Understanding the climate risks to sovereign debt: From data to models

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Abstract

European sovereigns are among the least vulnerable and better prepared countries globally when it comes to climate change. Nevertheless, they are still exposed to adverse effects that can create a potentially destabilising climate-debt loop, given the already high debt levels. However, the risks from climate change to fiscal stability do not seem to be receiving the same attention as climate risks for financial stability. In this paper I discuss the exposure of EU countries to climate change and present the channels through which climate change poses risks to sovereign debt. After highlighting the significance of the problem, the paper provides guidance on what data we need to streamline climate change risks into sovereign debt analysis, and asks what the data can tell us and what they can not. It also argues for linking integrated assessment models of the climate-economy nexus into debt sustainability analysis, and asks how much trust we may place in climate-economic models when it comes to public finance. Illustrative examples using two prominent integrated assessment models provide insights on the climate risks to sovereign debt. The analysis has policy implications for the institutions mandated with fiscal stability.

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1 Introduction

"even if the true scientists should all recognize the limitations of what they can do[], so long as the public expects more there will always be some who will pretend, and perhaps honestly believe, that they can do more to meet popular demands than is really in their power."

-Friedrich von Hayek, Nobel Prize Lecture, 1974.

A decade after the Eurozone debt crisis of 2011 the COVID-19 pandemic added $24 trillion to global debt. Government support programmes account for half of the increase, and the debt upswing is well above what was observed during the global financial crisis.[1] Eurozone public debt currently stands at about 100% of GDP. Unprecedented interventions by the European Central Bank and the European Commission have averted another debt crisis, but concerns are voiced that climate change risks and the cost of climate policies will imperil the ability to repay COVID-19 debts (Dibley et al., 2021). The year 2020 tied with 2016 for the hottest year on record since record-keeping began in 1880, and the seven hottest years have all been since 2015. The current decade is considered a make-or-break decade for climate action, and countries must act at a time when sovereign debt has reached levels not seen since World War II.

In this paper I do three things: First, I discuss the exposure of EU member states to climate change, Second, I present the channels through which climate change poses risks to public finance and sovereign debt. This part highlights the significance of the problem and provides guidance on what data we may need to streamline climate change risks into sovereign debt analysis. Third, I ask what the data can tell us and what they can not, argue for linking integrated assessment models of the climate-economy nexus into debt sustainability analysis, and ask how much trust we may place in these models when it comes to public finance. Two examples illustrate the link of integrated assessment models with debt sustainability analysis (DSA) and provide insights on the climate risks to sovereign debt.

Climate risks are receiving increasing attention by investors and regulators for their effects on asset prices and financial stability. Unfortunately, the same can not be said about the risks to public debt and fiscal stability. Here I make the distinction between attention paid to the use of fiscal resources to address climate change from (in)attention to climate risks to fiscal stability. This paper focuses on the latter. Let us look at some examples.

The Network for Greening the Financial System (NGFS), established in the Paris 2017 summit by eight central banks and supervisors, counts today 121 members and observers.[2] The Network focuses on enhancing the role of the financial system to manage risks and mobilize capital for investments in the broader context of meeting the Paris Agreement goals. Among other things, NGFS compiled a set of six scenarios under different assumptions about climate policy, emissions, and temperatures. These scenarios correspond to a future of "orderly transition", "abrupt change", and "hot-house" world. They utilise multiple climate models to provide a range of results for central banks and supervisors to explore the possible impacts of climate change on the financial system. NGFS has also issued guidelines for climate disclosures of central banks, and for supervisors to

[1]See the report by the International Institute of Finance at `https://www.reuters.com/article/us-global-debt-iif-idUSKBN2AH285`.

[2]See urlhttps://www.ngfs.net/en, accessed Jan. 2022.

take the necessary measures to foster a greener financial system. The recommendations are not binding, but within two years of publishings the guidelines 94% of the supervisors have made progress in developing a strategy to address climate-related risks, 83% have developing supervisory expectations for climate-related risks, and 78% have engaged with financial institutions under their supervision. These are self-reported results from an NGFS survey, so they should be taken with a grain of salt, but strong evidence of substantive activity is provided by the following two examples.

The European Central Bank conducted an economy-wide climate stress test (Alogoskoufis et al., 2021) to assess the resilience of non-financial corporates and euro area banks to climate risks, under the orderly transition and hot house scenarios. They used a comprehensive dataset of local climate and financial information for 4 million companies worldwide and approximately 1,600 consolidated euro area banks, and models of the transmission channels of climate change to firms and banks. The results show that under a business-as-usual scenario the effects of climate risk would increase moderately until 2050, but they would be concentrated in certain geographical areas and sectors. For those banks most exposed to climate risks, the impact could be very significant. The report concludes that in the absence of climate mitigating actions, climate change is a major source of systemic risk. It also finds clear benefits to acting early, arguing that "the short-term costs of the transition pale in comparison to the costs of unfettered climate change in the medium to long term".

The European Commission has been engaged in integrating climate-related developments into Solvency II. Its review of Directive 2009/138/EC aimed at strengthening the (re)insurers management of climate risks by requiring climate change scenario analysis for solvency assessment, so that climate risks may be reflected in capital requirements. The European Insurance and Occupational Pensions Authority (EIOPA) issued an opinion to welcome the Commission's proposal.[3] Ongoing consultations consider reforms for sustainable assets to receive lower capital charge. EIOPA perceived that stakeholders interprete "climate risks" narrowly as "natural catastrophe risks", and in issuing its opinion it took this bias into account to include all climate change risks. It went beyond extreme weather events and natural catastrophes, to trends such as rise in temperature or sea levels, or climate-related forced migration that could affect (re)insurance activity. In this paper I also take the broader view of climate change risks.

In contrast to the above initiatives relating to financial stability, much less attention seems to be placed on fiscal stability.

The EC does take up the issue in its debt sustainability monitor (European Commission, 2019), but, perhaps unsurprisingly, it totally drops the word "climate" from the 2020 monitor, referring instead nineteen times to "pandemic". A Google trends search since the Paris Agreement averages 73 for climate risks to financial stability and 41 for fiscal stability. The lagging interest remains unchanged over time, and only users in Mexico, Brazil, Spain, and France have more interest in the fiscal effects. On Google Scholar there are 1.94 million documents on financial stability and climate change and 0.3 million on fiscal stability. IAMC reaches out to asset managers and central banks but does not report interactions with fiscal authorities or debt issuers. A 2019 survey by the EU Network of Independent Fiscal Institutions found that none covers climate risks in their

[3]See `https://www.eiopa.europa.eu/media/news/eiopa-welcomes-solvency-ii-proposals-european-commission-sustainability_en`, and the EIOPA opinion on the Solvency II review at `https://www.eiopa.europa.eu/document-library/opinion/opinion-sustainability-within-solvency-ii`.

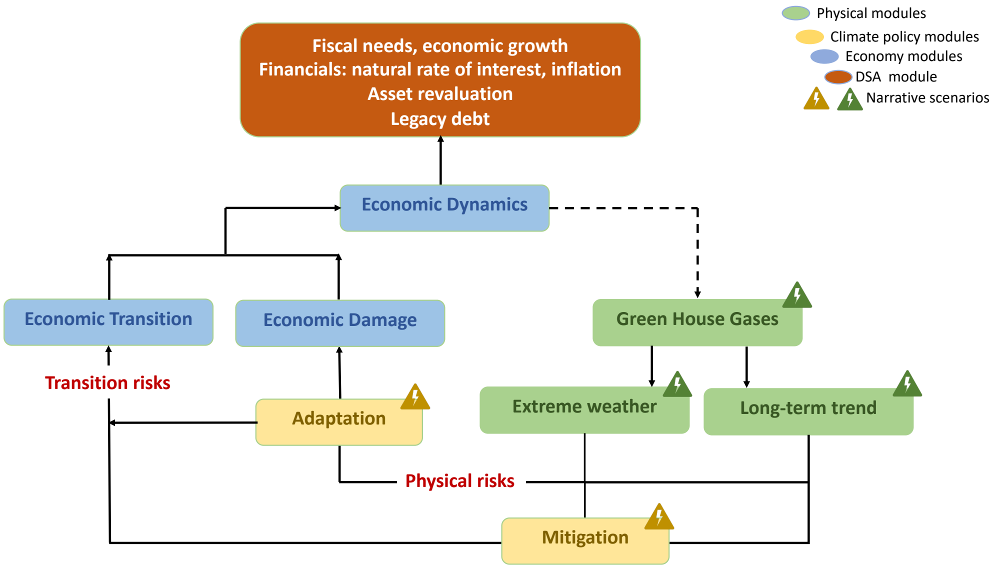
quantitative analyses. Only the UK Office for Budget Responsibility and the Irish Fiscal Council devote some space to the issue in their reports. The International Organisation of Supreme Audit Institutions, INTOSAI, publishes a guidance on the audit of public debt recognising "the technical complexity of sovereign debt issues", but climate change risks are not mentioned.[4] There seems to exist a gap in institutional assessments of climate risks to sovereign debt. The adverse effects of climate change to fiscal positions and the risks to debt sustainability create a need to incorporate climate change into debt analysis, taking a holistic view to integrate multiple channels of climate effects on sovereign debt.

In the rest of the paper I draw from and build upon my earlier work (Zenios, 2021), to look at the exposure of European sovereigns to climate change (Section 2), describe the channels through which climate change poses risks to public finance (Section 3), and ask what data we need to streamline the risks from climate change into public finance, what climate-economic models can tell tell us, and how much trust we may place in them (Section 4). The same section builds two illustrative examples linking IAM with DSA to illustrate the climate effects on debt. The paper concludes with policy implications (Section 5).

The story told by the paper is sketched in Figure 1, which illustrates the integration of climate change and climate policies into debt sustainability analysis. (Readers who are not familiar with the terminology of climate science should consult the box below.) The physical risks from climate change are mediated by climate policies which are costly and create transition risks, but can have positive effects, so the overall effects of climate change on public finance depend on the effects of climate policies on both the climate and public finance. Climate modules (green) specify chronic and acute climate effects which create physical risks. Societies pursue mitigation and adaptation policies (yellow modules), which are costly with potentially positive long-term effects. Mitigation create transition risks but can limit climate change, whereas adaptation reduces economic damages and improves resilience. These modules feed into the economic modules (blue) to estimate both damages and growth effects. Thus, physical and transition risks from climate change, with the costs and benefits of mitigation and adaptation policies, are transmitted to the DSA module (brown). The paper develops details of this sketch.

[4]See GUID 5250, *Guidance on the Audit of Public Debt*, 2020, available at www.issai.org, last accessed October 2021.

Figure 1 – Integrating climate risks to sovereign debt sustainability analysis



Source: (Zenios, 2021).

Basic terminology.

Mitigation. Reducing emissions and stabilizing the levels of heat-trapping greenhouse gases (GHG) in the atmosphere.
Adaptation. Adapting to climate changes through (i) improved data collection for a better evaluation of disaster policies, the identification of the factors driving loss trends, and the development of early warning systems; (ii) expansion of the role of disaster risk reduction, including, among other things, the upgrading of infrastructure and heath care services; and (iii) developing innovative finance mechanisms including insurance and risk transfer instruments.
Physical risks. The impacts today on insurance liabilities and the value of financial assets that arise from climate- and weather-related events, such as floods and storms that damage property or disrupt trade.
Liability risk. The impacts that could arise if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible. Such claims could come decades in the future, but have the potential to hit carbon extractors and emitters –and, if they have liability cover, their insurers– the hardest.
Transition risks. The financial risks which could result from the process of adjustment towards a lower-carbon economy. Changes in policy, technology and physical risks could prompt a reassessment of the value of a large range of assets as costs and opportunities become apparent.

(Source: Bank of England (Carney, 2015) and NASA (Bouwer et al., 2007).)

2 European sovereign exposures to climate change

When it comes to climate change, EU countries are among the world's best prepared and less vulnerable. Figure 2 maps the vulnerability and preparedness of EU member states according to the Notre Dame Global Adaptation Initiative.[5] All members are in the quadrant of less vulnerable and better prepared, but with significant differences in their ratings. The aggregate ND-GAIN Index ranges from 52 for Romania to 73 for Denmark and Finland, with the bottom tercile averaging 57 and the top tercile 70.

Figure 2 – Vulnerability and readiness of EU countries

Sources: The Notre-Dame Global adaptation Initiative, `https://gain.nd.edu/our-work/country-index/`, accessed Jan. 2022.

2.1 Damages

European countries are already experiencing climate disasters with estimated damages €446 billion between 1980 and 2019, which is only 3% of GDP over a 40-year period.[6] Less than one-third of these damages were insured. The effects can be material if we look at the more recent years and forward-looking projections. EU economic losses from extreme weather have amounted to about €12 billion annually in recent years, and are projected to grow by at least €170 billion per year (1.36% GDP). In addition to physical damages, the public budget can also be burdened by climate-induced social costs.

2.2 Mitigation and stranded assets

Mitigation will require costly upgrading of infrastructure, and the transition to a low-carbon economy will cause asset revaluation. Banque de France (2019) estimates that

[5] See `https://gain.nd.edu/`.

[6] European Environmental Agency estimates at `https://tinyurl.com/muvcz3b9`.

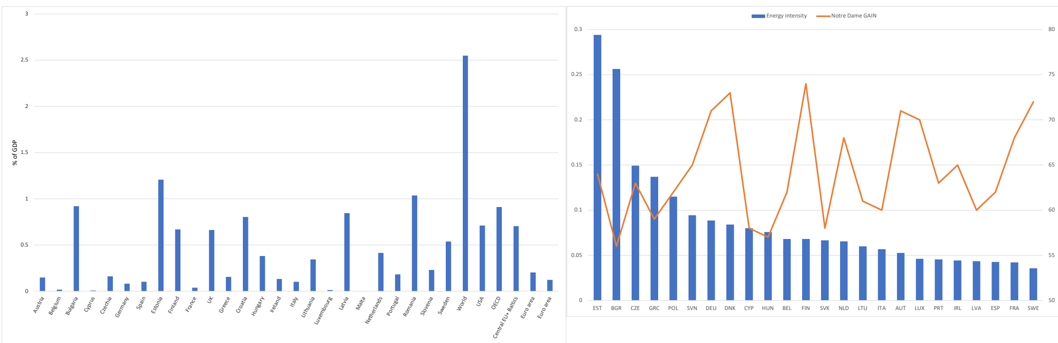
assets worth $12 trillion, or 3% of the capital stock, will be *stranded* by 2050. Financial Times[7] estimates that 84% of the remaining fossil fuels would remain in the ground under the Paris Agreement target of 1.5C global warming, 59% for the 2C target, and 4% if the warming target is revised up to 3C. Around $900bn, about one-third of current value of big oil and gas companies, would evaporate under the most stringent policy.

The EU has much lower extractive activity than the rest of the world (Figure 3, top panel), so, again, it can be less vulnerable to transition risks. However, the energy intensity (bottom panel), shows heavy reliance on fossil fuels, with significant differences between countries, which also appears disconnected from climate-change preparedness. With an EU-wide average of 71% of fossil fuels in the energy mix,[8] the transition risks can be significant even if asset repricing risks may not be. Countries with high energy intensity or high fossil-fuel extraction –Estonia, Bulgaria, Czechia, Greece and Poland– are more exposed to transition risks. Countries with low energy intensity –Austria, Finland, France, Spain, Sweden– can more easily weather the transition. High energy intensity countries are found in both south and central Europe, while low energy intensity countries are in north and south.

Figure 3 – Natural resources rents and fossil-fuel energy intensity in Europe

Panel (a) reports rents from extraction of natural resources as % of GDP, and (b) reports the energy intensity of fossil-fuel usage per dollar of added value to a country's GDP from fossil fuel energy, together with the ND-GAIN index.

(a) Rents **(b)** Energy intensity



Sources: Eurostat, the World Bank, Our World in Data `https://ourworldindata.org/fossil-fuels#what-share-of-pri-mary-energy-comes-from-fossil-fuels`, OECD, and ND-GAIN (2020).

The investments requirements to meet EU climate goals are estimated to be in the range 0.5-1% of GDP annually during this decade (Darvas and Wolff, 2021), and mitigation costs are already foreseen to burden public budgets. The European Green Deal assumes an annual investment gap of €260 billion (1.86% of 2019 EU27 GDP) to reach the 2030 climate targets. This is to be filled up by both the public sector and private investors.[9]

[7]Lex column of Feb. 4, 2020, at `https://www.ft.com/content/95efca74-4299-11ea-a43a-c4b328d9061c`, accessed Jan. 2022.

[8]See `https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html`, accessed Jan. 2022.

[9]NGFS (2019) estimates that up to 4% of 2030 global GDP will be needed for mitigation efforts to limit global warming to 2C.

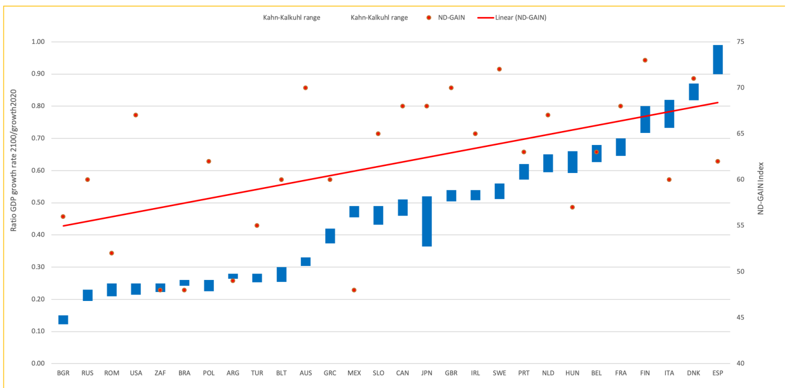
These pressures on public finance come as countries can suffer economic growth slowdown from climate change, as estimated by several integrated assessment models (IAM) or regressions from past observations. A survey of twenty-one studies (Tol, 2014) found that a 5C temperature rise by the end of the century could adversely impact the world economy by 3% to 15% of GDP compared to a scenario of no further warming. For 2.5C increase, the impact would be 2.5%. IMF (2013) reports 25% GDP losses under a 5C increase. Forecasts differ widely by region, and Tol puts losses at 14.6% for the worst hit region (South America) but finds positive effects for some countries (Baltics). NGFS estimates that an orderly transition would limit the economic losses to around 4% of GDP by the end of the century, whereas the will be 25% GDP in a hot house world.

In Figure 4 (Panel A) we show the range of ratios of 2100 GDP growth to 2020 growth as projected by an integrated assessment model of climate change, using different damage function. These values should be interpreted with caution, as they depend on the assumptions of the model about damage functions and scenarios of future socio-economic paths; more on *climate scenarios* in section 4. Nevertheless, the trend for lower growth rate and the larger effects on the less prepared countries is in line with the literature above. Quantitatively, the range of values displayed in Panel A is in line with the values estimated by an ensemble of models for OECD countries in Panel B.

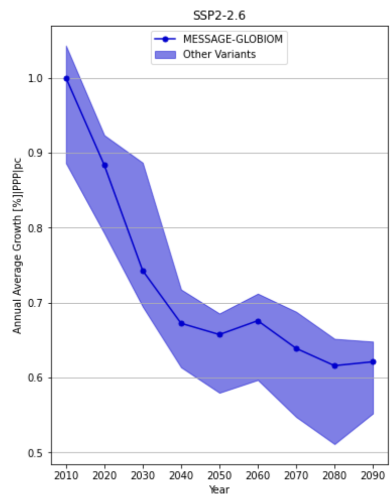
Figure 4 – Adjustments to GDP growth from climate change

This figure shows GDP growth projections, scaled so that 2020 projection is set at 1.

(a) EU member states



(b) OECD countries



Sources: Panel (a) reports results based on projections generated using the RICE50+ model under scenarios corresponding to successful implementation of the Paris Agreement (RCP2.6-SSP2, from section 4). Panel (b) reports results for the OECD countries using an ensemble of models from the IIASA database, under the same scenarios; `https://tntcat.iiasa.ac.at/SspDb/dsd?Action=html-page&page=40`.

The alternative "Porter hypothesis" (Porter and van der Linde, 1995), suggests that climate policies can trigger innovation and spur growth. Transition policies can bring benefits from more efficient technologies. Alas, recent empirical analysis by the OECD (Albrizio et al., 2014) does not justify placing high expectations on this hypothesis. Increasing stringency across OECD countries over the past two decades spurred primarily short-term adjustments of aggregate productivity, with only advanced industries showing a small improvement.

2.3 Political risks

Climate change could lead to increased political instability (Dell et al., 2014), which is recognized as a factor of asset prices, including sovereign bond yields (Gala et al., 2020).[10] Europe's neighbours in the Middle East and North Africa are more vulnerable and less prepared (Figure 2), and political risks that have been quite low in the EU could change through spillovers. Spillovers hit harder the EU periphery countries, creating a source of climate-induced tension.

Climate-induced tension also arises due to the asymmetric effects of the systemic climate shocks on EU member states. For instance, countries that use the European Green Deal to stimulate innovation will adapt to climate change, but more vulnerable states that fail to stimulate innovation will become laggards. This would aggravate existing imbalances and the reallocation of capital from laggards to innovators. (For further analysis see subsection 2.6). Political risks can arise not only from climate-vulnerable neighbours, but also from inequalities within the bloc. Such risks have an effect on sovereign bond yields, and consequently on sovereign debt.

2.4 Are climate risks priced?

Sovereign bonds have average maturities of roughly ten years, but significant amounts run into the 2060s and "century bonds" with 100-year maturity have been on the rise as borrowers lock-in record low interest rates. Investors seem to be pricing in climate risks (Barnett et al., 2020), although a survey of experts finds that they are most likely underpriced (Stroebel and Wurgler, 2021). Respondents believe, by a factor of 20 to 1, that prices of equity, insurance, and real estate assets do not sufficiently reflect climate risks.

With this underpricing bias in mind, we look at studies that establish the effects of climate risk on sovereign bond yields. Volz et al. (2020) use cross-section of countries to establish that climate change has an adverse effect on borrowing costs, and find that emerging countries' sensitivity of borrowing costs to climate vulnerability is 100bp, increasing to 250bp for high risk countries. Battiston and Monasterolo (2020) provide estimates of bond yield changes to the stringency of climate policies, and find that countries with high exposure to fossil fuels (Norway, Poland) can experience bond yield shocks of up to 2%, although countries with large share of renewable energies in the energy sector can experience lowering of their yields. Klusak et al. (2021) link climate-adjusted GDP to sovereign ratings and obtain estimates of the effects of climate change to sovereign borrowing costs. Under a 2C temperature increase they find that fifty-five sovereigns are downgraded, and the number increases to eighty under 4.2C. Within the Paris Agreement targets, most EU countries would be down-rated marginally (up to 2 notches), but the down-ratings under 4.2C are up to 6 notches. Interestingly, rating changes are noticeable

[10] The cited paper identifies a global political risk factor (P-factor) and shows that country political risks have a strong systemic component carrying economically and statistically significant premia in international stock prices. Further test (available from the authors) In a follow up paper (in preparation), we find strong evidence supporting the pricing of the global political risk factor in FX and sovereign bond returns.

as early as 2030. Climate risks to ratings are not as distant as we might think. Under the mild climate scenario they estimate cost of debt servicing increases of up to 0.5%, although for most countries they are below 0.1%. Such increases seem small, but they can be material for countries with tight fiscal space.

2.5 The climate-debt vicious loop

While individual components of climate risks may seem small, the compounded effects can become a first-order problem. Climate risks could precipitate a destabilizing vicious loop of sovereign debt for countries with tight fiscal space. Once aggregate climate costs raise concerns about the sovereign's ability to repay, the sovereign is down-rated and its financing rates go up. Increasing debt servicing costs add to the fiscal costs incurred from damages and climate policies, as countries' growth face adverse climate effects. These adverse effects are over and above the effects of increased debt on growth, as other factors come into play (e.g., reduced productivity, lower agricultural yields, increased health problems, lower educational performance, decreased judicial efficiency).[11] The sovereign can get caught in a debt trap.

2.6 An EU climate divide

The evidence we have presented so far shows asymmetric effects of climate change on the EU member states. This can create a new EU climate divide which is not quite the same as the usual north-south divide of the 2011 sovereign debt crisis. The potential for a divide is clearly shown in the map of Figure 2 from the broad-brush ND-GAIN vulnerabilities and readiness indices. This is further corroborated from the differential energy intensities and fossil fuel rents (Figure 3), and the differential effects on growth (Figure 4, Panel A).

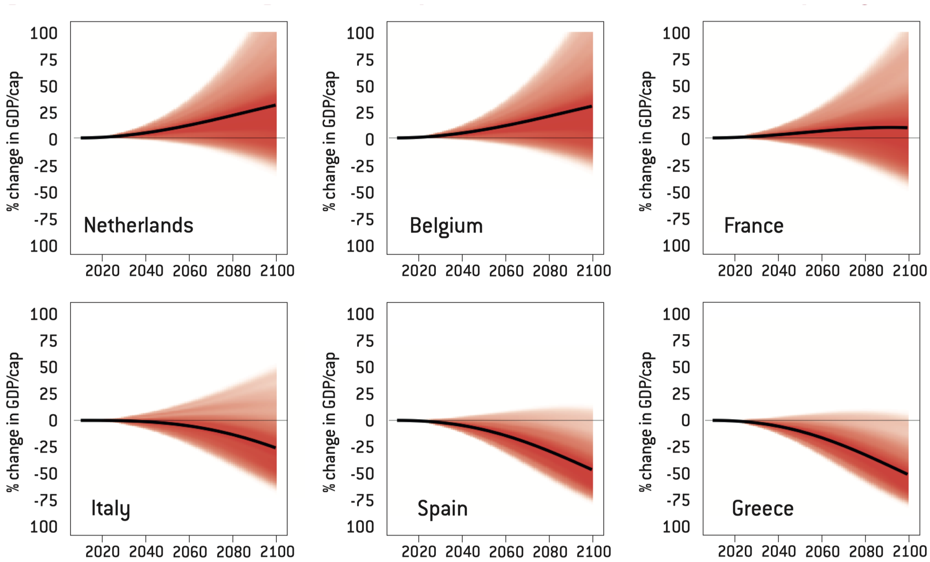
We push the analysis of climate risks to its limits, under a scenario which corresponds to end-of-century median warming by 4.5C. This is the most aggressive scenario of climate change (RCP8.5 from section 4), and is characterized by some as "alarmist", but a recent report by the US National Academy of Sciences (Schwalm et al., 2020) argues that it serves as a useful tool for quantifying climate risk, since emissions consistent with RCP8.5 are in close agreement with historical observations, and it also provides the best match out to midcentury under current policies. Using the integrated assessment model of Burke et al. (2015) we show in Figure 5 striking divergence of GDP per capita. Significant divergence is also documented by the historical cross-country estimation of Kahn et al. (2019), although the differences are not so striking, with GDP per capita losses ranging from 2.5% to 10%.

EU members with greater exposure to climate risks have more precarious public debt positions. The most vulnerable tercile have weighted average debt 133% of GDP, whereas the least vulnerable have average 78%. The available fiscal space limits the implementation of mitigation and adaptation policies, further exacerbating the climate divide.

To decide what potentially can be done to prepare for the climate risks to sovereign debt we need to understand the transmission channels from climate change to public finance, and to understand what kinds of data and models are available compared to what we need. We turn to these two issues next.

[11] Some of the effects noted here are obvious, and the adverse effects of increasing temperature on learning see Park et al. (2020) and on judiciary decisions see Heyes and Saberian (2019).

Figure 5 – Divergence of European economies without climate policy



Source: `https://web.stanford.edu/%7Emburke/climate/map.php`. The black line denotes the best estimate and the shaded area represents uncertainty.

3 Transmission of climate change risks to sovereign debt

The risks to public finance from climate change can be acute, from weather-related damages, or chronic, from the effects on long-term economic growth with the transition to a low carbon economy, and on financial stability that increases borrowing costs. Mitigation and adaptation policies introduce trade-offs to the analysis. Mitigation spending, for instance to shift to low-carbon economy or regulate the use of natural resources, creates transition risk and can put further pressure on public finance, while causing more benign climate change. Adaptation spending, for instance to upgrade infrastructure or improve public health services, further strains public finance but moderates future impacts.

Three main channels transmit climate risks, physical and transition, to public debt financing. First, we have fiscal costs of adaptation and mitigation policies, and damages, including social costs and bailout. Second, we have the effects of climate change and of climate policies on growth and financial stability. Third, we have repricing of assets.

Economic damages are caused by the adverse effects of climate change on natural resources, physical capital, labor, and productivity. Damages can be assessed from past extreme events, although extrapolating from historical data underestimates future damages as the number and severity of extreme events keeps increasing. Long term damages can also be projected through integrated assessment climate models endowed with a damage function (more in section 4). Adaptation costs burden sovereign debt but protect economic growth.

Damages are still mostly insurable, but insurance coverage is likely to become more costly and, even, unavailable. Governments in Australia, Japan, and New Zealand take a contingent liability approach to natural disasters that may spill over to the public purse. The Australian government assesses disaster-related contingent liabilities as part of budget planning and fiscal risk assessment. Central and subnational governments collect information based on past weather patterns, and project future expectations of relief spending, infrastructure replacement, social transfers, and contingent guarantees, as well as reduced tax revenue and worsening of the government's financing options. In Japan the government obligations in the event of disasters are enshrined in several laws, but fiscal forecasts include projected expenditures of ongoing disaster relief efforts and not any potential future liabilities. The country estimates average $6.4 billion per year in disaster prevention, $13.5 bn in land conservation, and $278 million on science and technology research for disaster risk reduction. New Zealand contingent liabilities are budgeted for natural disasters and a multi-agency project seeks to understand the fiscal risks. Treating climate risks as contingent liabilities can help finance sovereign debt. A Fed report (Mallucci, 2020) shows that "disaster clauses" for debt-servicing relief can improve the government ability to borrow for hurricane-exposed Caribbean countries, and Demertzis and Zenios (2019) show how sovereign contingent debt can provide insurance for European sovereigns.

Transition re-allocates resources from productive investments to adaptation investments or to new technologies, and has employment and social impacts. Transition has direct, indirect, and discretionary fiscal impacts (European Commission, 2019). Direct costs include social transfers to affected households and explicit contingent liabilities, such as insurance schemes backed by state guarantees or bank bailouts. Indirect costs include reductions in tax revenues. Discretionary costs arise from policies such as public investments to infrastructure or public health, and subsidies for clean energy. Expenditures on mitigation are already foreseen to burden public budgets. For instance, the European Green Deal assumes an annual investment gap of €260 billion (1.86% of 2019 EU27 GDP) to reach the 2030 climate targets. This is to be filled up by both the public sector and private investors, and contingent liabilities are likely to materialize on public balance sheets if private investments fall short.

Climate change also causes the repricing of sovereign wealth as assets are stranded. This affects the credit quality and debt financing rates (risk premia) of the sovereign. This consideration overlays other financial variables in DSA —the natural rate of interest r* and inflation— which are also affected. The increase in the frequency and severity of supply shocks due to extreme weather makes it harder for central banks to forecast output gaps, and transition policies also need to be considered when evaluating inflationary pressures. NGFS is studying the effects of climate change on financial variables (NGFS, 2019), and the monetary policy response to climate change should be factored into long-ranging DSA. The ongoing investigations on climate by central banks can refine these building blocks of DSA.

4 Data and models: what they tell us and what they don't

Climate change is a problem complicated by deep uncertainty (Barnett et al., 2020; Nordhaus, 2015). First, there is uncertainty within any given model when outcomes are know with probability. This is the case, for instance, of short to medium term projections of temperature or precipitation at a given location; given the time of the year we have a pretty accurate distribution of likely outcomes, including spatial correlations. Then there is ambiguity where the outcomes may be know, but their likelihood is not. For instance, we might know what the world could look like if the global temperature rise stays below 2C, or if it does not, but we cannot assign probabilities. Finally, there is misspecification when there is no consensus on data or models. We will see to what extend we can deal with this complexity to integrate climate risks into sovereign debt analysis.

To model risk we need historical data, to calibrate probabilities. To model ambiguity we need to postulate narrative scenarios that are transparent and accepted, to facilitate analysis. To deal with mis-specification we need ensembles of models or data from multiple sources, to avoid reliance on a single model and reach robust conclusions.

Figure 6 – Climate change stressors to the fiscal position

Non-discretionary (exogenously driven, by climate change phenomenon)	Discretionary impact (endogenously driven, through policy measures)
Direct (examples): • Public spending to replace damaged infrastructure/buildings • Social transfers to households affected by the weather event • Materialization of *explicit* contingent liabilities (e.g. insurance schemes backed by state guarantees)	*Adaptation policies (examples):* • Public investment in climate-proofing infrastructure, water management • Subsidies to support changing crop varieties, or relocation from coastal areas • "Rainy day" funds
Indirect (examples): • Reduction of tax revenue due to a reduction in economic activity • Increase of health care spending due to more diseases • Materialization of *implicit* contingent liabilities (e.g. to support financial institutions in distress) • Impact on the sovereign capacity to pay debt payment obligations over the medium-term (due to budgetary funds reallocation towards recovery/reconstruction)	*Mitigation policies (examples):* • Carbon taxes (e.g. on fossil fuels, and other carbon taxes). Adverse impact on economic activity in the short term, with uncertain net impact on the overall tax revenues in the medium and long-term • Emission trading schemes (ETS) revenues • Public subsidies for clean energy transition • Redistribution effects on the tax base

Source: (European Commission, 2019, Box 5.3).

Figure 6 summarizes the variables through which climate risks can stress public finance. It makes a distinction between discretionary and non-discretionary expenditures, and provides guidance on the data requirements to assess climate risks to debt. Discretionary expenditures can be estimated more accurately, as they are driven by any adopted policies: while climate change drives the policies, their cost to the public purse is climate-independent. The non-discretionary expenditures —infrastructure damages, implicit liabilities to support financial institutions, reallocation of funds towards recovery— are contingent on climate change. Missing from this figure are the indirect effects from government revenues and GDP growth. These are also climate-dependent. They can only be estimated if we know the climate conditions, and for this we need scenarios.

The Integrated Assessment Model Consortium (IAMC),[12] has developed a narrative scenario architecture of climate change. This architecture combines representative concentration pathways (RCP) of atmospheric greenhouse-gas (GHG), with narratives on shared socio-economic development pathways (SSP). This scenario architecture provides plausible states of the world for what-if analyses. The scenarios are publicly available, and both IAMC and NGFS are transparent about their methodologies. In addition to these standardized scenarios, we have the development of integrated assessment models (IAM) of the effects of GHG on the climate, the interaction of climate with natural systems, and the macroeconomic impact of increasing global temperatures. This very active line of work was pioneered by Nordhaus (2015), see, e.g., Emmerling et al. (2016); Gazzotti et al. (2021) for the recent examples used below. IAM project variables of interest —such as economic growth, land or energy usage— under different SSP-RCP combinations, providing input for analysis under temperature increase ranging from 2C to 4.2C

[12]IAMC was created in response to a call from the Intergovernmental Panel on Climate Change IPCC to pursue integrated assessment and analysis of climate change; `https://www.iamconsortium.org/about-us/`.

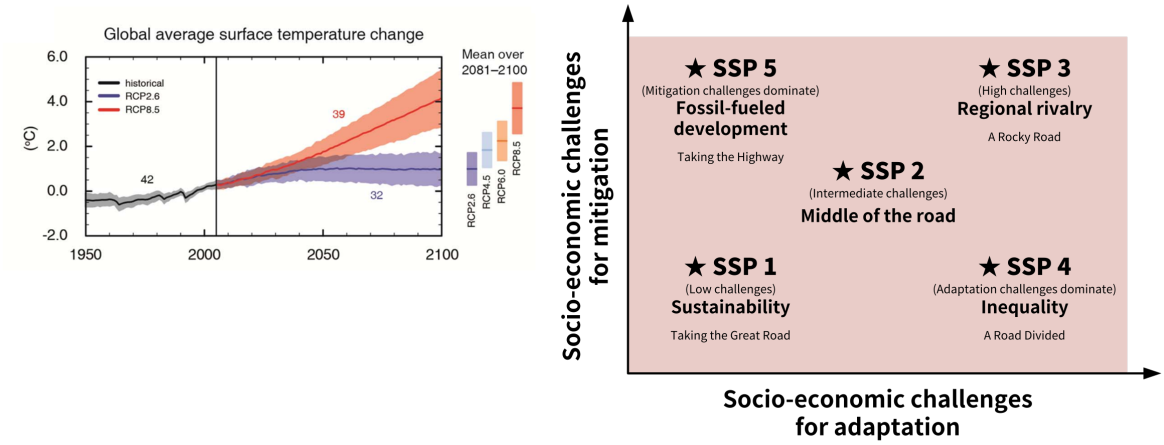
by 2100. They are used for scenario analysis and disclosure, strategy alignments, and academic research, and can be superimposed with the NGFS transition scenarios for a holistic view.

Figure 7, panels A and B, show the RCP and SSP developed through an IAMC deliberative process and published in a special issue of Climatic Change (2014). Panel C shows the *scenario matrix architecture*, with green cells consistent with the Paris Agreement, red cells corresponding to a fossil fuel world with large temperature increase, and intermediate yellow cells.Implausible states are left blank. Combining the NGFS transition scenarios with the IAMC architecture we obtain a holistic view of climate conditions and energy policies.

Each cell of the matrix displays the number of currently available IAM (Rogelj et al., 2018) that we can call upon for analysis of the climate-economy nexus. Such models generate projections of climate conditions that can be used in a three-step procedure (Kahn, 2021): (1) study the historical sensitivities of the variable of interest (e.g., GDP growth to the climate conditions (e.g., temperature); (2) use an integrated assessment model to project future climate conditions; (3) combine the outcomes of the first two steps to obtain the variable of interest under future climate conditions.

Figure 7 – Scenarios for the study of climate change

(a) Representative concentration pathways **(b)** Socio-economic pathways



(c) Scenario matrix architecture

	SSP1	SSP4	SSP2	SSP3	SSP5
RCP8.5					4
RCP6.0	6	6	6	4	4
RCP4.5	6	3	6	4√	4
RCP2.6	6√	3√	6√		3√
RCP1.9	5√	1√	4√		2√

Source: Climatic Change (2014) for panels (a) and (b), and Zenios (2021) for panel (c).

This procedure has two well-acknowledged shortcomings that hamper our ability to get precise answers from data and models. First, extrapolating from historical data can underestimate future values as the number and severity of extreme events increase with time. Second, the sensitivities to climate conditions change as societies invest in adaptation, and we may overestimate future impacts. Unfortunately, for now we must live with imprecision recognizing that climate scientists have limited ability to "give fine-grained and concrete answers to an impatient public" (Weitzman, 2011). We also need to work with ensembles of models to overcome misspecification by avoiding reliance on a single model. Nevertheless, the same way that weather forecasting accuracy in the 3-10 day range has been increasing by about one day per decade, we can expect continuous improvements in IAM accuracy.

Improvements are also anticipated in data availability. NGFS (2021) engages with stakeholders to identify data gaps in financial stability analysis. It identifies a need for forward looking data (e.g., emission targets), instead of relying on extrapolations from the past, and more granular data (e.g., geographical data), and promotes policy interventions to catalyze progress towards better data. These include disclosure standards, a global taxonomy, and development of decision-useful metrics. Fiscal stability authorities should engage with NGFS to provide input on their data needs and leverage available resources.

In conclusion, linking integrated assessment models of the climate-economy nexus, with data on damages, including social costs and bailouts, and the effects of adaptation, mitigation, and transition policies, we can advance our understanding of the climate effects on sovereign debt under a range of narrative scenarios. This approach may not provide precision forecasts but it allows us to conduct "what if" analyses of the impact of climate factors to provide policy insights. Stern and Stiglitz (2021) argue for a structured dialogue between policymakers and their models, to simplify the complex questions relating to climate change while getting to the heart of decision-making. For our purposes, IAM are a good place to start in developing our understanding on the climate risks to sovereign debt, but they are poor place to finish in assessing debt sustainability. We provide next illustrative examples.

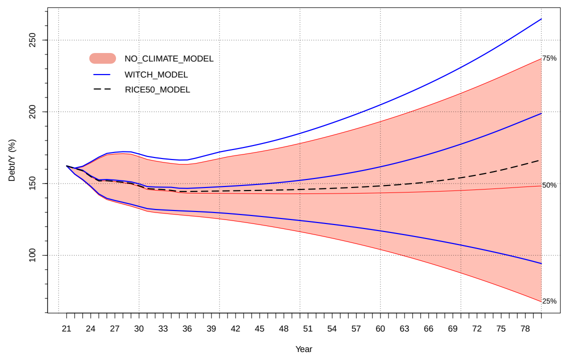
4.1 Illustrating climate effects on debt dynamics

We link the DSA model of Zenios et al. (2021) with two prominent IAM to look at the effects of climate change on the debt dynamics. The DSA model combines the economics of sustainable sovereign debt financing with normative models of financial risk management and planning under uncertainty. From risk management, the models adopts the idea of trading off risk with expected reward following the seminal work of Nobel laureate Markowitz (1952) on optimizing the tradeoff through efficient frontiers. The model also follows the increasing attention paid to uncertainty in stochastic DSA, and represents variables on a scenario tree to assess the tail risk of debt dynamics.

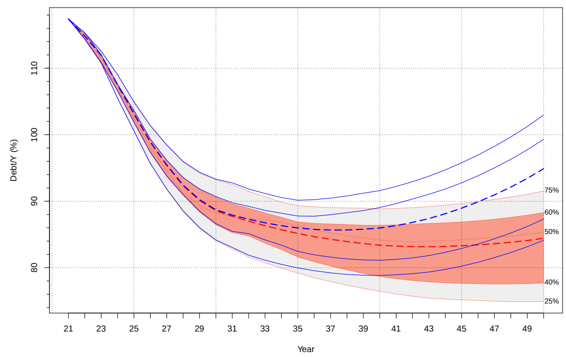
The DSA model optimizes the maturity of debt instruments to minimize expected interest costs, constrained by sustainability thresholds on debt stock and flow. Flow constraints reduce refinancing risks due to excessive funding requirements. Stock constraints set the minimum pace of debt reduction to avoid exploding stock dynamics (or the maximum sustainable debt increase for low debt countries), thereby reducing insolvency risk. The model was first developed in collaboration with staff from the European Stability Mechanism during 2017-2018, and became an essential building block of the methodological framework to assess debt sustainability of member states, mandated in ESM Treaty Article 13-1(b). The model was subsequently used for an assessment of the funding policy of the Dutch State Treasury Agency, in collaboration with the Italian Parliamentary Budget Office to evaluate the agreement between the Italian government and the European Commission after the March 2108 elections, and to study the effects of political risk on public debt (Consiglio and Zenios, 2020a). With the onset of the pandemic it was used to study ECB interventions (Consiglio and Zenios, 2020b).

Figure 8 – Climate risk effects on sovereign debt dynamics

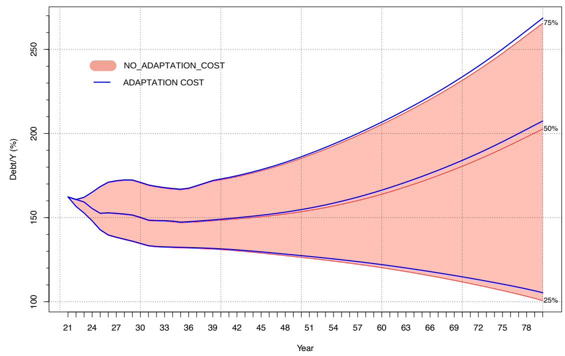
(a) Climate growth effects for Italy



(b) Climate growth effects for Cyprus



(c) Adaptation effects for Italy



Source: Zenios (2021) for panel (a), Consiglio et al. (2022) for panel (b), and author's calculations for panel (c).

We look at the climate effects on the debt-to-GDP dynamics of Italy through the growth channel, and the impact of adaptation; see Zenios (2021) for details. In Figure 8 (Panel A), the pink-shaded fan chart shows the debt dynamics without climate risks. The median debt ratio is stabilized slightly below 150% of GDP with significant upside risk. The uncertainty of the fan chart (25/75 percentiles) is due to the volatilities and correlations of GDP growth and output gap, inflation, primary balance, and the risk-free rates, calibrated from historical data.

We next introduce climate change from the scenario matrix cell RCP2.6-SSP2 corresponding to a path consistent with the Paris Agreement. We use WITCH (Emmerling et al., 2016) and RICE50+ (Gazzotti et al., 2021) to project climate adjustments to GDP growth, which we then apply to projections from the IMF World Economic Outlook. Thus, we combine expert knowledge about the country from WEO with climate projections from IAM. We superimpose the debt dynamics with WITCH and RICE50+

adjustments onto the fan chart, with the blue lines showing the median and 0.25/0.75 quantiles with WITCH, and the dashed line showing the median with RICE50+. The climate-adjusted debt dynamics shift upwards with both IAM, and climate risks become material from about 2030–2050.

In Panel B we show the results of a similar exercise for Cyprus using RICE50+. We notice a much more significant impact from climate change in Panel B than in Panel A, when comparing the blue lines with the fan chart. This is not due to any inherently greater exposure of Cyprus to climate risks compared to Italy. Instead, for Cyprus we assume, like Darvas and Wolff (2021), that the large mitigation investments will increase the real rate of interest, whereas for Italy we assume persistently low rates following Blanchard (2019).

We also incorporate climate policy effects for Italy, and run WITCH with adaptation, adding a quarter of the fiscal cost of adaptation to the public budget (Panel C). This analysis informs the potential costs and benefits of adaptation. In this particular example we find that adaptation measures do not offset the upside risks.

These examples show that climate risks can have significant effects on debt dynamics. Most importantly, they highlight the scope of integrating IAM into DSA to provide climate-adjusted debt dynamics, and the need for a holistic view in integrating multiple channels through which climate change affects public finance and sovereign debt.

5 Conclusions and policy implications

Whereas European sovereigns are among the least vulnerable and better prepared countries globally, they can still suffer from climate effects. Such effects can come from acute or chronic climate-related damages, transition to a low carbon economy, and increased political tensions from neighbouring countries that are more vulnerable and less prepared, and from a climate divide within the Union. Such risks are coming as governments need to finance mitigation and adaptation policies, and as economies may experience lower growth due to climate change. While each effect, by itself, seems small and inconsequential for EU member states, the compound effects can activate a climate-debt vicious loop, as markets price climate risks increasing a sovereign's borrowing rates and causing a climate divide.

The EU must decide how to react. COVID-19 prompted the Union towards community financing with the Next Generation EU recovery plan, but its focus on a green and resilient Europe is highly relevant during the current make-or-break decade for climate action. The EU has been a world leader in efforts to curb climate change, but when it comes to the effects of climate change on fiscal stability and sovereign debt, it seems that not much is done. Governments need need to plan for the risks from climate change to sovereign debt, to assess the resilience of public finance and estimate the available fiscal space to enact mitigation and adaptation policies. The same way NGFS is coordinating efforts on climate risks and financial stability, we need complementary effort regarding fiscal stability (Zenios, 2021).

Coordination

Climate challenges are global (and regional), and tackling them requires coordination. Many European institutions have a stake. The European Commission is already tasked with ensuring lasting, sound and robust management of public finances in Europe. The European Fiscal Board with the national fiscal councils, and the European Stability

Mechanism as the sovereign crisis resolution mechanism, have expertise and a stake as well. Climate change presents a common threat to the fulfilment of their mandates, creating a need for coordination to carry out assessments of the risks of climate change to sovereign debt. A network for climate-proofing public finance will bring together these institutions. A coordinated effort using the narrative scenario matrix architecture will deliver transparency and ensure acceptability of scenarios. Each sovereign can adapt their own local models, but the regional impacts of climate change is best approached through a common understanding.

Climate risk analysis in public finance

Fiscal authorities should mainstream climate risk analysis in public finance. Budgetary plans should account for damages and the costs of mitigation and adaptation policies, including potential social costs. Some of these costs can be immediate and direct, derived from national plans such as those related to the European Green Deal. Others will be for long-term adaptation derived from forward-looking plans. Still others can be contingent, such as damages from acute weather events. Planning for contingent liabilities requires databases of past extreme events to complement long-term projections from models. Also, the potential scale of weather-related contingent liabilities creates a need for risk-sharing. Climate risks are still mostly insurable, but in the long run tapping the markets through contingent instruments (catastrophe bonds, convertible debt, GDP-linked bonds) can provide fiscal space during shocks (Demertzis and Zenios, 2019).

Disclosure

The climate risks to public debt should be transparent. Transparency makes economies more resilient, and the Task Force on Climate-related Financial Disclosures recommends disclosures relating to governance, identification, assessment, and management of climate risks. Fiscal authorities should follow these guidelines. As we monitor compliance with the Paris Agreement and the alignment of national expenditures with climate goals, we also need transparency on the effects of climate change to public finance. The resilience of a country's debt to climate change is important, whether the country is contributing a lot or a little to climate change.

The risks from climate change to fiscal stability do not seem to be receiving the same attention as climate risks for financial stability. In the same way that central banks are taking a leading role on monitoring the climate risks to financial stability, the fiscal stability institutions should play a corresponding role.

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