Sep, 2025
GRINS DISCUSSION PAPER SERIES DP N° 52/2025 ISSN 3035-5576

GRINS

Breaking the economy: how climate tail risk and financial conditions can shape loss persistence and economic recovery

DP N° 52/2025

Authors:
Andrea Mazzocchetti, Irene Monasterolo, Nepomuk Dunz, Arthur Hrast Essenfelder

Sep, 2025
GRINS DISCUSSION PAPER SERIES DP N° 52/2025 **ISSN 3035-5576**

Breaking the economy: how climate tail risk and financial conditions can shape loss persistence and economic recovery

Andrea Mazzocchetti, Irene Monasterolo, Nepomuk Dunz, Arthur Hrast Essenfelder

KEYWORDS

Climate tail risk | Shock persistence | Public debt | Credit constraints | Economic recovery | Stock-Flow Consistent model

ACKNOWLEDGEMENTS

This study was funded by the European Union - NextGenerationEU, in the framework of the GRINS - Growing Resilient, INclusive and Sustainable project (GRINS PE00000018). The views and opinions expressed are solely those of the authors and do not necessarily reflect those of the European Union, nor can the European Union be held responsible for them.

CITE THIS WORK

Title: Breaking the economy: how climate tail risk and financial conditions can shape loss persistence and economic recovery. Publication Date: 2025.

Acute physical risks are becoming increasingly frequent and intense, with future climate scenarios suggesting further escalation. These events can generate severe and potentially persistent economic losses, while placing growing pressure on public finances through rising disaster response and recovery expenditures. Yet, macroeconomic models often fall short in consistently capturing the economic and fiscal impacts of physical climate risks. In particular, they tend to overlook critical shock transmission channels and the full implications of extreme weather events, resulting in an incomplete picture of disaster-related losses and recovery needs. This, in turn, limits our ability to assess the climate insurance protection gap and to design effective and financially viable public policy responses. To help close this gap, we adapt and extend EIRIN, a macro-financial Stock-Flow Consistent (SFC) model of an open economy, tailored at the national level. EIRIN features a limited number of heterogeneous agents across the real and financial sectors, which are integrated through a network of interlinked balance sheet positions grounded in real-world data, and governed by bounded rationality. This framework allows us to examine how climate tail risks, in conjunction with fiscal and credit constraints, can trigger persistent macroeconomic disruptions. We apply the model to Italy, a country particularly vulnerable to natural disasters, fiscal fragilities, and high public debt. Our findings show that extreme weather events causing a 15% destruction in firms' capital stock, combined with constrained credit conditions, can lead to deep and prolonged declines in GDP growth and a significant rise in public debt. These adverse effects are further exacerbated in the absence of targeted adaptation strategies and climate-aligned financial policies.
Keywords: Climate tail risk; Shock persistence; Public debt; Credit constraints; Economic recovery; Stock-Flow Consistent model

Finanziato dall'Unione europea
NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Discussion Paper Series

Breaking the economy: how climate tail risk and financial conditions can shape loss persistence and economic recovery

Discussion paper n. 52/2025

Andrea Mazzocchetti (a), Irene Monasterolo (b,c,d), Nepomuk Dunz (e), Arthur Hrast Essenfelder (f)

(a) Ca' Foscari University of Venice, (b) Utrecht University School of Economics, (c) Centre for Economic Policy Research, (d) Institute for Ecological Economics, (e) World Bank, (f) European Commission, Joint Research Centre Ispra

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
GRINS FOUNDATION

ISSN 3035-5567

Breaking the economy: how climate tail risk and financial conditions can shape loss persistence and economic recovery

Andrea Mazzocchetti (a), Irene Monasterolo (b,c,d), Nepomuk Dunz (e), Arthur Hrast Essenfelder (f)

(a) Ca' Foscari University of Venice, (b) Utrecht University School of Economics, (c) Centre for Economic Policy Research, (d) Institute for Ecological Economics, (e) World Bank, (f) European Commission, Joint Research Centre Ispra

Discussion Paper DP n°52/2025

Acute physical risks are becoming increasingly frequent and intense, with future climate scenarios suggesting further escalation. These events can generate severe and potentially persistent economic losses, while placing growing pressure on public finances through rising disaster response and recovery expenditures. Yet, macroeconomic models often fall short in consistently capturing the economic and fiscal impacts of physical climate risks. In particular, they tend to overlook critical shock transmission channels and the full implications of extreme weather events, resulting in an incomplete picture of disaster-related losses and recovery needs. This, in turn, limits our ability to assess the climate insurance protection gap and to design effective and financially viable public policy responses. To help close this gap, we adapt and extend EIRIN, a macro-financial Stock-Flow Consistent (SFC) model of an open economy, tailored at the national level. EIRIN features a limited number of heterogeneous agents across the real and financial sectors, which are integrated through a network of interlinked balance sheet positions grounded in real-world data, and governed by bounded rationality. This framework allows us to examine how climate tail risks, in conjunction with fiscal and credit constraints, can trigger persistent macroeconomic disruptions. We apply the model to Italy, a country particularly vulnerable to natural disasters, fiscal fragilities, and high public debt. Our findings show that extreme weather events causing a 15% destruction in firms' capital stock, combined with constrained credit conditions, can lead to deep and prolonged declines in GDP growth and a significant rise in public debt. These adverse effects are further exacerbated in the absence of targeted adaptation strategies and climate-aligned financial policies.

Keywords: Climate tail risk; Shock persistence; Public debt; Credit constraints; Economic recovery; Stock-Flow Consistent model

This study was funded by the European Union - NextGenerationEU, in the framework of the GRINS - Growing Resilient, INclusive and Sustainable project (GRINS PE00000018 - CUP D13C22002160001). The views and opinions expressed are solely those of the authors and do not necessarily reflect those of the European Union, nor can the European Union be held responsible for them.

Breaking the economy: how climate tail risk and financial conditions can shape loss persistence and economic recovery

Andrea Mazzocchetti[a], Irene Monasterolo[b,c,d], Nepomuk Dunz[e], Arthur Hrast Essenfelder[f]

[a] *Ca' Foscari University of Venice*
[b] *Utrecht University School of Economics, Utrecht University*
[c] *Centre for Economic Policy Research (CEPR)*
[d] *Institute for Ecological Economics, Vienna University of Economics and Business (WU)*
[e] *World Bank*
[f] *European Commission, Joint Research Centre Ispra*

Abstract

Acute physical risks are becoming increasingly frequent and intense, with future climate scenarios suggesting further escalation. These events can generate severe and potentially persistent economic losses, while placing growing pressure on public finances through rising disaster response and recovery expenditures. Yet, macroeconomic models often fall short in consistently capturing the economic and fiscal impacts of physical climate risks. In particular, they tend to overlook critical shock transmission channels and the full implications of extreme weather events, resulting in an incomplete picture of disaster-related losses and recovery needs. This, in turn, limits our ability to assess the climate insurance protection gap and to design effective and financially viable public policy responses. To help close this gap, we adapt and extend EIRIN, a macro-financial Stock-Flow Consistent (SFC) model of an open economy, tailored at the national level. EIRIN features a limited number of heterogeneous agents across the real and financial sectors, which are integrated through a network of interlinked balance sheet positions grounded in real-world data, and governed by bounded rationality. This framework allows us to examine how climate tail risks, in conjunction with fiscal and credit constraints, can trigger persistent macroeconomic disruptions. We apply the model to Italy, a country particularly vulnerable to natural disasters, fiscal fragilities, and high public debt. Our findings show that extreme weather events causing a 15% destruction in firms' capital stock, combined with constrained credit conditions, can lead to deep and prolonged declines in GDP growth and a significant rise in public debt. These adverse effects are further exacerbated in the absence of targeted adaptation strategies and climate-aligned financial policies.

Keywords: Climate tail risk; Shock persistence; Public debt; Credit constraints; Economic recovery; Stock-Flow Consistent model

---

1. Introduction

Climate-related disasters and extreme-weather events such as heatwaves, floods, and droughts are increasingly urgent global concern (WMO, 2024). Over the last five decades, the frequency of such events has increased fivefold (WMO, 2021). Between 2000 and 2019 alone, they caused approximately 1.2 million fatalities, affected 3.2 billion people, and generated over 1.6 trillion US dollars in economic losses (CRED, 2021). Future projections of the climate system indicate that extreme weather events are likely to intensify and become more frequent as the planet gets warmer (Seneviratne et al., 2021). This trend poses growing risks to both populations and economies (Birkmann et al., 2022), while also forcing governments to face increased public expenditures for disaster response and recovery (Bayar and Yarbrough, 2024), thus potentially straining public finances and affecting fiscal and financial risk management (OECD and WBG, 2019).

In the past decade, significant progress has been made in undertanding and modeling the direct effects of climate-related disasters, particularly acute physical risks (NGFS, 2019), through empirical and theoretical studies (Noy, 2009; Hsiang, 2016; Botzen et al., 2019; Kalkuhl and Wenz, 2020; Gourdel et al., 2024; Kotz et al., 2024; Waidelich et al., 2024). However, the tail risk dimension of these events remains largely unexplored, as it does its impacts on the economy and financial system. Many macroeconomic models so far project limited climate-related physical impacts and struggle to capture the full range of transmission channels, often neglecting the full extend of not viewing climate impacts as macro-critical threats to economic and financial stability (Woillez et al., 2020; IPCC, 2021, 2022). Moreover, the conditions under which fiscal and financial interventions either exacerbate the persistence of economic losses or, conversely, facilitate a smooth recovery during the post-disaster reconstruction received little attention. Existing research has largely focused on the one-sided direction of the impact of temperature increase in the economy. However, the dynamic interplay between acute climate tail risks, governments' fiscal policies (and fiscal space) and banks' credit conditions can lead to shock persistence, particularly in the context of compound risk (Dunz et al., 2023b). These interaction may trigger cascading economic (e.g. employment and GDP), social (e.g. inequality) and financial (e.g. credit risk) impacts (Carter et al., 2021). Cascading impacts may amplify losses substantially, and when not accounted for can lead to inaccurate assessment of risk, and of the adequate policy actions (e.g. climate change adaptation) (Hallegatte, 2015; Bressan et al., 2022). Socio-economic damages of climate-related disasters keep increasing in a warming climate also in high-income countries (ECB-EIOPA, 2023), which also face more stringent fiscal and financial conditions to spend in the recovery (see e.g. the European Union (EU) revised fiscal compact rules, Darvas et al. (2023)), challenging the post-disaster economic recovery.

In this context, it is essential to assess the conditions under which climate tail risks, coupled with sovereign fiscal and financing conditions, could disrupt a economy's growth trajectory and persist in the mid term, what we call *breaking the economy.* To address this knowledge gap, we study the condition for climate-related disasters to break the economy, preventing a full recovery in the short to mid-term (i.e. a 25 years' time horizon). In particular, we analyse *"How resilient a country's economy is given a dynamic, systemic view on the interactions between acute tail risk, fiscal and financial stability conditions?"*. Similarly to stress-testing exercises, which analyse how bad it could get for the balance sheets of individual investors and of the financial system conditioned to the occurrence of very adverse scenarios, here we analyse how bad it could get for the economy of a country conditioned to the occurrence of high-end climate risk scenarios that lead to very adverse impacts in capital stock (being the entry point of the shock in the economy). Therefore, we contribute to the literature by providing an approach to assess the macrofinancial implications of tail risks, which plays a main role in the context of analysis of tipping points, thus complementing the existing literature.

Addressing this question is important to understand:

- Under which conditions tail climate risk could lead breaking points in the economy that lead to a persistence of the shock and prevent the recovery in the short to mid term (25 years)
- To what extent the compounding of supply shocks (capital stock destruction) and impaired macro-financial conditions shocks (e.g. banks' credit constraints) could amplify the magnitude and duration of the impact of the climate-related disaster (see e.g. Ranger et al. (2021) and Simpson et al. (2021))

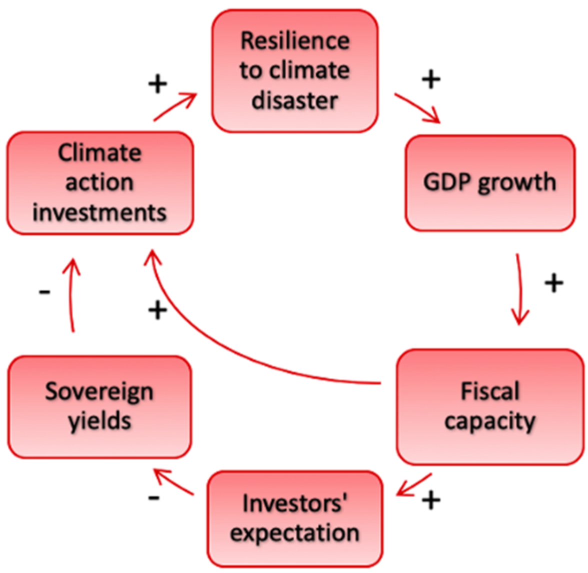

Figure 1: Climate-economy-finance feedback loops. The arrows indicate the causal relationships, while the signs indicate the direction of the corresponding effects, either reinforcing (+) or balancing (-). Source: adapted from Monasterolo et al. (2024).

.

This information, in turn, can support the design of policy measures aimed to increase socio-economic competitiveness and sovereign financial stability against growing climate impacts. In this regard, Figure 1 shows the feedback loops between climate risks, economic competitiveness and sovereign financial stability. By sustaining fiscal capacity, early climate adaptation interventions contribute to improve investors' expectations about the country's climate risk, lowering its perceived solvency risk. This, in turn, would translate into lower yields on debt and lower cost to finance climate investments, reinforcing the positive effect of greater fiscal capacity. On the contrary, in absence of timely adaptation actions, multiple equilibria could arise, and the economy may be trapped in an inefficient equilibrium of low climate investment and resilience, low growth and high sovereign solvency risk.

Filling this knowledge gap is essential to support informed decision-making for the design of effective adaptation policies and coherent climate adaptation investment strategies. Understanding the conditions under which an economy may experience persistent disruptions that hinder recovery is particularly important for: (i) quantifying adaptation investment needs and priorities within the territory, especially under climate change scenarios that include tail risks, (ii) identifying optimal fiscal and financial policy responses to build resilience to climate change, such as expanding the EU fiscal spending (Becker et al., 2023), issuing joint EU debt (Monasterolo et al., 2024), deploying public guarantees[1]), and fostering mixed public and private interventions (such as insurance products for banks that lend to firms in affected areas for reconstruction, with the support of government's guarantee), and (iii) designing financial risk management policies (ECB/ESRB, 2023).

We focus on assessing the macro-financial implications of climate tail risks, which are especially relevant for analyzing climate tipping points. We evaluate how extreme climate scenarios could affect a country's economy. These high-end scenarios involve significant adverse effects on capital stock, a key transmission channel through which physical hazards translate into economic and financial losses at the firm level (NGFS, 2020; Semieniuk et al., 2021), and consequently into fiscal strain (Gourdel et al., 2024). Therefore, we focus on

[1]See e.g. the Austrian Katastrophenfonds`https://www.bmf.gv.at/themen/budget/finanzbeziehungen-laender-gemeinden/katastrophenfonds.html`

high-end, adverse scenarios to understand the magnitude of shock required to significantly disrupt our model economy's growth trajectory. While the shock sizes we simulate may appear hypothetical when compared to historical damages to country-wide capital stock in advanced economies, recent events, such as the flood in Valencia or Austria, with return periods near one in 500 year event, show how such extremes are becoming more frequent across EUrope. In absence of climate insurance and adequate adaptation investments, and in presence of weaker regional resilience, the impact of shocks on capital could be significantly greater than in the past. It is also important to note that we consider only a limited set of transmission channels and a one-time acute climate shock event. In reality, climate change is likely to manifest as recurring acute and chronic events, suggesting that smaller, more frequent shocks could have similar disruptive effects.

We consider Italy as a case study due to its high exposure to climate acute physical risks (in particular floods, droughts, and heatwaves), which have already caused major economic losses in key productive sectors, such as the agri-food district of the Emilia-Romagna region. Despite this vulnerability, Italy has one of the lowest natural disaster insurance protection coverages in the EU (around 3% of the total insured assets) (ECB-EIOPA, 2023). In addition, Italy exited the COVID-19 crisis and the energy price crisis with low fiscal space, which is expected to shrink even further with the application of the revised Stability and Growth Path from 2024. Finally, Italy has one of the highest public debts in the EU[2], leaving the country with limited spending capacity for climate adaptation investments (e.g., water management to prevent floods, water reservoirs to dampen the impact of droughts, coastline defense against sea-level rise, etc.).[3] These fiscal and financial constraints severely limit the country's capacity to invest in climate adaptation measures, with negative implications on credit ratings. A reinforcing feedback loop between government spending on climate change, investors' risk perception (about the country's fiscal and financial stability) could then emerge. Notably, the Italian government has recently launched the proposal to introduce compulsory firms' insurance against climate-related disasters (Legge di bilancio 2024, Articolo 1, commi 101-111 "Misure in materia di rischi catastrofali").

We tailor and extend the EIRIN macro-financial SFC model (Dunz et al., 2023b; Gourdel et al., 2024), calibrating it to the Italian economy. EIRIN is a Stock-Flow Consistent behavioral model that is parsimonious in complexity and yet able to represent key structural and behavioral characteristics of countries' economies (e.g. credit demand and supply; monetary and fiscal policy decisions; households' consumption and investment decisions; capital requirements and risk management of financial actors). We use the model to identify under which conditions climate tail risk scenarios could lead to a persistent shock on macroeconomic variables, and the transmission channels to fiscal and sovereign financial stability. In particular, we analyze both supply-side and demand-side drivers that could contribute to a macroeconomic breakdown in the aftermath of extreme climate events.

The remainder of the paper is structured as follows. Section 2 describes the methodology, focusing on the main characteristics of the EIRIN model. Section 3 describes the model calibration on Italian data and the scenarios. Section 4 presents and discusses the simulation results. Section 5 concludes with recommendations for further research steps ahead in the assessment of climate tail risk and identification of the adaptation financing needs and tools, at the country level.

[2]See `https://ec.europa.eu/eurostat/web/products-euro-indicators/w/2-22102024-bp`
[3]Italy's public debt is expected to overtake the Greece's one in 2028 (141% in 2025, +4% in two years).

2. Methodology

2.1. Model overview

EIRIN is a macro-financial Stock Flow Consistent (SFC) model of an open economy populated by a limited number of heterogeneous agents and sectors of the real economy and financial system, each with distinct behavioral features. In the model, accounting criteria hold irrespective of behavioral characteristics and assumptions, thus allowing us to capture the dynamics of shocks and their transmission channels, and to increase the transparency and accountability of results. In the last decades, SFC models gained relevance in macroeconomics (Godley and Lavoie, 2006; Caverzasi and Godin, 2015; Caiani et al., 2016; Nikiforos and Zezza, 2017; Mazzocchetti et al., 2020). In the context of climate economics and finance (Dunz et al., 2023a; Ponta et al., 2018; Monasterolo and Raberto, 2019; Naqvi and Stockhammer, 2018; Carnevali et al., 2021; Dafermos et al., 2017) SFC models have been recently implemented to study the macro-financial effects of green financial policies and climate risks (Dafermos and Nikolaidi, 2021), of the transition in energy production systems (Jackson and Jackson, 2021) and of the macroeconomic opportunities and vulnerabilities emerging from the low-carbon transition (Moreno et al., 2024; Godin et al., 2023).

Advantages of the SFC structure of the EIRIN model include the possibility to capture:

- The entry point of a shock in the economy, the shock transmission channels to agents and sectors of the economy and finance, as well as the indirect or cascading impacts
- Rich behavioural rule of the agents, including the departure from rational expectations
- Financial sector dynamics and financial-macro feedback via risk assessment
- Differentiated impacts across high and low-carbon investments, high and low-resilience investments
- Endogenous money creation (banks create money through lending)
- The departure from a single optimal intertemporal equilibrium, which is important to analyse conditions for and implications of multiple equilibria

EIRIN's agents and sectors are modelled as a network of interconnected balance-sheet items, allowing us to identify climate risks' transmission channels in the economy and finance. Indeed, a clear understanding of the risk transmission channels is fundamental for the quantitative assessment of the direct and indirect impacts of climate risks on the economy, banking sector and sovereign. In particular, EIRIN agents are heterogeneous (e.g. in terms of skills, optimizing goals, wealth and income) and are characterized by bounded rationality and adaptive expectations about the future of the economy, i.e. they make projections based on past information and the present state of the economy, internalizing policy changes.

Adaptive expectations, in presence of heterogeneity, lead to time delayed and uncoordinated response to shocks, with implications on the size and the persistence of the economic impact. As a difference from models with rational expectations, in presence of adaptive expectations the economic shock (e.g. GDP) is larger and can be persistent in the mid-term. Given the fundamental uncertainty associated with future climate change, agents are likely to depend on heuristics, rules of thumb, and conventions as they are unable to assign probabilities for forming rational expectations. This forms the core rationale behind our model setup.

EIRIN allows us to consider how the uncertainty of climate risks and their impacts affect agents' heterogeneous beliefs, inter-temporal preferences, and investment decisions in response to shocks. Furthermore, since climate risks in the economy and finance can be characterised by non-linearity and tipping points (Lenton et al., 2019; Steffen et al., 2018), to consider the potential non-linearity of climate risks in the economy, and understand the conditions for persistence and hysteresis to emerge, is crucial. In this regard, EIRIN embeds the heuristics and behavioural patterns of agents and representative sectors that contribute to the generation of emerging phenomena and out-of-equilibrium states of the economy.

2.2. EIRIN agents and markets

EIRIN is composed by a limited number of heterogenous agents and sectors of the real economy and finance (figure 2), which interact in a number of markets (figure 3). In particular, EIRIN's agents and sectors include:

- a wage-earning household (H_W) and a capital income-earning household (H_K)
- a consumption goods (F_K) and a services sector (F_L) that produce for final consumption
- a high-carbon capital goods producer (K_B) and a low-carbon capital goods producer (K_G)
- a utility company that produces energy from fossil fuels (high-carbon, EN_B) and one that produces energy from renewables (low-carbon, EN_G)
- a mining and fossil fuel extraction company (MO)
- a commercial banking sector (BA)
- a government (G) in charge of fiscal policy and regulation (e.g. carbn tax), public debt issuance and management
- a central bank (CB) that sets the policy rate according to a Taylor-like rule (Taylor, 1993).
- the rest of the world (ROW) with which the economy trades commodities (e.g. raw materials), goods and services

The accounting framework of EIRIN is composed of three main matrices: i) a balance sheet matrix that accounts for all the stocks held by agents and sectors; ii) a transaction flow matrix that describes all the flows between agents and sectors at each period; iii) a net worth change matrix that shows how sectors' net worth changes due to both net cash flows and the price changes of financial assets.[4] EIRIN's accounting identities represent structural specifications that have to be fulfilled at any time step in the model simulation, thus providing relevant binding constraints for the model dynamics. Therefore, the SFC constraints contribute to strengthen both the model and code validation, and the transparency and accountability of results, overcoming a main limitation of simulation models. Moreover, the rigorous SFC accounting framework allows us to display the dynamic relations between agents and sectors' balance sheets, and to analyse in a consistent way the chains of causation and transmission channels throughout the economy. The capital and current account flows of the model are presented in figure 2. The EIRIN model is initialised with calibrated quantities for each balance sheet entry and each parameter which determines the functional form of the behavioural equations. Consequently, the model is simulated for a predetermined number of periods within which it converges to stability. In the current setting each period represents a quarter.[5]

[4]See Appendix A in Mazzocchetti et al. (2025)

[5]For an overview of the agents and sectors' behavioural characteristics see Mazzocchetti et al. (2025)

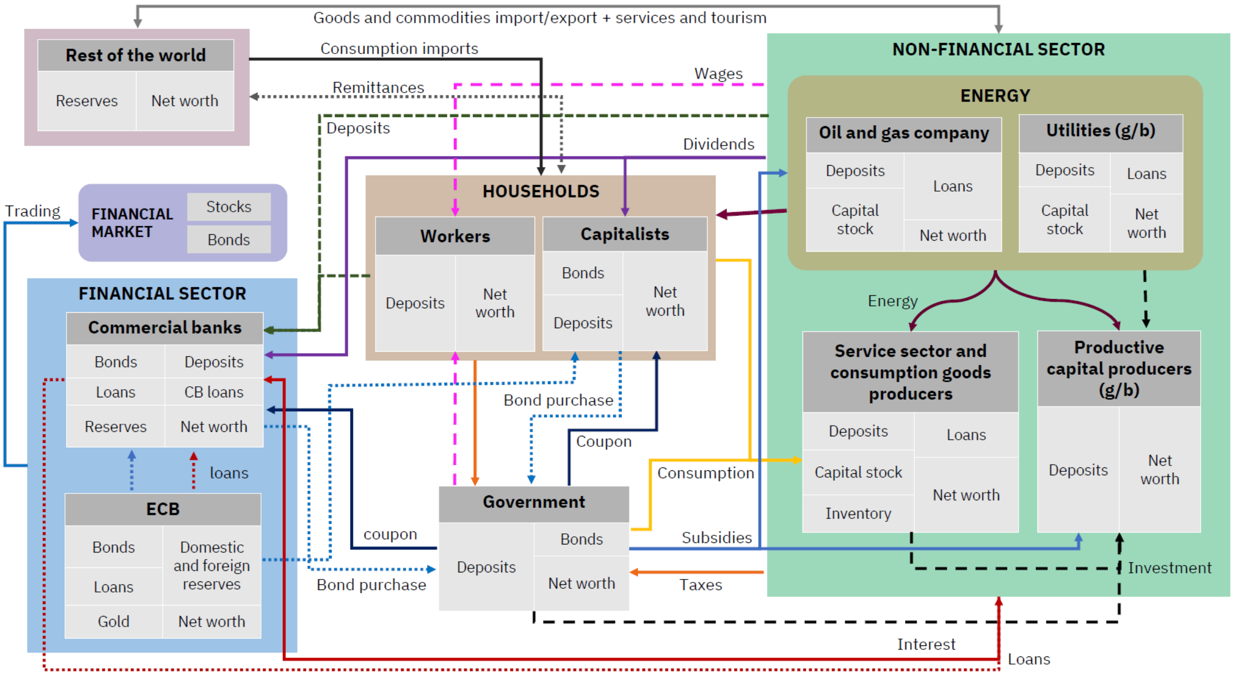

Figure 2: The EIRIN model framework: capital and current account flows of the EIRIN economy.
For each sector and agent of the economy and finance, a representation in terms of their balance sheet entries (i.e. assets and liabilities) and their connections, is provided. The dotted lines represent the capital account flows, while the solid lines represent the current account flows.
Source: Authors' own elaboration.

In figure 3 we display the main agents and sectors of the EIRIN economy (grey boxes), and the markets through which they interact. In particular, financial markets (light blue box) include the markets for government bonds and stock shares (see Monasterolo et al. (2022) for details), and the credit market. The real markets (wheat box) include consumption goods and service markets, the labor market, the energy market, the tourism market, the capital goods markets, and the raw material market (oval boxes).

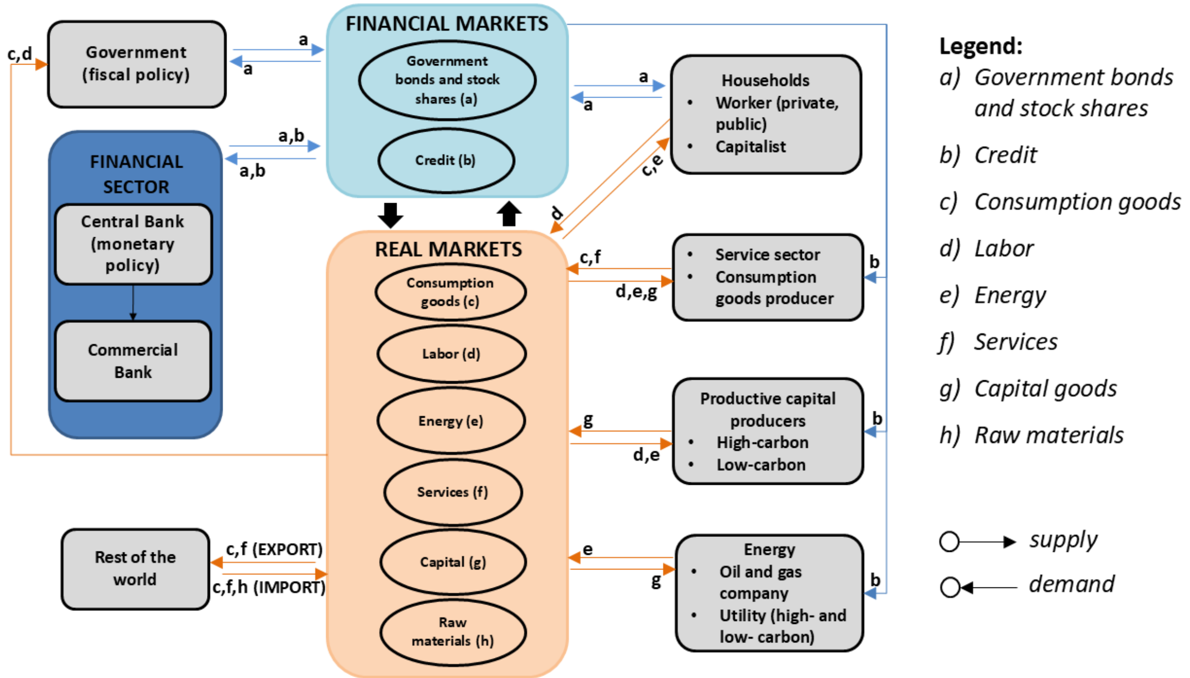

Figure 3: Agents, sectors and markets of the EIRIN economy.
Black boxes include agents and sectors, the light blue box contains financial markets and the light orange box includes the real markets. The agents and sectors interact through real and financial markets; outgoing arrows represent supply, while incoming arrows represent demand.
Source: Authors' own elaboration.

3. Model calibration and scenarios

3.1. Model dimensioning and calibration

We initialize and calibrate the EIRIN model to the selected characteristics of the Italian data. We rely on official data and forecasts provided by European Commission, by the IMF and by the OECD.[6]

The model depends on more than 100 parameters, and the calibration is split into two sets of parameters and benchmark values. The first part considers parameters that appear explicitly in the model dynamics and are also observable from data (for example, tax rates on labour income, corporate or dividends). The second part consists of ex-post calibration of the stable level of the economy, which is crucial to adjust the endogenous behaviour of the model to mimic realistic dynamics. It relies on a set of free parameters that cannot be observed directly and, thus, are set to allow for endogenously produced time series that match observed data, such as GDP, debt to GDP, etc. In this second part of the calibration, we initialize the model to a state where key dynamics are stable. This represents a baseline scenario in which the economy keeps on evolving following a stable growth path.

In table 1, we present a set of outcomes of this second-step calibration by comparing the model's indicator means with economic forecast for 2024, which serve as benchmark values to calibrate the model.

Our double calibration strategy allows us to ensure that the modelled economy produces outcomes in line with the ones observed in reality, when subjected to the same policy variables. For all parameters, it is possible to test the impact of deviations on key outputs, including GDP growth, inflation and debt to GDP.

Variable	**Model value (2024)**	**Economic forecast (2024)**
Real GDP growth rate (%)	1.08	0.9
Public debt (% of GDP)	136.22	138.6
Gov consumption (% of GDP)	18.54	19.55
Inflation rate (% YoY)	1.2	1.6
Public deficit (% of GDP)	4.7	4.4

Table 1: Calibration of EIRIN on the Italian economy.
The first column reports the 2024 values compared the economic forecast of the European Commission (https://economy-finance.ec.europa.eu/economic-surveillance-eu-economies/italy/economic-forecast-italy_en).

3.2. Climate physical risk scenarios

We consider the impact of a natural hazard that enters the economy by destroying productive capital, thus reducing production (direct impact), since the capital is an input factor for firms. Capital stock destruction represents a supply shock that limits firms' ability to serve demand in the aftermath of the impact, with cascading impacts on unemployment, debt to GDP and firms' financial conditions (indirect impact). We simulate a single event leading to a capital stock destruction of either 5% or 15% in four quarters.

In addition to the natural hazard, we take into account also the financial conditions in the aftermath of the shocks. In particular, we consider scenarios in which the banking sector is not providing the required credit needed by the firms for reconstruction purposes. This is modeled as the banking sector constraining credit in the year following the shocks. We assume that the banking sector provides only a share of required credit by the firm (no credit constraints imposed, 50% credit constraints imposed, 100% credit constraints imposed), which need to borrow to invest and recover from the capital losses.

[6]See https://economy-finance.ec.europa.eu/economic-surveillance-eu-economies/italy/economic-forecast-italy_en, https://www.imf.org/en/Publications/WEO/Issues/2024/04/16/world-economic-outlook-april-2024 and https://data.oecd.org/ respectively.

4. Discussion of results

We employ the EIRIN model to analyse both the direct and indirect impacts of extreme natural hazards, along with the key transmission channels through which these shocks affect the economy and financial sector. Furthermore, we explore the macro-financial conditions that may amplify these shocks, potentially resulting in persistent economic disruptions and incomplete recoveries over the long term.

Our analysis focuses primarily on the destruction of capital stock, which is one of the most frequently observed immediate consequences of flooding. We test the shocks in capital stock occurring for 4 consecutive quarters in 2025. Additionally, we evaluate the macro-financial conditions by examining the impact of compounding financial constraints. This is quantified by the ratio of credit extended to credit requested, reflecting the reality that firms' ability to rebuild post-disaster, often a driver of robust GDP growth and recovery, is contingent upon their access to financing for such investments. Notably, the baseline scenario assumes no credit constraint, representing the most optimistic scenario.

Our study aims to identify the conditions under which an economy fails to return to its pre-shock growth path, a state we define as the economy 'breaking'. To this end, we examine the varied effects of different levels of capital stock destruction and financial constraints post-shock. Figure 4 shows the impact of these variables on real GDP, represented as the average over the five years following the shock. As expected, the figure reveals that greater destruction of capital stock correlates with more significant reductions in GDP. Yet the relationship is not linear: larger capital losses generate disproportionately larger economic impacts. This is due to a decrease in demand, which leads firms to downscale their capacity requirements, subsequently lowering their expectations for demand and investment. This dynamic is exacerbated and can lead to the economy 'breaking', measured by permanently subdued GDP and unsustainable public debt amounts (Figure 5), when credit constraints become an insurmountable barrier for businesses.

4.1. Acute Physical risk and financial constraints

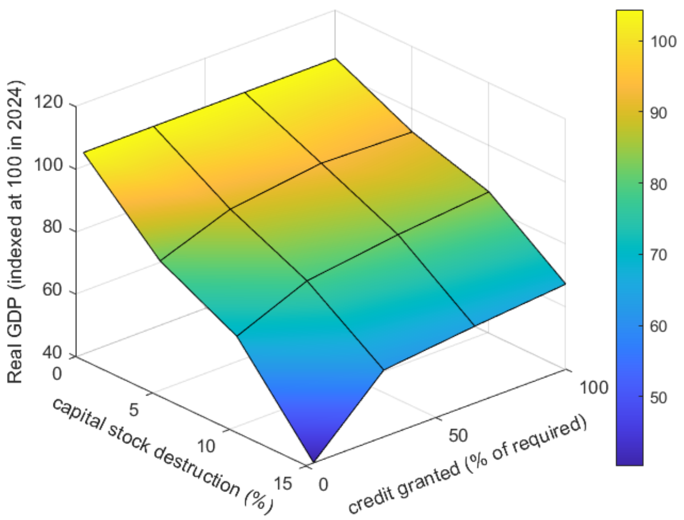

Figure 4: Real GDP - 3D plot. Mean of real GDP over 5 years following the climate-related shock, indexed on pre-shock level (pre-shock(2024)=100). The x-axis includes the share of credit granted by the banking sector over the firms' demanded credit. The y-axis shows the share of firms' destroyed capital. The z-axis includes the real GDP, indexed at 100 in 2024.
Source: Authors' own elaboration.

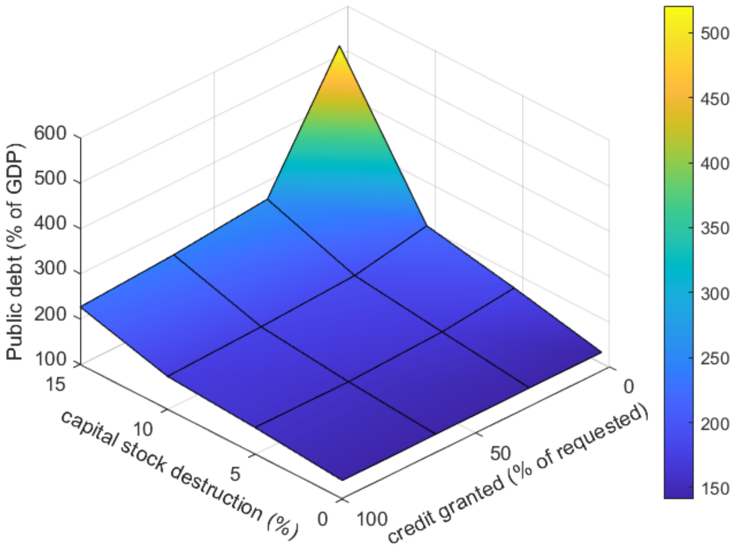

Figure 5: Debt to GDP - 3D plot. Mean of public debt to GDP ratio over 5 years following the shock. The x-axis includes the share of credit granted by the banking sector over the firms' demanded credit. The y-axis shows the share of firms' destroyed capital. The z-axis includes the debt to GDP ratio.
Source: Authors' own elaboration.

In the scenario featuring a 5% loss in capital stock, a significant amount by historical standards for Italy, the economy exhibits a notable capacity for recovery, gradually converging back toward its business-as-usual (BAU) growth path within approximately twenty years (Figure 6). This recovery is primarily driven by a surge in post-disaster investment (Figure 10), which boosts GDP dynamics and facilitates the stabilization of public debt levels (Figure 7) and unemployment (Figure 8) in line with pre-shock trends. In addition, results show an increase in the probability of default (PD) among firms, as indicated in Figure 9, due to the necessity for higher credit and leverage to finance their recovery efforts. When credit constraints are introduced, particularly at the extreme of 100%, the economic outlook dims, with dampened GDP growth, elevated public debt, and higher unemployment rates. The probability of default for firms is subject to two opposing forces. On one hand, stringent credit constraints hinder firms' recovery capabilities, leading to reduced overall indebtedness. On the other hand, the weakened economic environment increases firms' default risk. In the scenario with 50% credit constraints, these effects counterbalance each other, resulting in PD levels comparable to those in the scenario without credit constraints. However, in the 100% credit constraint scenario, the adverse impact of a sluggish economy on PDs overshadows the effect of reduced credit volume.

When the economy experiences a 15% loss in productive capital, the macroeconomic consequences intensify sharply and exhibit a non-linear pattern. Such a large-scale shock triggers a strong and immediate contraction in GDP, which is further exacerbated over time by a prolonged economic downturn. While the initial decline is caused by a supply-side disruption, due to insufficient capacity to meet demand, the extended downturn emerges from a contraction in aggregate demand. This demand shortfall stems from higher unemployment and lower labor income, which in turn cause investment behavior to become more erratic before recovery investments can stabilize GDP growth. Despite these efforts, the overall GDP fails to catch up with the Business-As-Usual (BAU) scenario due to hysteresis effects that permanently dampen aggregate demand. As a result, unemployment levels (Figure 8), public debt (Figure 7), and the probability of default (Figure 9) remain high. These dynamics are further exacerbated when credit is constrained, expecially in the immediate aftermath of the disaster. Under such conditions, the negative economic impacts are long-lasting, preventing the economy from returning to its previous growth trajectory for decades. Under these worst-case conditions, macroeconomic indicators stabilize at levels significantly below pre-shock trends: real GDP remains about 60% below the BAU baseline, while public debt and unemployment continue to rise, and the probability of default among firms increases steadily in the following years.

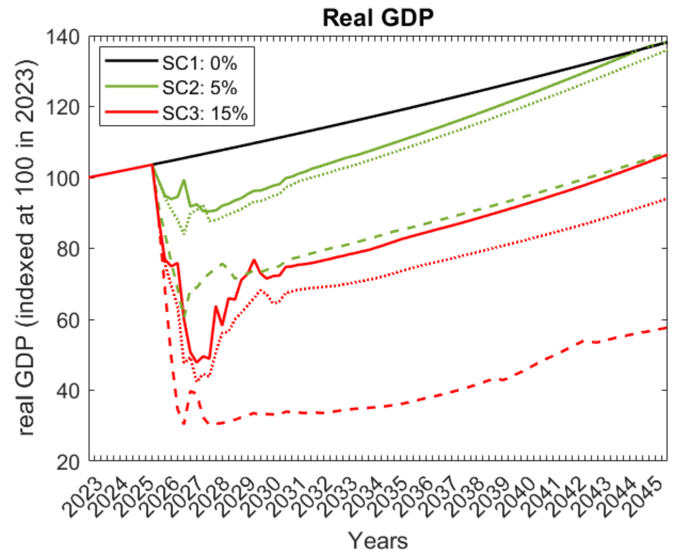

Figure 6: Real GDP including capital stock destruction and credit rationing. The solid lines represent the scenario without credit constraints. The dotted lines represent the scenarios including 50% of credit constraints, while dashed lines represent the scenarios including 100% of credit constraints.
Source: Authors' own elaboration.

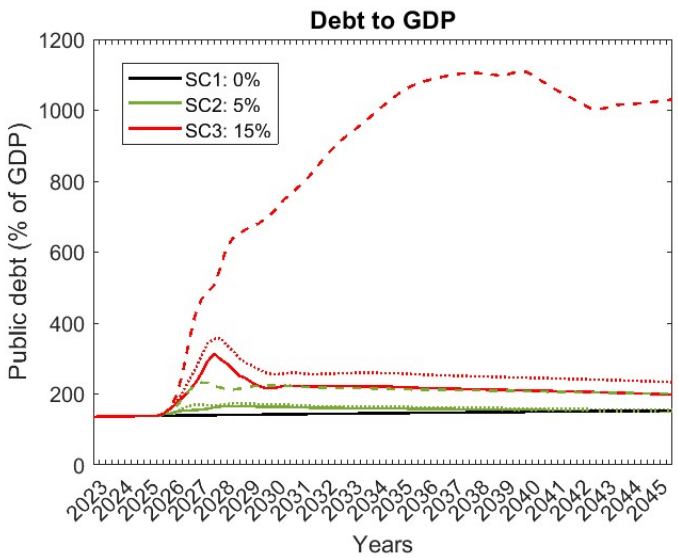

Figure 7: Real GDP including capital stock destruction and credit rationing. The solid lines represent the scenario without credit constraints. The dotted lines represent the scenarios including 50% of credit constraints, while dashed lines represent the scenarios including 100% of credit constraints.
Source: Authors' own elaboration.

In light of the analysis presented, it becomes evident that banks play a crucial role in mitigating the aftermath of economic shocks, such as those caused by climate-related extreme events. By acting counter-

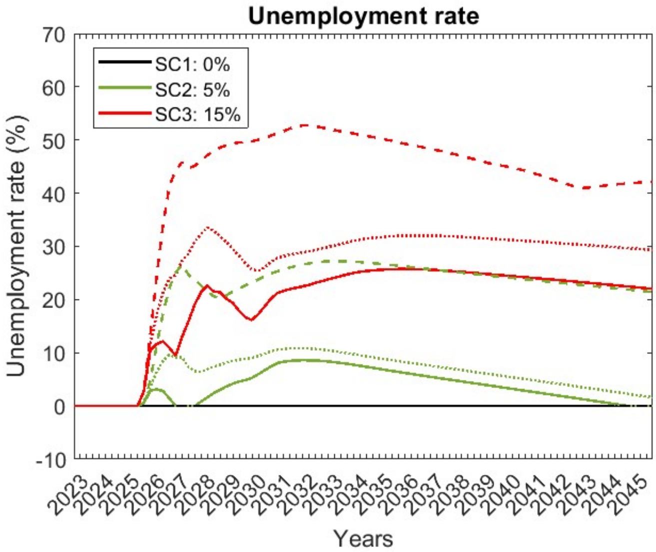

Figure 8: Unemployment rate including capital stock destruction and credit rationing. The solid lines represent the scenario without credit constraints. The dotted lines represent the scenarios including 50% of credit constraints, while dashed lines represent the scenarios including 100% of credit constraints.
Source: Authors' own elaboration.

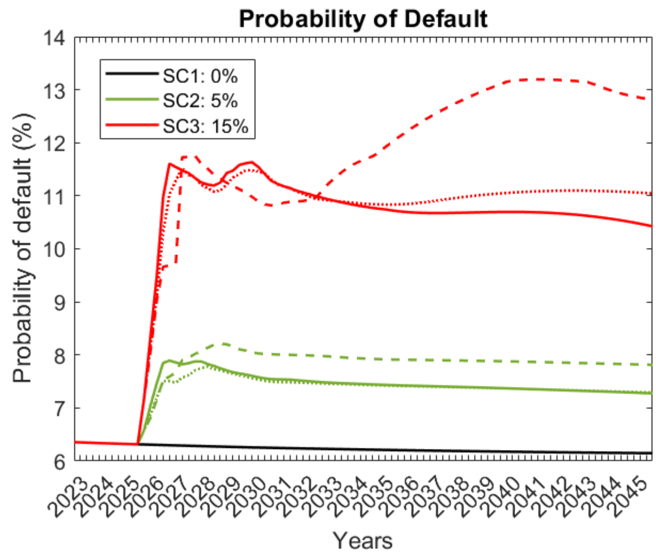

Figure 9: Firms' probability of default including capital stock destruction and credit rationing. The solid lines represent the scenario without credit constraints. The dotted lines represent the scenarios including 50% of credit constraints, while dashed lines represent the scenarios including 100% of credit constraints.
Source: Authors' own elaboration.

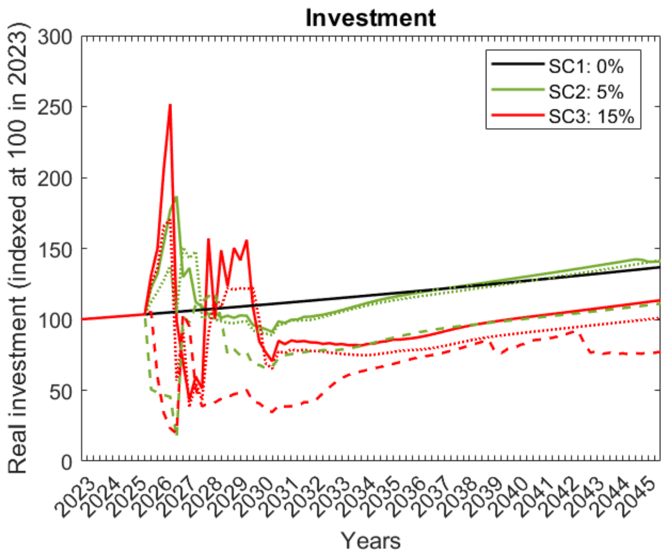

Figure 10: Firms' investment including capital stock destruction and credit rationing. The solid lines represent the scenario without credit constraints. The dotted lines represent the scenarios including 50% of credit constraints, while dashed lines represent the scenarios including 100% of credit constraints.
Source: Authors' own elaboration.

cyclically, banks can provide the necessary credit to firms seeking to rebuild and recover, thereby facilitating a return to stable economic growth. The ability of banks to perform this function is highly dependent on their financial health; sound financial buffers are essential to absorb the increased risks during crises without compromising their operational stability.

For policymakers, the implications are clear: there is a need to support regulatory frameworks that encourage banks to maintain robust capital reserves during economic upturns, which can then be drawn upon in times of crisis. Furthermore, policies that promote rapid and flexible credit extension to creditworthy firms after shocks can help sustain investment and consumption, thus shortening the duration of economic downturns. Furthermore, developing comprehensive risk assessment models that account for non-linear effects of capital stock destruction and credit constraints on the economy can guide more effective policy interventions.

5. Conclusions

This paper examines how severe climate shocks, particularly acute physical risks, can generate persistent macroeconomic disruptions when combined with constrained financial conditions and delayed recovery responses. Using the EIRIN Stock-Flow Consistent (SFC) behavioral model, calibrated to the Italian economy, we analyze high-impact scenarios in a country highly exposed to natural hazards, with limited fiscal space and low insurance coverage, conditions that make adaptation more challenging and costly.

Our analysis emphasize the critical interplay between climate tail risks, financial stability, and economic resilience. By using the EIRIN macro-financial SFC model, we provide a methodology to (i) assess climate tail risks and their potential persistency in the economy, and (ii) inform the design of fiscal policy and financial regulation aimed to build system resilience to the threats posed by climate change and its compound with other systemic shocks.
We find that severe impacts on capital stocks driven by climate tail risks can lead to sustained economic setbacks in the absence of adequate adaptation and mitigation strategies. These results show the importance of considering structural breaks and systemic vulnerabilities in the macroeconomic modeling of climate risks, as well as the urgent need for integrated approaches that address both climate risks and financial resilience.

Three main policy implications emerge. First, in the context of the economic scenarios analyzed, the role of financial policy in times of crisis is relevant. Banks, by acting countercyclically, can provide a lifeline to economies reeling from shocks, such as climate-related disasters. However, their capacity to do so depends on having substantial financial buffers in place. This, in turn, underscores the importance of forward-looking financial policies that not only address immediate recovery needs, but also contribute to build resilience against future risks. Second, policymakers should prioritize the development and implementation of robust climate adaptation measures and financial instruments to build resilience against these risks. Long-term investments in disaster risk reduction, adaptation infrastructure, and the introduction of accessible and comprehensive insurance schemes against climate-related disasters play an important role in enhancing economic resilience. These measures can reduce the impact of capital stock destruction, steer investors' expectations about the country's recovery, and thus foster a faster recovery through investments that significantly contribute to GDP growth and stabilization. Third, central banks and financial regulators should consider climate tail risk scenarios in their financial stability analyses (e.g. in the assessment of banks' capital reserves), and in the design of policies that promote a rapid and flexible credit extension in the post-disaster recovery. To this end, it is crucial to use adequate macro-financial models capable of assessing such risks in a comprehensive way.

Finally, our research highlights the importance of developing climate risk management strategies that are economically viable, socially equitable, and that promote adaptation to climate change. At the same time, it highlights the ongoing need to intensify global mitigation efforts to prevent the emergence of the most severe tail risks, where adaptation may reach its limits. By fostering a deeper understanding of the complex interactions between climate tail risks and economic systems, we can better prepare for and tame the adverse effects of climate change. This includes recognizing the non-linear and potentially long-lasting economic implications of such shocks. Addressing climate-related risks is not only an environmental necessity, but also a strategic economic priority for strengthening fiscal and financial resilience. In turn, safeguarding macro-financial stability in the face of climate change is fundamental to ensure sustainable development and long-term prosperity.

Future research steps in this direction include (i) a comprehensive approach that integrates acute and chronic risks, (ii) exploring additional financial, fiscal and economic conditions under which climate tail risks could persistently disrupt the economy's growth trajectory, and (iii) assessing the role of adaptive measures, financial policies, and insurance products in addressing the short-term impacts of climate-related physical risk, while promoting long-term sustainability.

References

Bayar, O., Yarbrough, T.R., 2024. The fiscal consequences of natural disasters: Evidence from the u.s. states. Public Finance Review 52, 222–252. URL: https://doi.org/10.1177/10911421231179535, doi:10.1177/10911421231179535.

Becker, H., Paetz, C., Watt, A., Watzka, S., in the Hans Boeckler Foundation, M.P.I.I., 2023. Reform der EU-Fiskalregeln: Kommissionsvorschlag erster Schritt in die richtige Richtung. IMK Kommentar, Hans-Böckler-Stiftung. URL: https://books.google.it/books?id=tl0IOAEACAAJ.

Birkmann, J., Liwenga, E., Pandey, R., Boyd, E., Djalante, R., Gemenne, F., Leal, F.W., Pinho, P., Stringer, L., Wrathall, D., 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press. chapter Poverty, livelihoods and sustainable development. Climate Change 2022: Impacts, Adaptation and Vulnerability, p. 1171–1274. URL: https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-8/, doi:10.1017/9781009325844.010.

Botzen, W., Deschênes, O., Sanders, M., 2019. The economic impacts of natural disasters: A review of models and empirical studies. Review of Environmental Economics and Policy doi:10.1093/reep/rez004.

Bressan, G., Duranovic, A., Monasterolo, I., Battiston, S., 2022. Asset-level assessment of climate physical risk matters for adaptation finance. SSRN 11. URL: http://dx.doi.org/10.2139/ssrn.4062275, doi:10.2139/ssrn.4062275.

Caiani, A., Godin, A., Caverzasi, E., Gallegati, M., Kinsella, S., Stiglitz, J.E., 2016. Agent based-stock flow consistent macroeconomics: Towards a benchmark model. Journal of Economic Dynamics and Control 69, 375–408. doi:https://doi.org/10.1016/j.jedc.2016.06.001.

Carnevali, E., Deleidi, M., Pariboni, R., Veronese Passarella, M., 2021. Cross-border financial flows and global warming in a two-area ecological SFC model. Socio-Economic Planning Sciences 75, 100819. doi:https://doi.org/10.1016/j.seps.2020.100819. decision-Making for Environmental Sustainability.

Carter, T.R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., Reyer, C.P., West, C., 2021. A conceptual framework for cross-border impacts of climate change. Global Environmental Change 69, 102307. URL: https://www.sciencedirect.com/science/article/pii/S0959378021000868, doi:https://doi.org/10.1016/j.gloenvcha.2021.102307.

Caverzasi, E., Godin, A., 2015. Post-keynesian stock-flow-consistent modelling: a survey. Cambridge Journal of Economics 39, 157–187. doi:https://doi.org/10.1093/cje/beu021.

CRED, 2021. The human cost of disasters - an overview of the last 20 years 2000-2019. URL: https://www.preventionweb.net/files/74124_humancostofdisasters20002019reportu.pdf.

Dafermos, Y., Nikolaidi, M., 2021. How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis. Journal of Financial Stability 54, 100871. doi:https://doi.org/10.1016/j.jfs.2021.100871.

Dafermos, Y., Nikolaidi, M., Galanis, G., 2017. A stock-flow-fund ecological macroeconomic model. Ecological Economics 131, 191–207. doi:https://doi.org/10.1016/j.ecolecon.2016.08.013.

Darvas, Z., Welslau, L., Zettelmeyer, J., 2023. Global economic impacts of physical climate risks. Imf Working Paper .

Dunz, N., Essenfelder, A., Mazzocchetti, A., Monasterolo, I., Raberto, M., 2023a. Compounding COVID-19 and climate risks: The interplay of banks' lending and government's policy in the shock recovery. Journal of Banking & Finance 152, 106306. doi:https://doi.org/10.1016/j.jbankfin.2021.106306.

Dunz, N., Hrast Essenfelder, A., Mazzocchetti, A., Monasterolo, I., Raberto, M., 2023b. Compounding covid-19 and climate risks: The interplay of banks' lending and government's policy in the shock recovery. Journal of Banking & Finance 152, 106306. URL: https://www.sciencedirect.com/science/article/pii/S0378426621002582, doi:https://doi.org/10.1016/j.jbankfin.2021.106306.

ECB-EIOPA, 2023. Policy options to reduce the climate insurance protection gaps. Discussion paper. ECB & EIOPA. URL: https://www.ecb.europa.eu/pub/pdf/other/ecb.policyoptions_EIOPA~c0adae58b7.en.pdf.

ECB/ESRB, 2023. Towards macroprudential frameworks for managing climate risk. Technical Report. ECB/ESRB Project Team on climate risk. URL: https://www.esrb.europa.eu/pub/pdf/reports/esrb.report202312~d7881028b8.en.pdf.

Godin, A., Yılmaz, D., Santos, A.M., 2023. Modelling low-carbon transitions in Colombia: Macrofinancial opportunities and risks. Agence Française de Développement (AFD), Paris, France. URL: https://afd.fr/en/ressources/modelling-low-carbon-transitions-colombia-macrofinancial-opportunities-and-risks. accessed: 2024-12-18.

Godley, W., Lavoie, M., 2006. Monetary economics: an integrated approach to credit, money, income, production and wealth. Springer.

Gourdel, R., Monasterolo, I., Dunz, N., Mazzocchetti, A., Parisi, L., 2024. The double materiality of climate physical and transition risks in the euro area. Journal of Financial Stability 71, 101233. URL: https://www.sciencedirect.com/science/article/pii/S1572308924000184, doi:https://doi.org/10.1016/j.jfs.2024.101233.

Hallegatte, S., 2015. The Indirect Cost of Natural Disasters and an Economic Definition of Macroeconomic Resilience. The World Bank. URL: https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-7357, doi:10.1596/1813-9450-7357, arXiv:https://elibrary.worldbank.org/doi/pdf/10.1596/1813-9450-7357.

Hsiang, S.M., 2016. Climate Econometrics. NBER Working Papers 22181. National Bureau of Economic Research, Inc. URL: https://EconPapers.repec.org/RePEc:nbr:nberwo:22181.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. URL: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf.

IPCC, 2022. Climate change 2022: Impacts, adaptation, and vulnerability - annex ii. URL: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Annex-II.pdf.

Jackson, A., Jackson, T., 2021. Modelling energy transition risk: The impact of declining energy return on investment (EROI). Ecological economics 185, 107023. doi:https://doi.org/10.1016/j.ecolecon.2021.107023.

Kalkuhl, M., Wenz, L., 2020. The impact of climate conditions on economic production. Evidence from a global panel of regions. Journal of Environmental Economics and Management 103, 102360. doi:https://doi.org/10.1016/j.jeem.2020.102360.

Kotz, M., Levermann, A., Wenz, L., 2024. The economic commitment of climate change. Nature 628, 551–557. URL: https://doi.org/10.1038/s41586-024-07219-0, doi:10.1038/s41586-024-07219-0.

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., Schellnhuber, H.J., 2019. Climate tipping points—too risky to bet against. Nature 575, 592–595.

Mazzocchetti, A., Lauretta, E., Raberto, M., Teglio, A., Cincotti, S., 2020. Systemic financial risk indicators and securitised assets: an agent-based framework. Journal of Economic Interaction and Coordination 15, 9–47. doi:10.1007/s11403-019-00268-z.

Mazzocchetti, A., Monasterolo, I., Dunz, N., Essenfelder, A.H., 2025. Breaking the economy: How climate tail risk and financial conditions can shape loss persistence and economic recovery. Ecological Economics 237, 108685. URL: https://www.sciencedirect.com/science/article/pii/S0921800925001685, doi:https://doi.org/10.1016/j.ecolecon.2025.108685.

Monasterolo, I., Dunz, N., Mazzocchetti, A., Gourdel, R., 2022. Derisking the low-carbon transition: investors' reaction to climate policies, decarbonization and distributive effects. Review of Evolutionary Political Economy 3, 31–71. doi:https://doi.org/10.1007/s43253-021-00062-3.

Monasterolo, I., Pacelli, A., Pagano, M., Russo, C., 2024. A European Climate Bond. Technical Report. CEPR Discussion Paper No. 18988. CEPR Press, Paris & London. URL: https://cepr.org/publications/dp18988.

Monasterolo, I., Raberto, M., 2019. The impact of phasing out fossil fuel subsidies on the low-carbon transition. Energy Policy 124, 355–370. doi:https://doi.org/10.1016/j.enpol.2018.08.051.

Moreno, A., Guevara, D., Andrade, J., Pierros, C., Godin, A., Yilmaz, S.D., Valdecantos, S., 2024. Low-carbon transition and macroeconomic vulnerabilities: A multidimensional approach in tracing vulnerabilities and its application in the case of colombia. International Journal of Political Economy 53, 43–66. URL: https://doi.org/10.1080/08911916.2024.2318995, doi:10.1080/08911916.2024.2318995, arXiv:https://doi.org/10.1080/08911916.2024.2318995.

Naqvi, A., Stockhammer, E., 2018. Directed technological change in a Post-Keynesian ecological macromodel. Ecological Economics 154, 168–188. doi:https://doi.org/10.1016/j.ecolecon.2018.07.008.

NGFS, 2019. First comprehensive report 'a call for action'. URL: https://www.ngfs.net/sites/default/files/medias/documents/ngfs_first_comprehensive_report_-_17042019_0.pdf.

NGFS, 2020. NGFS climate scenarios for central banks and supervisors. URL: https://www.ngfs.net/en/ngfs-climate-scenarios-central-banks-and-supervisors.

Nikiforos, M., Zezza, G., 2017. Stock-Flow Consistent Macroeconomic Models: A Survey. Technical Report 891. Levy Economics Institute of Bard College. doi:10.2139/ssrn.2973485.

Noy, I., 2009. The macroeconomic consequences of disasters. Journal of Development Economics 88, 221–231. URL: https://www.sciencedirect.com/science/article/pii/S030438780800031X, doi:https://doi.org/10.1016/j.jdeveco.2008.02.005.

OECD, WBG, 2019. Fiscal resilience to natural disasters. OECD Publishing. URL: https://doi.org/10.1787/27a4198a-en, doi:https://doi.org/https://doi.org/10.1787/27a4198a-en.

Ponta, L., Raberto, M., Teglio, A., Cincotti, S., 2018. An agent-based stock-flow consistent model of the sustainable transition in the energy sector. Ecological Economics 145, 274–300. doi:https://doi.org/10.1016/j.ecolecon.2017.08.022.

Ranger, N., Mahul, O., Monasterolo, I., 2021. Managing the financial risks of climate change and pandemics: What we know (and don't know). One Earth 4, 1375–1385. URL: https://www.sciencedirect.com/science/article/pii/S259033222100539X, doi:https://doi.org/10.1016/j.oneear.2021.09.017.

Semieniuk, G., Campiglio, E., Mercure, J.F., Volz, U., Edwards, N.R., 2021. Low-carbon transition risks for finance. WIREs Climate Change 12, e678. doi:https://doi.org/10.1002/wcc.678.

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S.M., Wehner, M., Zhou, B., Allan, R., 2021. Climate Change 2021: The Physical Science Basis. Cambridge University Press. chapter Weather and climate extreme events in a changing climate. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, p. 1513–1766. doi:10.1017/9781009157896.013.

Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., New, M.G., O'Neill, B., Otto, F., Pörtner, H.O., Reisinger, A., Roberts, D., Schmidt, D.N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E., Trisos, C.H., 2021. A framework for complex climate change risk assessment. One Earth 4, 489–501. URL: https://www.sciencedirect.com/science/article/pii/S2590332221001792, doi:https://doi.org/10.1016/j.oneear.2021.03.005.

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., et al., 2018. Trajectories of the earth system in the anthropocene. Proceedings of the National Academy of Sciences 115, 8252–8259. doi:10.1073/pnas.18101411.

Taylor, J.B., 1993. Discretion versus policy rules in practice. Carnegie-Rochester Conference Series on Public Policy 39, 195–214. doi:10.1016/0167-2231(93)90009-L.

Waidelich, P., Batibeniz, F., Rising, J., Kikstra, J., Seneviratne, S., 2024. Climate damage projections beyond annual temperature. Nature Climate Change URL: https://doi.org/10.1038/s41558-024-01990-8, doi:10.1038/s41558-024-01990-8.

WMO, 2021. Atlas of mortality and economic losses from weather, climate and water extremes (1970–2019). URL: https://library.wmo.int/idurl/4/57564.

WMO, 2024. State of the global climate 2023. URL: https://library.wmo.int/idurl/4/68835.

Woillez, M.N., Giraud, G., Godin, A., 2020. Economic impacts of a glacial period: a thought experiment to assess the disconnect between econometrics and climate sciences. Earth System Dynamics 11, 1073–1087. URL: https://doi.org/10.5194/esd-11-1073-2020, doi:10.5194/esd-11-1073-2020.