the inundation of agricultural lands, residential areas, and critical infrastructure. The immediate impacts of flooding are severe, including damage to property and disruption of transportation and access to essential services.An average flood results in total losses amounting to 2.4% of GDP. [7] Additionally, the stagnation of floodwaters can contribute to public health concerns, particularly through the proliferation of waterborne diseases.

2.2 Impacts of Climate Change on Key Sectors in Madagascar

Disruptive climate events have inflicted considerable damage on key sectors in Madagascar, and future climate change is expected to exacerbate these impacts.

Climate change is anticipated to undermine agricultural productivity through three primary mechanisms: (i) loss of arable land caused by erosion, increased rainfall intensity, cyclones,

Figure 2: Cyclone, Drought, and Flood Risks, and the Severity of Land Degradation



Source : World Bank Climate Risk and Adaptation Country Profile, 2011, USAID, 2018

and floods 10; (ii) diminished land productivity due to severe droughts and pest infestations, including locust outbreaks; and (iii) reduced labor productivity resulting from extreme heat [6] [12] [2].

Major cyclones between 2017 and 2019 led to significant contamination of drinking water, resulting in outbreaks of waterborne diseases. Ongoing droughts have exacerbated food shortages and acute malnutrition, particularly in the Grand South. Climate change continues to pose indirect challenges to public health by degrading water quality and worsening food security issues related to drought.

Extreme weather events cause severe damage to natural capital, while gradual climate changes significantly impact Madagascar's terrestrial and marine ecosystems. On land, altered rainfall patterns contribute to tree loss, affecting growth and reproduction, and leading to biodiversity loss that impairs forest regeneration [4]. In coastal and marine environments, climate change accelerates the decline of natural resources such as mangroves, marine vegetation, and fisheries [5]. These ecological disruptions negatively affect economic sectors such as agriculture and tourism, which rely heavily on Madagascar's unique biodiversity and coastal resources.

Climate change poses substantial threats to infrastructure and buildings through extreme events such as floods and high winds from tropical cyclones, landslides exacerbated by ecosystem degradation and intense rainfall, and increased wear and tear from droughts and heat. Under current climate conditions, estimated annual damage to roads and railways amounts to approximately 0.2% of GDP in Madagascar [9]. Additionally, fluctuations in precipitation may affect the energy sector, particularly hydropower, which provides 29% of Madagascar's energy supply.

3 Methodology

To analyze the impacts of natural disasters on the Madagascar context, we will utilize the DIGNAD model, a sophisticated extension of the Debt-Investment-Growth (DIG) model. The DIGNAD model is a type of Dynamic Stochastic General Equilibrium (DSGE) model specifically designed to address the complexities faced by economies that are highly vulnerable to natural disasters. This model provides a comprehensive framework for assessing alternative investment programs and serves as a critical tool for Climate Macroeconomic Assessment Programs. [3] [11]
We project that tropical cyclones, floods, and droughts will follow the historical patterns observed over the past 43 years. These disasters impact the economy by damaging public and private assets and causing short-term productivity losses. While Madagascar's "building back better" approach helps with immediate recovery, the gaps between disasters are usually shorter than the time needed to fully restore capital and productivity. The model assumes that, without further disasters, the economy will slowly return to its normal state, with capital rebuilding, productivity recovery, and GDP growth resuming.. [8]

3.1 Structure of the DIGNAD Model

The DIGNAD model is organized into several interconnected blocks

3.1.1 Private Demand Block

This component distinguishes between two types of households: liquidity-constrained households, which are unable to save, and savers, who have access to various financial instruments for investment. Households receive income from labor and domestic transfers and consume both domestic and foreign goods. Savers make investment decisions based on the available options.

3.1.2 Private Supply Block

This block focuses on firms operating in two sectors: tradable and non-tradable goods. The production process within firms requires several inputs, including labor, private capital, and public infrastructure. Public infrastructure is categorized into standard infrastructure and climate-resilient infrastructure aimed at adaptation. The production function within the model is expressed as:

$$y = A \cdot z^{\zeta} \cdot k^{\alpha} \cdot l^{1-\alpha} \tag{1}$$

where:

$$z = \frac{z_i^{\xi-1}}{\xi} + \frac{\eta_a \cdot z_a^{\xi-1}}{\xi} \tag{2}$$

In this function, ξ and η_a represent technological factors and climate adaptation efforts, respectively.

3.1.3 Policy Block

This component includes a range of fiscal and debt instruments. Fiscal tools encompass taxes on consumption, labor taxes (such as VAT), and investments in public infrastructure, whether standard or climate-resilient. Debt instruments consist of domestic and external debt, as well as donor grants. Policy instruments may be either fixed or adjusted endogenously in response to fiscal gaps. Specifically, the fiscal rule allows for tax rate adjustments based on fiscal gaps and deviations from target debt levels, as follows:

$$\tau_t = \tau_{t-1} + \lambda_1 \cdot (\text{fiscal gap}) + \lambda_2 \cdot (\text{deviation of debt from target}) \tag{3}$$

where λ_1 and λ_2 are non-negative parameters.

3.2 Impact of Natural Disasters in the DIGNAD Model

Natural disasters impact the DIGNAD model in several key ways. They reduce production by a factor of $(1 - D)$, where D denotes the damage intensity, directly lowering overall output. Damage also reduces the capital available for production, decreasing productive capacity. Additionally, public infrastructure damage further diminishes production efficiency. There is also a temporary drop in productivity that affects economic performance during and after the disaster. Lastly, disasters lead to lower credit ratings, increasing the cost of external borrowing. This effect is represented by:

$$r_t = (1 + D \cdot r) \cdot (r_f + \cdots) \tag{4}$$

where r_t is the adjusted interest rate, D is the damage factor, and r_f is the base interest rate.

3.3 Resilient Infrastructure in the DIGNAD Model

Resilient infrastructure provides several advantages. It has a lower depreciation rate ($\delta_{z_a} < \delta_{z_i}$), enhancing its durability over time compared to standard infrastructure. Resilient infrastructure also sustains less damage during natural disasters (D), thereby reducing repair and reconstruction costs. Additionally, it offers a higher marginal return on capital (MRPK), resulting in a superior return on investment ($R_{z_a} > R_{z_i}$). Despite these benefits, the construction of resilient infrastructure may incur higher initial costs. Therefore, the decision to invest in such infrastructure must weigh these benefits against the additional costs involved.

3.4 Model Parameters

The parameters listed in table 2 are critical for understanding the dynamics and behavior of the economic model we use. These parameters include economic ratios, tax rates, and depreciation rates, which are essential for simulating the impact of various policy measures and economic shocks. Each parameter plays a role in defining how public infrastructure investments, taxation, and other economic factors influence overall growth and stability.

3.5 Scenario Analysis

This section presents four distinct scenarios to analyze the impact of climate disasters and various investment strategies on Madagascar's economy. Each scenario is designed to provide insights into how different levels of investment in infrastructure and adaptation measures can influence the country's resilience to climate-related events. The scenarios are as follows:

3.5.1 Scenario 0: Baseline Scenario with Climate Disaster Impact

In this scenario, we establish a baseline within the DIGNAD model to exclusively analyze the impact of a climate disaster occurring in 2027. This scenario aims to evaluate and observe the resultant effects on Madagascar's economy.

3.5.2 Scenario 1: Adaptation Baseline with Natural Disaster

In this scenario, the investment strategy involves allocating 1% of Gross Domestic Product (GDP) annually toward the development of adaptation infrastructure. This investment is intended to be implemented over a period of five years, concluding in 2026, and is financed entirely through grants. The primary objective of this investment is to enhance the country's resilience to climate-related impacts by improving the capacity of infrastructure to withstand environmental stressors.

Before the occurrence of a significant natural disaster in 2027, the adaptation infrastructure investments are expected to substantially bolster Madagascar's ability to manage and mitigate climate-related risks. The infrastructure enhancements aim to reduce vulnerabilities and improve the country's preparedness for climate stress. When the natural disaster strikes in 2027, the fall in GDP is estimated to be 6%. The advanced adaptation infrastructure is anticipated to play a crucial role in alleviating some of the immediate impacts and potentially minimizing the overall damage. However, the effectiveness of this investment in mitigating the disaster's effects will depend on the magnitude of the event and the robustness of the adaptation measures put in place.

3.5.3 Scenario 2: Standard Infrastructure Baseline

In this scenario, the country invests 1% of its GDP annually in standard infrastructure development over a period of five years, concluding in 2026. This investment strategy is funded through grants and focuses on general infrastructure development rather than specific adaptation measures. The primary goal of this approach is to address basic infrastructure needs without an explicit emphasis on climate resilience.Given that this scenario does not account for the occurrence of a natural disaster within the investment period, the emphasis remains on enhancing general infrastructure. However, the lack of targeted adaptation efforts may lead to increased vulnerabilities when facing climate-related stresses. Consequently, in the event of a natural disaster, this investment strategy could result in higher levels of damage and elevated recovery costs due to the infrastructure's limited resilience to climate impacts.

3.5.4 Scenario 3: Rising Public Investment Efficiency (PIE) and Increased Adaptation Investment

This scenario outlines a strategy to increase Public Investment Efficiency (PIE) from 31% to 51% while simultaneously investing 2% of GDP annually in adaptation infrastructure over a period of five years, concluding in 2026. The financing for this strategy is provided through a combination of grants and concessional debt. The enhanced investment in adaptation infrastructure represents a more substantial commitment compared to the previous scenarios and is aimed at significantly improving the country's resilience to climate-related impacts.

The increase in PIE is intended to ensure that investments are utilized more effectively, thereby maximizing the impact of the adaptation measures. With the combination of higher investment in adaptation infrastructure and improved efficiency, Madagascar is expected to achieve a notable enhancement in its capacity to cope with climate-related challenges. This increased resilience is likely to reduce the severity of damage and lower recovery costs in the event of a natural disaster, providing a more robust defense against climate stress.

4 Results and discussion

The following figures (fig3 fig4) present the results derived from the model. These graphical representations illustrate the outcomes and analyses based on the model's predictions and computations. Each figure provides visual insights into different aspects of the model's results, highlighting key trends, patterns, and relationships observed during the analysis.

4.1 The Macroeconomic Consequences of a 2027 Natural Disaster on Madagascar's Economy

In the zero-scenario, the occurrence of a natural disaster in 2027 results in a reduction of the growth rate to 5.78% (real GDP growth relative to the steady state) (see figures 3). This decline is attributed to a severe contraction in production and economic activity, particularly affecting crucial sectors such as agriculture and infrastructure.

The increased demand for imports necessary for the reconstruction of destroyed infrastructure leads to an expansion of the current account deficit. This development places additional strain on the balance of payments and may impact monetary stability and foreign exchange reserves. Furthermore, the depreciation of the local currency is likely to exacerbate imported inflation, thereby increasing the costs of goods and services.

Public expenditures rise significantly in response to the extensive needs of reconstruction. This surge in spending could result in higher public debt if not counterbalanced by increased revenues or reductions in other expenditures. Over time, this may affect the fiscal stability of the state and elevate borrowing costs.

Real wages experience a notable deviation from the steady state, reflecting a decline in household purchasing power. This decrease is further intensified by inflation driven by higher prices for imported goods and services associated with reconstruction efforts. Consequently, this could impact consumption and savings patterns, potentially constraining future economic growth.

Overall, the natural disaster in 2027 introduces considerable macroeconomic imbalances for Madagascar, adversely affecting growth, the balance of payments, public finances, and household purchasing power. Addressing these issues may necessitate both domestic policy adjustments and international support to stabilize the economy.

4.2 Result of the adaptation scenarios

This subsection evaluates the impact of investing in resilient infrastructure on Madagascar's economic growth and financial stability. We explore three distinct scenarios, each with different implications for macroeconomic management in the context of natural disaster preparedness.(see figures 4)

In the first scenario, where Madagascar invests in resilient infrastructure designed to withstand natural disasters, the GDP growth rate experiences a decline of 2.96%. These infrastructures are engineered to resist seismic, cyclonic, and hydrological shocks, thus mitigating productivity losses and reconstruction costs. In comparison, investments in standard infrastructure result in a GDP decline of 5.97%, while investments in slightly improved infrastructure lead to a reduction of 1.31%. The average difference of 2% in GDP reduction between resilient and standard infrastructure highlights the superior capacity of resilient infrastructure to buffer economic shocks.

Resilient infrastructure requires substantial initial investment, which results in a temporary increase in the current account deficit. This deficit can exceed the standard by 1% of GDP, exerting additional pressure on the balance of payments and potentially affecting monetary stability and foreign exchange reserves. Furthermore, increased depreciation of the local currency may exacerbate imported inflation, leading to higher costs for essential goods and services.

During the investment phase, Madagascar faces a significant rise in public debt due to the high costs associated with resilient infrastructure. This increase in debt may lead to higher short-term financing costs. However, the long-term benefits of resilient infrastructure become more apparent post-disaster. The current account deficit is less severe in scenarios involving resilient infrastructure, with an average improvement of 2% of GDP compared to standard infrastructure. Additionally, post-disaster debt stabilizes more rapidly due to the slower depreciation of resilient infrastructure, reducing the need for additional financing for reconstruction.
In the long term, resilient infrastructure offers substantial economic advantages. It facilitates a faster and more stable recovery following natural disasters, reducing reconstruction costs and aiding in economic stabilization. The long-term savings realized from reduced economic losses and enhanced macroeconomic stability more than offset the high initial expenditures. Ultimately, resilient infrastructure contributes to greater economic resilience and supports sustainable growth by minimizing disruptions to economic activities and enhancing macroeconomic stability.

5 Conclusion

This work presents a comprehensive evaluation of the macroeconomic impacts of a natural disaster in 2027 and the effectiveness of various investment scenarios in resilient infrastructure for Madagascar. We use 4 scenarios to modelling thi effect on Madaagscar's economy.

In the zero-scenario, the occurrence of a natural disaster in 2027 results in a significant reduction in Madagascar's GDP growth rate to 5.78%, driven by severe contractions in key sectors such as agriculture and infrastructure. The subsequent demand for imports for reconstruction exacerbates the current account deficit, strains the balance of payments, and risks undermining monetary stability and foreign exchange reserves. Moreover, the depreciation of the local currency aggravates imported inflation, heightening the costs of essential goods and services, while rising public expenditures further strain fiscal stability and elevate borrowing costs. The resultant decline in real wages compounds the economic challenges by reducing household purchasing power, potentially constraining future economic growth and affecting consumption and savings patterns.

In contrast, the investment in resilient infrastructure presents a strategic advantage. Despite the substantial initial costs, which temporarily increase the current account deficit and public debt, the long-term benefits are pronounced. Resilient infrastructure reduces the GDP decline by 2.96%

compared to standard infrastructure scenarios and 1.31% compared to slightly improved infrastructure. The capacity of resilient infrastructure to absorb shocks minimizes reconstruction costs and stabilizes the economy more swiftly post-disaster. The long-term economic advantages, including reduced damage and enhanced stability, outweigh the initial financial burdens.

Investing in resilient infrastructure offers a sustainable path for Madagascar's economic stability and growth. While the substantial initial investment poses a significant challenge, it is essential for mitigating the impacts of natural disasters and fostering long-term resilience. Overcoming the initial financial burden through strategic investments and international support will be crucial for ensuring Madagascar's recovery and sustainable development.

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Table 1: Madagascar: Climate Hazard Profile

Temperature and Heatwaves	• From 1991 to 2020, the average temperature increased by 0.53°C compared to the 30-year period from 1960 to 1990. • The number of hot days and tropical nights has been rising steadily since 1961. • By mid-century, average annual temperatures are expected to increase by 0.87°C to 1.67°C under a moderate climate change scenario (SSP1-4.5). • The duration of warm spells is projected to extend by 70 days per year (median value) in a moderate climate change scenario (RCP 4.5).
Precipitation and Drought	• Since 1961, precipitation patterns have shown regional and seasonal variability. Annual rainfall has been decreasing in the central and eastern coastal regions between 1961 and 2005, with reductions in winter and spring rainfall across most of the country. • The decline in rainfall in the central and eastern coastal regions has led to longer dry spells. • By mid-century, annual precipitation is expected to remain relatively stable, but in already drought-prone areas, the number of consecutive dry days may increase significantly under a moderate climate scenario (RCP 4.5). • Recent observation: The 2021/2022 drought affected much of the country, with the southern region experiencing 70 percent less rainfall than normal.
Flooding	• By mid-century, Madagascar is expected to experience more intense single-day rainfall events compared to the 1961-2015 baseline, increasing the risk of hydrological flooding under a moderate climate scenario (RCP 4.5). • Land degradation exacerbates flood risks, leading to more severe impacts. • Recent observation: The January 2022 flood, caused by intense rainfall, resulted in landslides, infrastructure damage, and loss of life, affecting Antananarivo and other areas in the Analamanga Region.
Cyclones	• While the frequency of cyclones remains uncertain, their intensity is expected to increase. • Recent observation: Major tropical cyclones have struck Madagascar approximately once every three years since 1998. In January and February 2022 alone, four cyclones hit the island, two of which were category 3-4 events.

Table 2: Table of Parameters and Values

Parameter	Value
Public infrastructure investment to GDP ratio	0.052
Consumption tax rate (VAT)	0.2
Labor income tax rate	0.21
Remittances to GDP ratio	0.048
Imports to GDP ratio	0.234
Trend per capita growth rate in absence of natural disasters	0.05
Efficiency of public infrastructure investment	0.31
Depreciation rate of public capital (standard infrastructure)	0.075
Depreciation rate of public capital (adaptation)	0.03
Years of Disasters	2027

Source: Author calculations

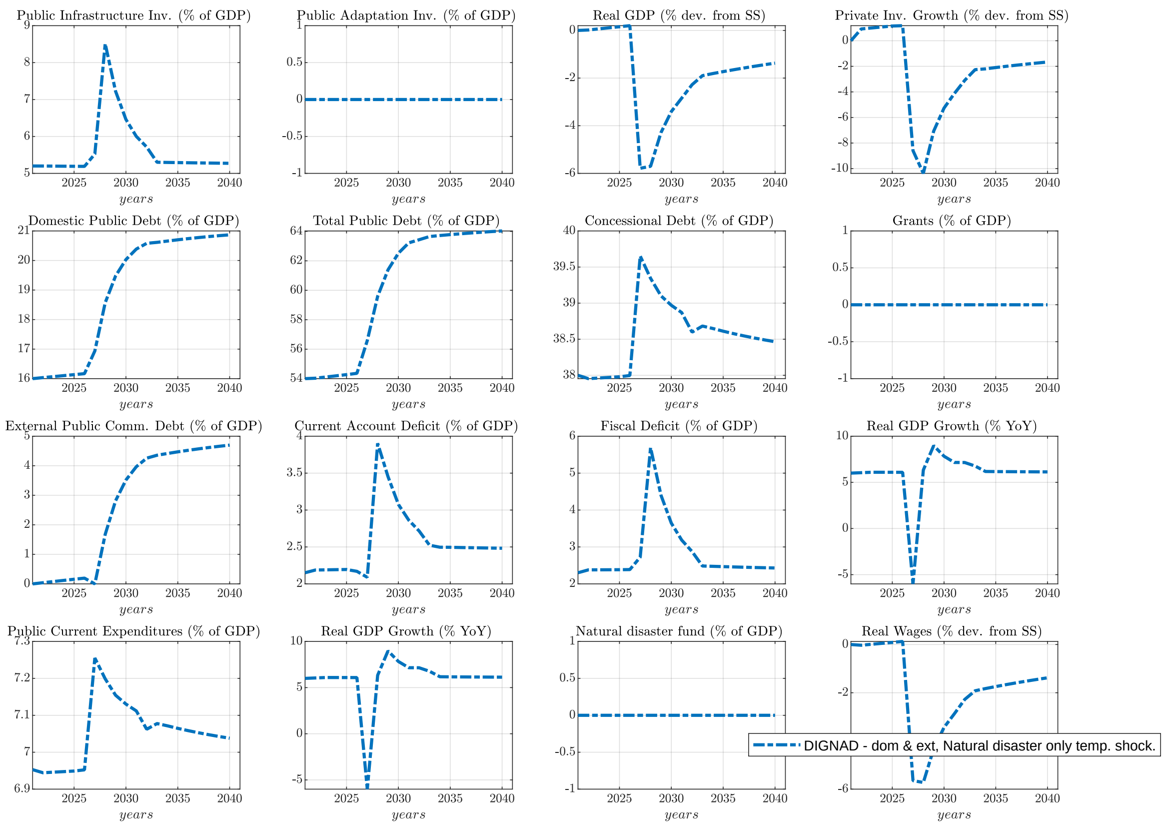

Figure 3: Result of the scenario zero

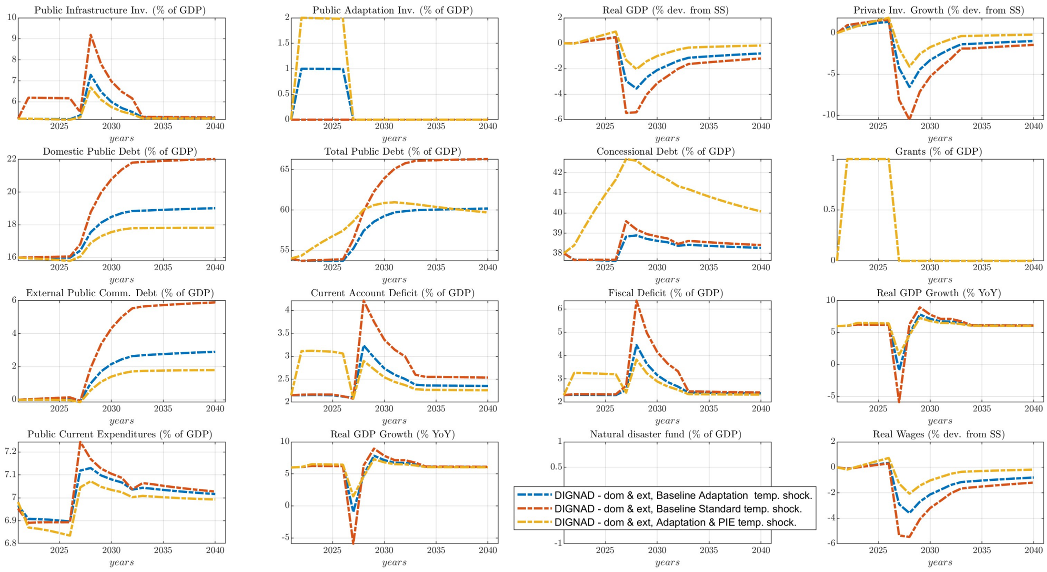

Figure 4: Result of the 3 scenarios