



Climate Adaptation and Fiscal Sustainability: When Timing Matters

Nicola Campigotto⁴ · Simone D'Alessandro³ · Tiziano Distefano^{1,2}

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Abstract

Climate change is expected to cause significant socio-economic damage, posing risks to fiscal sustainability. While mitigation remains the primary strategy, individual countries must implement adaptation policies to anticipate and reduce expected harm. This creates a trade-off between adhering to present public deficit constraints—imposed by the EU financial framework—and investing in measures that could limit future economic losses and debt accumulation. First, we develop a theoretical model highlighting the role of adaptation policies in mitigating climate-related productivity losses. We then extend the EUROGREEN model (D'Alessandro et al. *Nat Sustain* 3(4):329–335, 2020) to incorporate climate damage under the RCP 6.0 scenario, analyzing macroeconomic indicators from 2010 to 2050 across different policy scenarios. As expected, Italy is projected to experience GDP losses, leading to a significant rise in public deficit and debt without intervention. We introduce two adaptation strategies to explore potential solutions: *Fast* and *Slow*. In the *Fast* scenario, the government invests €10 billion over three years, whereas in the *Slow* scenario, it allocates €1 billion annually over 30 years. Numerical simulations indicate that *timing matters*: only swift and substantial adaptation (*Fast*) effectively limits climate-related economic damage and enhances long-term debt sustainability. In contrast, gradual interventions (*Slow*) have a small impact, despite the same total investment. These findings suggest that fiscal austerity

✉ Tiziano Distefano
tiziano.distefano@unifi.it

Nicola Campigotto
nicola.campigotto@unitn.it

Simone D'Alessandro
simone.dalessandro@unipi.it

¹ Department of Economics and Management, University of Florence, Via Delle Pandette, 32 (edificio D1), 50127 Firenze, Italy

² Fondazione per il Futuro delle Città, Via di Novoli, 10, 50127 Città Metropolitana di Firenze, Italy

³ Department of Economics and Management, University of Pisa, Via C. Ridolfi, 10, 56124 Pisa, Italy

⁴ Department of Economics and Management, University of Trento, via Vigilio Inama 5, 38122 Trento, Italy

could create a “lose-lose” scenario, restricting the ability of highly indebted countries to protect their economies from climate change while exacerbating long-term fiscal instability.

Keywords Adaptation policies · Scenario analysis · Climate change · Debt sustainability

Mathematics Subject Classification Q54 · H68 · C63 · C67

JEL Classification E12 · E17 · Q54 · Q57 · H68

1 Introduction

The IPCC WGIII Report (April 2022) highlights the urgency of swift and decisive action to mitigate the adverse effects of climate change on both natural ecosystems and human societies. This urgency underscores the critical role of governments and public institutions in leveraging fiscal policy tools—such as taxation, subsidies, and public investments—not only for climate mitigation but also for adapting economic systems to future climate-related damages. However, fiscal sustainability challenges arise as governments seek to balance social, economic, and environmental objectives.

Despite its growing importance, the fiscal implications of climate adaptation policies have only recently gained attention in the literature. Fabio and Evi (2021) emphasizes that timely responses to climate-related disasters can significantly reduce their impact and that countries with more flexible budgetary frameworks are better equipped to address climate damages. Catalano et al. (2020) demonstrates that preventive adaptation measures contribute to higher GDP growth, enhanced resilience to economic shocks, and reduced financial constraints. Parrado et al. (2020) finds that adaptation efforts can mitigate the direct consequences of sea-level rise and alleviate public deficits.

The European Commission’s proposed reform of the EU’s economic rules has raised concerns about a potential return to austerity and its consequences for climate action. Since 2020, these rules have been temporarily suspended to mitigate the economic fallout from the COVID-19 pandemic. In this context, this paper explores whether the continued suspension of austerity measures should be considered essential for addressing climate change. The importance of timely and decisive intervention is well established in the macroeconomic literature, which emphasizes the need for a rapid, rather than gradual, transition to sustainability (van der Ploeg 2011) and highlights the crucial role of governments in financing climate mitigation and adaptation efforts (Wang et al. 2024). Given the sudden and non-linear nature of climate change impacts on economic systems, this study examines the role of *timing* in the implementation of public adaptation policies. Specifically, it assesses how the duration of such policies influences economic performance, inequality, labour markets, and long-term fiscal sustainability.

To address these issues, we first develop a simple theoretical framework to clarify the key relationships between alternative public adaptation spending strategies. Our

analytical model suggests that adaptation policies can foster GDP growth and improve fiscal sustainability, provided that adaptation expenditures are sufficiently effective. Next, we extend the Italian EUROGREEN model (Distefano and D'Alessandro 2023) to incorporate climate damage projections under the RCP 6.0 scenario. This enables us to evaluate a range of macroeconomic indicators from 2010 to 2050 across various policy scenarios. For a comprehensive analysis, the Appendix presents the outcomes under the RCP 4.5 scenarios, which are comparatively less severe, although they do not alter the key findings of this study. Italy represents a particularly relevant case study due to its high public debt and its projected severe exposure to climate change impacts (Burke et al. 2015). Moreover, following the global financial crisis, Italy has repeatedly faced scrutiny over its large public debt and challenges in reducing fiscal deficits. This context raises a potential trade-off: on the one hand, rigid fiscal frameworks may constrain the implementation of effective adaptation policies to comply with short-term fiscal targets; on the other hand, delaying action could lead to greater future damages, ultimately increasing public debt due to economic losses and the rising costs of recovery.

2 Related Literature

2.1 Debt Sustainability

The concept of *debt sustainability* is rather elusive. From the theoretical point of view it implies that, excluding the possibility to finance public expenditure by *fiat money*, the government is respecting its *inter-temporal budget constraint*, i.e. the sum of expected revenues, discounted by adequate discount rates, are higher than the sum of expected expenditure, again discounted by adequate discount rates, where the latter includes also the actual stock of public debt. For instance, (Blanchard et al. 2021, p. 201) argued that “a working definition is that debt is sustainable so long as the probability of a debt explosion, and thus of eventual debt default, remains very low.” Thus, debt sustainability depends on various factors and their long-run trends—e.g., productivity growth, GDP, primary balances, and interest rates—that generate high uncertainties that weaken the commitment of government to long-run fiscal policy.¹ This leads economists and practitioners towards alternative and more operative definitions.

The evaluation of the European Commission of Member States' debt sustainability is based on a fiscal sustainability framework (European Commission 2020) grounded on two main instruments: the debt sustainability analysis (DSA) and some *fiscal sustainability indicators*, used to enrich the evaluation and to address some of DSA's limitations. Key results are reported in an overall summary heat map of fiscal sustainability risks. This multidimensional procedure considers risks across time (from short to medium term) and across countries in order to design an appropriate policy

¹ In macroeconomics, there is a significant debate on the conditions to achieve long-term debt sustainability when the interactions between fiscal policies and economic growth are taken into consideration. Recent developments in research also suggest that a rise in the fraction of GDP devoted to public investment can improve debt sustainability (e.g., DeLong and Summers 2012; Cottarelli and Jaramillo 2013; Heimberger et al. 2021).

response. The DSA used in the European Commission is based on the forecasts of fiscal variables that affect the level of debt (i.e. real GDP growth rate, inflation, primary balance, interest rates, exchange rate and stock-flow adjustment).²

A detailed discussion of the methods and limitations of DSA goes well beyond the scope of this paper.³ As Wyplosz (2011) *provocatively* points out, debt sustainability analysis is impossible since it can only provide educated guesses. It is worth noticing that some important issues and potential problems within this framework are exacerbated by climate change impacts. More importantly, since DSA provides projections for a maximum of ten years, taking into consideration climate change calls for a different approach, where government decisions can have long-term effects on economic growth and debt dynamics. Furthermore, this prevents DSA from considering the long-run effects of fiscal policies, such as public expenditure in adaptation and, in turn, the feedback effects that the latter has on GDP growth. These policies can increase public debt, but this negative effect can be more than compensated by a reduction of climate damages, with positive effects on GDP growth and public revenues in the long run.

2.2 Economic Losses from Climate Change

Concerns related to the severe impacts of climate change on economic activity and human well-being were once again confirmed in the Conference of the Parties (COP26), held in Glasgow IN 2021, based on up-to-date scientific literature (see, for instance, Burke et al. 2015) and the projections published by the Intergovernmental Panel on Climate Change (IPCC). The Sixth Assessment Report (AR6)⁴ acknowledges, beyond any level of reasonable doubt, that climate change due to anthropogenic activity is widespread and intensifying. The list of risks Europe is subject to, on a medium confidence level, includes risk to people, economies, and infrastructures due to coastal and inland flooding; stress and mortality to people due to increasing temperatures and extreme heat; disruption of marine and terrestrial ecosystems; water scarcity to multiple interconnected sectors; losses in crop production, due to compound heat and dry conditions, and extreme weather.

In numbers, the European Environmental Agency claims that economic losses related to climate extremes added up to an estimated EUR 487 billion in the EU-27 Member States between 1980 and 2020, and could result in even greater losses in the coming years.⁵ Moreover, a relatively small number (3%) of unique events was responsible for a large proportion (around 60%) of the economic losses, resulting in high variability from year to year. Looking at the impact on GDP, by using a multi-sector, multi-country computable Climate assessment General Equilibrium Model (CaGE model), Szweczyk et al. (2020) estimate the expected losses under different scenarios (1.5, 2, and 3°C of global warming compared to the pre-industrial level) for Europe. Exposing the present economy to global warming of 3°C would

² For more details about the methodology used by European Commission, see Annex 6 in European Commission (2020).

³ See, for instance, Debrun et al. (2019) for an overview of the different methodologies developed.

⁴ “Climate Change 2021: The Physical Science Basis”, see <https://www.ipcc.ch/report/ar6/wg1/>.

⁵ See <https://www.eea.europa.eu/ims/economic-losses-from-climate-related>.

result in an annual welfare loss of at least €175 billion (1.38% of GDP). Under a 2°C scenario, the yearly welfare losses would be of €83 billion (0.65% of GDP), while restricting warming to 1.5°C would keep welfare losses at about €42 billion/year (0.33% of GDP).

Neoclassical economists made notable efforts to incorporate climate change into mainstream models, with the Dynamic Integrated Climate-Economy (DICE) model by Nordhaus (1993) being one of the significant attempts. However, it's important to recognize that these endeavors faced criticism due to the unrealistic assumptions underpinning the DICE model and the broader limitations of neoclassical models. Many scholars consider these models to be flawed and inadequate for supporting effective climate policy interventions (Stiglitz 2018; Lavoie 2018). Such critiques emphasize the need for more robust and realistic models to address the complex challenges posed by climate change and to guide appropriate policy actions (Sterman 2002). Roberts and Huq (2015) considers economic and non-economic impacts from both extreme events, such as floods, droughts, and heatwaves and slow-onset events due to anthropogenic activity like sea level rise and loss of biodiversity to assess the overall "loss and damages". Among the most relevant forms of economic losses, which have a direct impact on markets, we may list damages to housing and infrastructure, changes in agricultural production, and tourism patterns. Non-economic losses include biodiversity loss, human life, human health, and human mobility. These also have indirect economic impacts on crops, migration, and human displacement following extreme weather events. A broader contextualization of climate damages allows us to better appreciate the level of uncertainty related to measuring it and explain the large variation between different damage functions (Russell et al. 2022).

Some models project divergent climate damage trajectories between southern and northern Europe. For instance, Burke et al. (2015) estimated the likelihood of GDP per capita reduction in 2100 by more than 20% at 83% in Spain, 57% in Italy, 19% in France, and 2% in Germany.⁶ Attempts to counter greater damages with public investment on adaptation could, therefore, impose a double burden on southern European countries that are expected to be hit hardest from global warming when compared to northern European nations. Reduced revenue from taxes and increased expenditures to either reduce future damages or rebuild communities affected by extreme weather events could accelerate public deficits in the Mediterranean.

2.3 Climate-Related Fiscal Risks

Although current estimates on the impact of climate change on European economies are severe in some regions and sectors but overall limited, there are reasons to believe that impacts on public finance can be more distressing. Despite the relevance of these effects, climate-related fiscal risks are generally disregarded in climate-economy models and were only recently considered in the fiscal sustainability frameworks of official institutions (see, for instance, European Commission (2020)). Climate change directly affects government deficits through the cost of replacing damaged public infrastruc-

⁶ For additional details and projections for other countries see <https://web.stanford.edu/%7Emburke/climate/map.php>.

ture, social transfers to households, and insurance schemes backed by state guarantees. Moreover, indirect costs can have substantial fiscal impacts, such as the reduction of tax revenues due to a slowdown in economic activity, the increase in healthcare spending, and the support to financial institutions in distress due to extreme climate-related events. These, in turn, can lead to an increase in interest rates, further deteriorating public balances (Zenios 2021). All these effects may have a substantial impact on the labor market, which is already dealing with the consequences of deregulation policies, as highlighted by Brancaccio et al. (2020). These additional challenges could result in negative implications for unemployment rates.

Public investments in mitigation and adaptation policies interact with debt dynamics, resulting in a trade-off between current public deficits and future climate risks. According to the IPCC WGIII Report (April 2022), mitigation policies are interventions aiming at reducing the sources or enhancing the sinks of greenhouse gases. They commonly include carbon taxes, emission trading schemes, and public subsidies for the clean energy transition. Their effects on government revenues and on debt sustainability can be different in the short and in the long run. Adaptation, on the other hand, takes into consideration adjustment in natural or human systems in response to actual or expected climatic shocks and their effects by moderating damages. Mitigation and adaptation policies are strictly related since mitigation reduces all impacts of climate change, thus reducing the adaptation challenge. However, mitigation has global advantages, but its benefit depends on the decisions of a sufficiently large number of major global emitters.

3 Insights from a Simple Model

This section presents a simplified model to examine the relationship between climate change, public expenditure on climate change adaptation, and debt sustainability. The points made here are intended to serve as a theoretical reference for interpreting the simulation results obtained with the EUROGREEN model, which are presented in the next section.

3.1 Setup

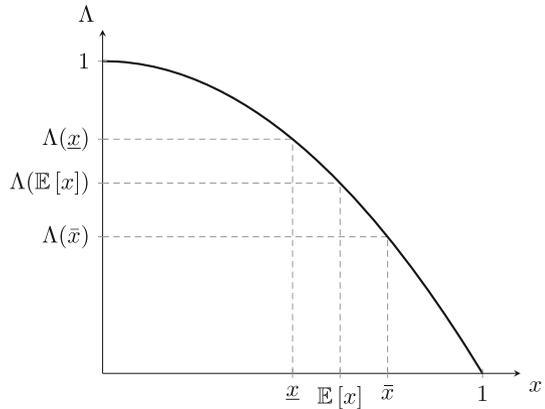
Consider a two-sector, three-period economy where production is described by a Leontief input–output function:

$$y_j = \min \left\{ \frac{z_{1,j}}{a_{1,j}}, \frac{z_{2,j}}{a_{2,j}} \right\}, \quad j = 1, 2 \quad (1)$$

where y_j is sector j 's output, $z_{i,j}$ denotes inter-industry sales from sector i to sector j , and $a_{i,j}$ is the technical coefficient describing the relation between sector j 's output and its input from sector i .

Climate change affects the economy directly through multiplication with output. Climate damage is denoted by $\Lambda \in (0, 1)$, where the values 0 and 1 indicate no

Fig. 1 Climate events and damage



production and no damage, respectively. Thus, a lower value of Λ means more damage. For the moment, we assume no sector-specific damage (this will be relaxed later). Using the superscript D to denote production net of damage, we therefore have:

$$y_{j,t}^D = \Lambda_t y_j = \min \left\{ \frac{z_{1,j}}{\Lambda_t^{-1} a_{1,j}}, \frac{z_{2,j}}{\Lambda_t^{-1} a_{2,j}} \right\}, \quad t = 0, 1, 2 \tag{2}$$

implying that climate damage increases the input requirement from sector i per output unit of sector j . This may be due to, e.g., changes in productivity and damaged inputs that need to be replaced. Total output Y is the sum of all sectoral outputs, that is, $Y = y_1 + y_2$ and $Y_t^D = y_{1,t}^D + y_{2,t}^D = \Lambda_t (y_1 + y_2)$.

Climate damage can be the result of extreme weather events, such as floods and droughts, and slow-onset changes, such as sea-level rise. The severity of these events is denoted by $x \in (0, 1)$. For mathematical convenience, and with no difference in qualitative results with respect to the EUROGREEN model, let damage at time t be given by:

$$\Lambda_t \equiv \Lambda(x_t) = 1 - x_t^2 \tag{3}$$

meaning that more severe climate events result in greater damage and less production.

In each period, x is a random variable uniformly distributed over the interval $[x, \bar{x}]$. This interval is influenced by two forces. On the one hand, it tends to increase in size and shift to the right from period to period, resulting in greater climate damage. This tendency can be interpreted as due to rising temperatures, which are taken as exogenous and not modeled here. On the other hand, the interval can be shifted to the left and reduced in size by government spending on climate change adaptation. Thus, put simply, global warming and adaptation spending increase and decrease the severity of weather events and climate damage, respectively. Figure 1 shows an interval of possible damages and the damage corresponding to the expected value of x , that is $\Lambda(\mathbb{E}[x]) = \Lambda\left(\frac{x+\bar{x}}{2}\right)$.

Formally, we assume that x_0 is given and that for each $t = 1, 2$ we have:

$$\underline{x}_t = x_{t-1} - \beta S_{t-1} \tag{4}$$

where x_{t-1} is the realized value of the random variable x at time $t - 1$, S_{t-1} is government expenditure on climate change adaptation at time $t - 1$, and $\beta > 0$ measures the effectiveness of adaptation spending, with higher values, corresponding to greater effectiveness. We further assume that:

$$\bar{x}_t = \underline{x}_t + f(\underline{x}_t) \tag{5}$$

where $f' > 0$, which makes the effect of climate change nonlinear (Burke et al. 2015) and implies that as climate events get more severe (i.e. as x increases), the range of possible future damages and the expected future damage both increase. Finally, for ease of exposition, in the remainder of this section, we let $f(\underline{x}_t) = \underline{x}_t/2$ and we assume that $\underline{x}_t > 0$ and $\bar{x}_t < 1$ for every t . We thus have:

$$x_t \sim U \left[\underline{x}_t, \frac{3\underline{x}_t}{2} \right] \subset (0, 1).$$

Let public debt in period zero be:

$$B_0 = \bar{B} + S_0 \tag{6}$$

where \bar{B} is the initial debt net of adaptation spending. Public debt in period one is instead:

$$B_1 = B_0 (1 + i) + S_1 - \tau Y_1^D \tag{7}$$

where i is the interest rate on debt, $Y_1^D = y_{1,1}^D + y_{2,1}^D = \Lambda(x_1)(y_1 + y_2)$ is total production net of damage, τ is the tax rate, and τY_1^D denotes tax revenues. The time-zero expectation of B_1 is:

$$\begin{aligned} \mathbb{E}_0 [B_1] &= B_0 (1 + i) + S_1 - \tau \mathbb{E}_0 [Y_1^D] \\ &= B_0 (1 + i) + S_1 - \tau \Lambda (\mathbb{E}_0 [x_1]) (y_1 + y_2). \end{aligned} \tag{8}$$

Similarly, in period two we have:

$$B_2 = B_1 (1 + i) - \tau Y_2^D \tag{9}$$

and

$$\begin{aligned} \mathbb{E}_0 [B_2] &= \mathbb{E}_0 [B_1] (1 + i) - \tau \mathbb{E}_0 [Y_2^D] \\ &= \mathbb{E}_0 [B_1] (1 + i) - \tau \Lambda (\mathbb{E}_0 [x_2]) (y_1 + y_2). \end{aligned} \tag{10}$$

3.2 Adaptation Spending Rules

The government can be of two types, named T' and T'' . A government of type T' takes strong, early action on climate change adaptation, with the aim of keeping the expected damage in period two at the same level as the damage in period zero. Specifically, S_0 is chosen so as to have $\mathbb{E}_0 [x_2] = x_0$, whereas S_1 is kept at zero. If $S_0 > 0$ and $S_1 = 0$, then

$$\underline{x}_1 = x_0 - \beta S_0, \quad \bar{x}_1 = \frac{3(x_0 - \beta S_0)}{2}, \quad \mathbb{E}_0 [x_1] = \frac{5(x_0 - \beta S_0)}{4}$$

in period one, and

$$\begin{aligned} \mathbb{E}_0 [\underline{x}_2] &= \frac{5(x_0 - \beta S_0)}{4} = \mathbb{E}_0 [x_1], \quad \mathbb{E}_0 [\bar{x}_2] \\ &= \frac{15(x_0 - \beta S_0)}{8}, \quad \mathbb{E}_0 [x_2] = \frac{25(x_0 - \beta S_0)}{16} \end{aligned}$$

in period two. The adaptation expenditure level chosen in period zero by a government of type T' is therefore:

$$S_0|_{T'} = \frac{9x_0}{25\beta} \tag{11}$$

which implies that

$$\mathbb{E}_0 [x_1]|_{T'} = \frac{4x_0}{5} \tag{12}$$

and

$$\mathbb{E}_0 [x_2]|_{T'} = x_0. \tag{13}$$

As an illustrative example, suppose that $x_0 = \frac{1}{5}$. In this case, $S_0|_{T'} = \frac{9}{125\beta}$, which in turn yields $\mathbb{E}_0 [x_1]|_{T'} = \frac{4}{25}$ and $\mathbb{E}_0 [x_2]|_{T'} = \frac{1}{5}$.

A government of type T'' can only spend a fraction $\alpha < 1$ of $S_0|_{T'}$ on climate change adaptation in period zero and a fraction $1 - \alpha$ in period one. That is, the amount $S_0|_{T'}$ spent on adaptation is distributed over two periods. This may be due to e.g. a fiscal constraint, since in the model climate adaptation is financed by deficit spending. For instance, letting $\alpha = \frac{1}{2}$ yields a per-period adaptation spending of:

$$S_0|_{T''} = S_1|_{T''} = \frac{S_0|_{T'}}{2} = \frac{9x_0}{50\beta} \tag{14}$$

in which case we have:

$$\mathbb{E}_0 [x_1]|_{T''} = \frac{41x_0}{40} > \mathbb{E}_0 [x_1]|_{T'}. \tag{15}$$

Moreover, since $\mathbb{E}_0 [\underline{x}_2]|_{T''} = \mathbb{E}_0 [x_1]|_{T''} - \beta S_1|_{T''}$ and $\mathbb{E}_0 [\bar{x}_2]|_{T''} = \frac{3}{2} \mathbb{E}_0 [\underline{x}_2]|_{T''}$, in period 2 we have:

$$\mathbb{E}_0 [x_2]|_{T''} = \frac{169x_0}{160} > \mathbb{E}_0 [x_2]|_{T'}. \tag{16}$$

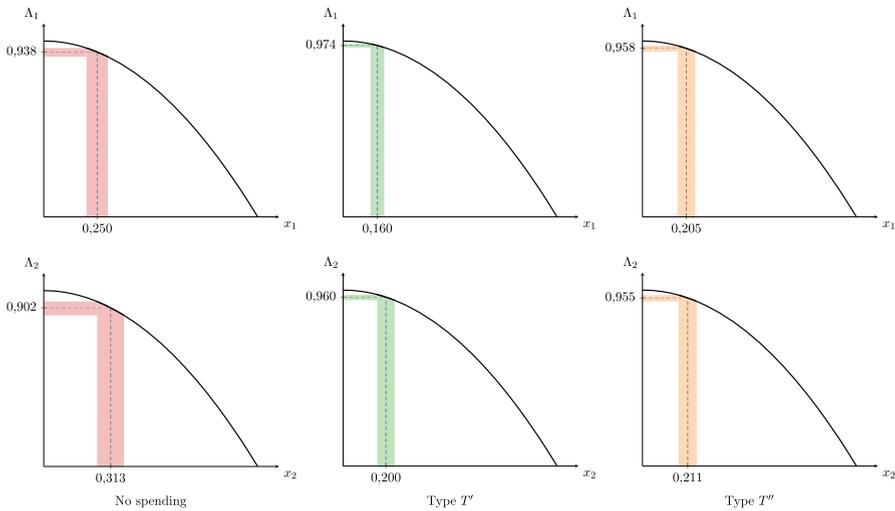


Fig. 2 Climate damage under different spending rules. $x_0 = 0.200$. Top row: period 1; Bottom row: period 2. The shaded areas denote the range of possible damages

For instance, if $x_0 = \frac{1}{5}$, then $S_0|_{T''} = S_1|_{T''} = \frac{9}{250\beta}$, implying $\mathbb{E}_0[x_1]|_{T''} = \frac{41}{200}$ and $\mathbb{E}_0[x_2]|_{T''} = \frac{169}{800}$. Figure 2 shows the change in climate damage between periods one and two under spending rules T' (green) and T''' (yellow) as well as under no-spending conditions (red) when $x_0 = \frac{1}{5}$.

Equations (15) and (16) show that the damage expected in each period by a government of type T''' exceeds the damage expected by a government of type T' . That is, a climate adaptation strategy that distributes spending over several periods is less effective than a strategy in which spending is concentrated in the first period. Furthermore, since $\mathbb{E}_0[x_t]|_{T'} < \mathbb{E}_0[x_t]|_{T'''}$ and $\Lambda(\mathbb{E}_0[x_t]|_{T'}) > \Lambda(\mathbb{E}_0[x_t]|_{T'''})$ for every $t = 1, 2$, it is easy to see that:

$$\mathbb{E}_0[Y_t^D]|_{T'} > \mathbb{E}_0[Y_t^D]|_{T'''} \tag{17}$$

meaning that early and strong action on climate adaptation results in a higher expected income.

Since climate change adaptation is financed by deficit spending, a government of type T' may end up with a higher debt burden in period two than a government of type T''' . This will typically be the case when climate adaptation costs are larger than the income foregone due to climate damage. Substituting Eqs. (12), (15), (13) and (16) into Eqs. (8) and (10), we obtain that

$$\mathbb{E}_0[B_2]|_{T'} \leq \mathbb{E}_0[B_2]|_{T'''} \tag{18}$$

holds if and only if

$$x_0 \geq \frac{512i(1+i)}{\beta\tau Y(441+112i)} \equiv \tilde{x}_0 \tag{19}$$

that is, if and only climate damage at time zero is sufficiently large, resulting in a substantial forgone income. If this is the case, then a government facing tight budget restrictions will choose a suboptimal adaptation strategy, with negative consequences in terms of both growth and debt.

Two points are worth noting here. First, the condition in Eq. (19) is sufficient but not necessary for the expected debt-to-GDP ratio of a government of type T' to be lower than that of a government of type T'' . If $\mathbb{E}_0[Y_2]_{T'}$ exceeds $\mathbb{E}_0[Y_2]_{T''}$ by a substantial margin, then a type- T' strategy may be more fiscally sustainable even when $x_0 < \tilde{x}_0$, i.e. when $\mathbb{E}_0[B_2]_{T'} > \mathbb{E}_0[B_2]_{T''}$. Second, the expenditure level given in Eq. (11) does not guarantee that a government of type T' will not suffer from increasing climate damages. A high realisation of the random variable x may still result in a loss of income.

The model is perhaps best understood in terms of current and future generations. From this perspective, the results are also relevant to the issue of intergenerational equity. The literature on climate change mitigation often examines the intergenerational trade-offs between the welfare costs of reducing emissions today and the climate damages incurred by future generations. This debate, commonly referred to as the discounting debate (see e.g. Heal and Millner 2014), centers on the evaluation of future generations' welfare today. This issue is of great importance, as the decision on optimal mitigation efforts crucially depends on how the future is discounted.

Adaptation, on the other hand, does not seem to pose such a dilemma. The additional deficit produced today can improve the welfare of future generations by preventing a decrease in income and making debt more sustainable. It is the introduction of limits on government spending today (with rules based on the past) that can create a conflict between current and future generations.

The model presented above provides a stylized picture of how public expenditure on climate adaptation may not worsen, and conversely may even contribute to debt sustainability when climate damages are taken into account. However, the model still fails to provide meaningful insights into other important effects of adaptation spending. How is climate damage likely to affect income distribution, and how can adaptation policies mitigate this effect? How much do current deficits contribute to GDP growth in the long run? What is the difference in terms of long-run public debt between a climate adaptation strategy that concentrates spending in the present and one that spreads spending over a longer period? To address these questions and quantify the impact of climate damage and adaptation spending, we take a simulation approach and compare different scenarios.

4 Macrosimulation Model

The previous sections clarify that the impact of climate damages on debt sustainability is crucially mediated by the presence of several channels and feedback loops. Moreover, the choice of adaptation policies will introduce additional inter-temporal trade-offs that increase this complexity. To provide a reliable analysis of policy options, we employ an extended version of the EUROGREEN model, applied to Italy (Cieplin-

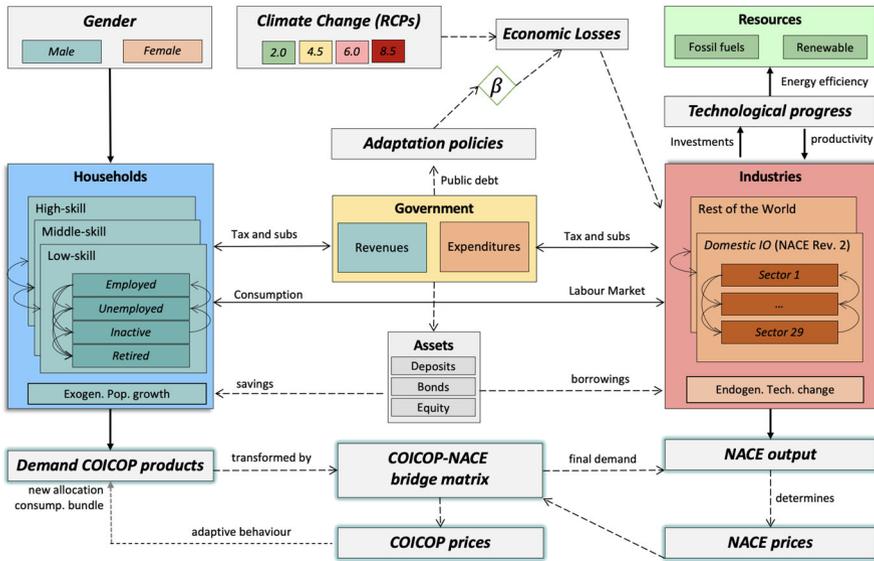


Fig. 3 Model macro-view. Main variables and relations of the current version of the *EUROGREEN* model adapted from D’Alessandro et al. (2020), Distefano and D’Alessandro (2023). In the present version, we introduce adaptation policies and their impact on the abatement of economic losses mediated by the parameter β , i.e. the adaptation effectiveness

ski et al. 2021; Distefano and D’Alessandro 2023). Figure 3 shows the main variables and the causal relations of the updated version of the model.

As described in detail in D’Alessandro et al. (2020), the *EUROGREEN* model is grounded on three main methodological pillars:

1. *Post-Keynesian economics*: considers that output is driven by effective demand and the economy does not show any spontaneous tendency towards full employment of factors of production, prices are determined as a markup over average costs of production. Moreover, the distribution of the product among the social classes is not determined entirely by technological variables but reflects their relative bargaining power, in a process influenced by the historical evolution of nominal incomes and employment rates.
2. *System dynamics (SD)*: approach to analyse the interconnections and feedbacks among the socio-economic and environmental components. SD has a high degree of flexibility and a graphical structure that allows the identification of feedback mechanisms;
3. *Environmentally extended social accounting matrix and input–output*: that provides a consistent economic framework, coherent with the official national accounts, to study inter-industry connections. This includes the composition of the labour force (skills, working time, and wages) and the resource uses (e.g., energy) by sector.
4. Innovation dynamics in *EUROGREEN* have a stochastic component that determines the availability and efficiency increases of new technologies that tend to reduce technical coefficients, increase labour productivity, or both. The least-cost

technology will be adopted by the industry, resulting in labour and/or intermediate resources saving.⁷

The combination of these approaches stands also at the core of “Ecological Macroeconomics”. Moreover, to replicate the effects of the COVID-19 pandemic, we included exogenous shocks to private consumption, investment, exports, and imports in 2020 and 2021.

4.1 Climate Change Damage

The primary novelty introduced in the current study involves the incorporation of a climate damage function, which is expected to alter economic productivity by modifying the technical coefficient, as explained in Appendix B. Climate change is considered exogenous, given that Italy contributes to only approximately 1% of global emissions.⁸ For the sake of simplicity, results are presented exclusively for the Representative Concentration Pathways 6.0 (RCPs 6.0), which projects global temperature increases between 3 and 3.5°C by 2100.⁹ Nevertheless, Appendix C.2 provides a comparison with the less severe scenario, RCP 4.5, which induces relatively minor damages, although the key conclusions of the study remain unchanged. Climate projection data are taken from the global climate model compilations of the Coupled Model Inter-comparison Projects (CMIPs), overseen by the World Climate Research Program, and provided by the World Bank¹⁰

In every simulation period (year) industry-specific damages are drawn from a Beta distribution similar to those applied in Desmet and Rossi-Hansberg (2015) with modifications to account for extreme climate events (see Appendix B). The climate damages drawn for every industry, from the distribution increase their respective technical coefficients in the input–output tables that determine output and intermediate consumption. Hence, it is equivalent to an increase in the amount of inputs necessary to produce the same output. Thus, to meet a certain level of final demand, industries affected by climate change must increase their demand for intermediate products. Thus, the output of upstream industries may also increase.

Changes in industry output directly affect employment levels. However, at the aggregate level, the impact of climate change on unemployment and inequality remains complex and non-linear. While an increase in intermediate demand for a given level of final demand can reduce value-added and profits—assuming relatively sticky wages—the overall effects on the labour market are not straightforward. Certain climate change impacts discussed in Sect. 2.1 are not explicitly accounted for in this analysis, such as direct capital losses or shifts in demographic structures. However, many effects are indirectly incorporated. For instance, since industries include both the public

⁷ See section 1.6 in the Supplementary Information of D’Alessandro et al. (2020) for a detailed description.

⁸ See <https://ourworldindata.org/co2/country/italy>.

⁹ See <https://www.ipcc.ch/assessment-report/ar5/>.

¹⁰ Please, refer to Appendix Table 4 for the projections of average temperatures and their variations, until 2050, under Representative Concentration Pathways 6.0 and 4.5, grounded on the models incorporated in the Coupled Model Inter-comparison Projects (CMIPs). See also <https://climateknowledgeportal.worldbank.org/country/italy/climate-data-projections>.

sector and services, rising public healthcare expenditures enter the model through increased technical coefficients in that sector. Additionally, other fiscal effects emerge through changes in government spending, driven by variations in tax revenues linked to income, value-added, and profits—as well as fluctuations in unemployment benefits due to labor market dynamics. In particular, a decline in unemployment contributes to improving public finances not only through higher income and value-added tax revenues but also via lower expenditure on unemployment benefits. These effects are captured through the endogenous relationship between labour market dynamics and government revenues and expenditures.

4.2 Debt Dynamics

Public debt increases with government deficits.¹¹ The public sector revenue in EURO-GREEN is a function of social security contributions, carbon taxes, value-added taxes, income taxes, financial income taxes, and corporate income taxes. Government expenditures include unemployment and other social benefits, pensions, public investments, public expenditures on goods and services, and interest on the outstanding public debt. Therefore, there is a reinforcing cycle on public debt: deficits increase future expenditure on interest and, thus, favor further increases in public debt. However, public expenditure and investments also have a multiplier effect on growth that increases future taxes, which can more than compensate for the future expenditures on debt interest.

From the discussion above on the impact of climate change on production, it is clear that climate damages affect public expenditure and revenues in a variety of ways. However, while on the government expenditure side, we expect small changes; the impacts on government revenues are relevant since reductions in value-added and profits have a direct impact on tax income, as argued in the model developed in Sect. 3. The minor impact on government expenditure depends on the assumption that climate change only affects technical coefficients without taking into account other direct costs associated with social security or climate-related migration. This means that the cost of climate change included in the model is a conservative estimate of the impact of climate change on government expenditure.

4.3 Adaptation Policies

We assume that the government can increase public deficit and debt to finance adaptive strategies to reduce the potential economic losses due to climate change. In our model, this effect is captured by a single parameter (α), which indicates the effectiveness of public expenditure on adaptation. In other words, it measures the percentage of economic damages avoided for every euro spent on adaptation. Hence, we assume that adaptation policies have no impact on the probability of occurrences of extreme events, but they mitigate the negative effects associated with the increase in technical coefficients of the input–output.

¹¹ For a description of the private debt dynamic in the EUROGREEN model, see the Supplementary Material of D'Alessandro et al. (2020).

Let us define $a_{i,j}(t)$, the technical coefficient, representing the relation between sector j 's output and its input from sector i . Introducing a sectoral climate damage multiplier $(1 - \Lambda_j(t)) \in [0, 1]$, in every period t we have that the technical coefficient is $\frac{a_{i,j}(t)}{1 - \Lambda_j(t)}$. The adaptation policy proportionally reduces the magnitude of $\Lambda_j(t)$ by means of parameter $\alpha(t)$. Thus, the impact of climate change becomes $\frac{a_{i,j}(t)}{1 - \alpha(t)\Lambda_j(t)}$, with

$$\alpha(t + 1) = \alpha(t) - \gamma_t \cdot S(t), \text{ or} \quad (20)$$

$$\Delta\alpha(t) = -\gamma_t \cdot S(t), \quad (21)$$

where $S(t)$ is the adaptation expenditure, in billion euros, and γ_t is the effectiveness or efficiency of adaptation expenditure. While a growing body of literature is attempting to calculate the effectiveness of adaptation policies for specific sectors (e.g., Cortignani et al. 2021), there is no consensus on the effectiveness of adaptation at a macroeconomic level. To account for uncertainty in the effectiveness of public adaptation, we assume that in each period, (γ_t) is drawn from a uniform distribution (i.e., $\gamma_t \sim U[0.017, 0.033]$). This ensures that the cumulative effect will range between 51% and 99% when the total investment is fully deployed. Specifically, (γ_t) is scaled by the total expenditure in billions of euros, so with a maximum expenditure of 30 billion, we obtain $(0.017 \times 30 = 0.51)$ and $(0.033 \times 30 = 0.99)$. Consequently, after hundreds of simulations, the median effect is expected to converge around the midpoint, yielding an average impact of approximately 75%. We further assume that $\alpha \in [0, 1]$ since adaptation can have no effect ($\alpha = 1$) or it can fully recover the productivity in the absence of climate change ($\alpha = 0$), but it cannot increase it beyond that limit.

4.4 Scenarios Definition and Design

We employ a “sequential scenario” strategy (Nieto et al. 2020) to define the narratives, facilitating the isolation of the impacts of each hypothesis and the evaluation of their cumulative effects. Initially, we adopt as a benchmark the baseline articulated within the EUROGREEN model, which presupposes the absence of climate damage, thereby establishing a hypothetical reference scenario. Subsequently, we incorporate climate change projections from the Representative Concentration Pathways RCP 6.0 and quantify the impacts on a range of socio-economic and environmental indicators. To sum up, we simulate four scenarios:

1. *Benchmark*. This scenario takes the baseline developed in the EUROGREEN model without climate damage to obtain a referential optimistic (and hypothetical) scenario to be compared with the outcomes coming from climate change and adaptation policies.
2. *Damage*. This scenario considers the impact of climate change, under the RCP 6.0 scenario, at the industry level without the introduction of any targeted adaptation policy.

Table 1 Summary of the main assumptions for every scenario

Scenarios	Climate change	Economic damage	Yearly expenditure	Duration
BAU				
RCP 6.0	✓	✓		
RCP 6.0 Fast	✓	✓	10 billion €	3
RCP 6.0 Slow	✓	✓	1 billion €	30

3. *Fast adaptation.* From 2024 to 2026 (3 years), the government plans a new expenditure in adaptation with a budget of €10 billion per year.
4. *Slow adaptation.* The second strategy assumes a less proactive governmental response to climate change (possibly constrained by “austerity” measures), with the same budget being distributed over a 30-year span.

The comparison between the first two scenarios delineates the impact of climate change on the socioeconomic system and debt sustainability. The last two scenarios investigate the timing of public intervention and the possibility of a trade-off between a “fast” adaptation that increases the deficit today (and interest on debt tomorrow) with the aim of a fast reduction in climate damage and a “slow” strategy which tends to be more conservative on fiscal balance today but delays adaptation to climate change.

The budget of €30 billion for the adaptation expenditure is based on the resources that can be mobilized in the next few years stated in the Italian Recovery and Resilience Plan (Presidenza del Consiglio 2021). The total projected investments amount to about €190 billion, while €60 billion of these are directed to “the ecological transition and the green revolution”. However, a significant share of the latter funds are directed to mitigation (€23 billion for energy transition) and other objectives not directly linked to adaptation policies. The plan also highlights a budget of €15 billion for “protection of land and water resources”, €15 billion for “energy efficiency”, and €5 billion for “circular economy and sustainable agriculture”. Most of this budget is expected to be financed with the issuance of new debt. Thus, the assumption that €30 billion can be devoted to adaptation in three years, as new government spending, is not far from projected expenditure in adaptation-like objectives (Table 1).

5 Simulation Results

The graphs plot the median and the 95% confidence interval (represented by the shaded area) for both the Baseline and RCP 6.0 scenarios, derived from 300 simulations for each respective scenario. Furthermore, the impact of adaptation policies, Fast and Slow, is reported as the difference in median values, for the sake of simplicity.

5.1 Climate Damage

Figure 4 compares the dynamics of the Benchmark scenario (BAU, without climate change) with the climate damage scenario (RCP 6.0). The projected effects of climate

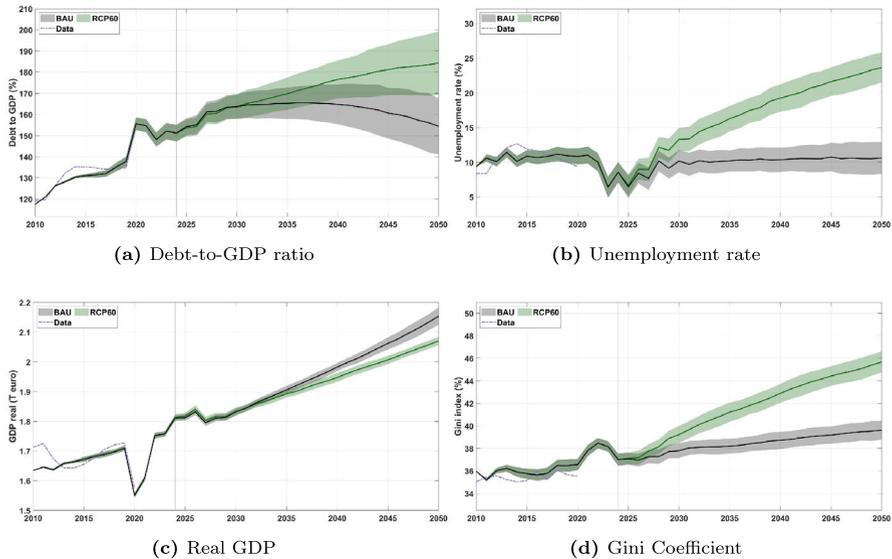


Fig. 4 Main macroeconomic indicators. The lines represent the median of 300 simulations for each scenario: baseline (black) and damage RCP 6.0 (green). The shaded areas indicate the 95% confidence interval. The vertical dotted line marks the starting year for calculating climate damage and policy adaptations (2024)

change on real GDP (Fig. 4c) are relatively mild, consistent with Kahn et al. (2021), as more severe impacts are expected to materialize after 2050. Despite this moderate GDP reduction, the effect on the debt-to-GDP ratio is substantial, reaching nearly 30% higher in 2050 (Fig. 4a). Notably, these fiscal divergences emerge as early as 2030, when rising temperatures begin to exert a more pronounced economic impact.

As discussed in the previous section, EUROGREEN captures the effects of climate change through modifications in the technical coefficients of the input–output matrix. Consequently, the increase in deficit and debt primarily stems from a decline in tax revenues—particularly from value-added and corporate income taxes—which are impacted earlier and more significantly than other fiscal components. This mechanism also explains the observed inequality dynamics, measured by the Gini coefficient (panel 4d). Hence, the impact of climate change on productivity leads to reduced output, which in turn decreases labour demand and wages, negatively affecting household income. This reduction in income lowers consumption, leading to a contraction in aggregate demand that further depresses output and employment, creating a self-reinforcing cycle of economic contraction. Additionally, the model captures job polarization, which exacerbates income inequality by disproportionately affecting lower-income households and contributing to the widening of income disparities.

Even before 2030, inequality under the RCP 6.0 scenario diverges significantly from the BAU trajectory, leading to a sharp increase in income disparities. By 2050, the Gini coefficient reaches an alarming level of almost 46%, nearly 15 points higher than in the baseline, which itself already indicates a worsening of inequality. Closely linked to this trend is the impact on unemployment rates, which follow a similar trajectory.

Under the RCP 6.0 scenario, unemployment soars to nearly 25%—almost double the level expected under the BAU scenario—highlighting the severe socio-economic consequences of unmitigated climate change.

5.2 Adaptation Policies

The Benchmark scenario serves as a useful counterfactual to better understand the impact of climate change, even though it remains a purely hypothetical construct. To assess the effectiveness of adaptation policies, we calculate the ratio of key economic and environmental outcomes under each adaptation policy relative to the Benchmark scenario. Specifically, for quantitative indicators (e.g., monetary values, Mtoe, Mton, etc.), we compute the ratio the percentage difference as $\Delta\% = 100 \cdot (x_1/x_0 - 1)$, where x_j represents the median value of the indicator under the given adaptation policy, and x_0 is the corresponding median value in the Benchmark scenario. A ratio close to 0 indicates that the adaptation policy enhances the system's resilience by bringing outcomes closer to the ideal scenario without climate change. For indicators already expressed as percentages (e.g., Debt-to-GDP ratio, unemployment rate, Gini coefficient), we plot the absolute difference in percentage points ($\Delta\% = x_1\% - x_0\%$). For absolute values, we compute the percentage difference as ($\Delta\% = 100 \cdot (x_1/x_0 - 1)$). Figures 5 and 6 display the main result of the study which compares the outcomes only from 2023, the year before the implementation of the policy, until 2050. To enhance the comparative assessment, we included the 'no policy intervention' scenario as a reference line in all figures. This allows for a clearer evaluation of the effectiveness of adaptation strategies. Notably, the Slow adaptation scenario remains closer to the trajectory with climate damage but without policy intervention, whereas the Fast adaptation scenario approaches the Benchmark (BAU) path with no climate change. This pattern suggests that the Fast adaptation strategy is more effective in mitigating climate damages, as it enables the system to recover a larger share of the baseline welfare and economic performance levels.

Overall, the Fast adaptation scenario (green lines) proves more effective in ensuring long-term fiscal sustainability. The deficit-to-GDP ratio (Fig. 5a) initially increases during the first three years of implementation but then stabilises around 0.1–0.2%, although a peak of about 0.5%, eventually approaching zero by the end of the period. In contrast, the Slow adaptation scenario (red lines) exhibits a steady and continuous increase until 2045, peaking at nearly 1.5% above the BAU level before experiencing a sudden decline. These dynamics mirrors in the Debt-to-GDP ratio (Fig. 5b), where the Fast adaptation scenario remains closer to the BAU trajectory, while the Slow adaptation scenario follows an upward trend to almost 30 percentage points higher than BAU, indicating a worsening fiscal outlook.

The high value of the debt-to-GDP ratio is also due to lower yearly GDP growth rates under the two adaptation scenarios. Panel 5c reinforces the previous findings, as the economic growth rate remains consistently higher under the Fast adaptation scenario compared to the Slow adaptation scenario. The Fast adaptation strategy nearly offsets climate-related economic damage by the end of the period, with differences as small as 2%. In contrast, the Slow adaptation scenario has minimal or no impact

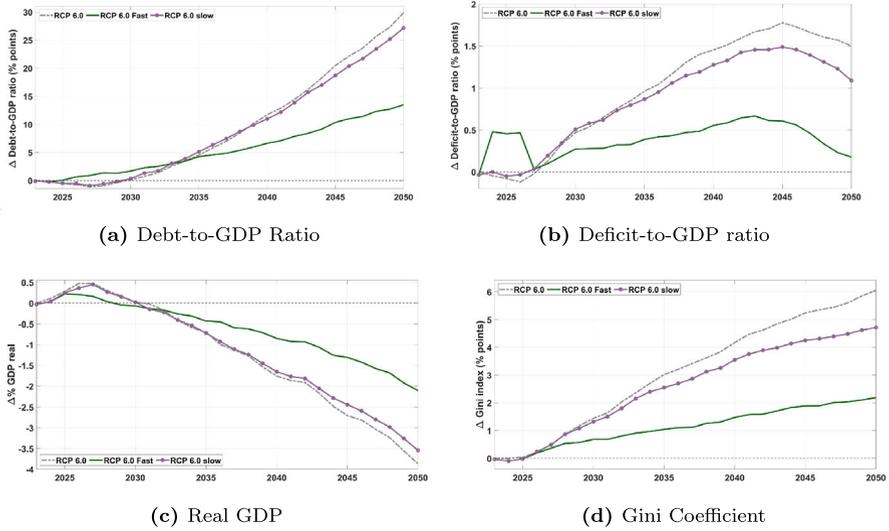


Fig. 5 Economic adaptation effectiveness. The lines represent the percentage difference* in medians between the fast (green) and slow (red) adaptation scenarios relative to the Benchmark. The horizontal dotted black lines indicate the ideal value under the reference scenario (BAU) with no climate change, while the grey dotted lines represent the impact of climate damage (RCP 6.0) with 'no policy interventions'. *For indicators already expressed as percentages, we plot the absolute difference in percentage points ($\Delta\% = x_1\% - x_0\%$). For absolute values, we compute the percentage difference as ($\Delta\% = 100 \cdot (x_1/x_0 - 1)$)

even in the medium term, with an increasing divergence reaching up to -4% . Furthermore, Fig. 5d highlights the significant impact of different adaptation strategies on income distribution and inequality. Under the Fast adaptation scenario, the Gini coefficient remains close to the BAU throughout the period, with a maximum deviation of about 2 Gini points. In contrast, the Slow adaptation scenario leads to a steady deterioration in income inequality, resulting in a Gini coefficient approximately 5 Gini points higher than the Benchmark by the end of the simulation period. Similarly, Fig. 6b demonstrates that the choice of adaptation strategy has profound implications for labour market outcomes. Under the Fast adaptation scenario, the unemployment rate increases at a slow pace, deviating from the BAU scenario, with a maximum difference of more than 4 percentage points. In contrast, the Slow adaptation scenario leads to a continuous rise in unemployment, peaking at a dramatic 10 percentage points above the Benchmark by the end of the period. A comparable pattern emerges for the labour share (Fig. 6a), where the Fast adaptation scenario helps maintain a more equitable distribution of income between workers and capitalists, while the Slow adaptation scenario results in a persistent decline in labour share, exacerbating economic disparities.

Climate change hits industries in asymmetric ways. The most affected are trade and agriculture, with a loss in the value added at the end of the simulation period of approximately 24% and 14%, respectively. In contrast, damages in other industries are negligible, also because the reduction in efficiency in the sectors mentioned above creates an additional demand for intermediate products for units of output, which com-

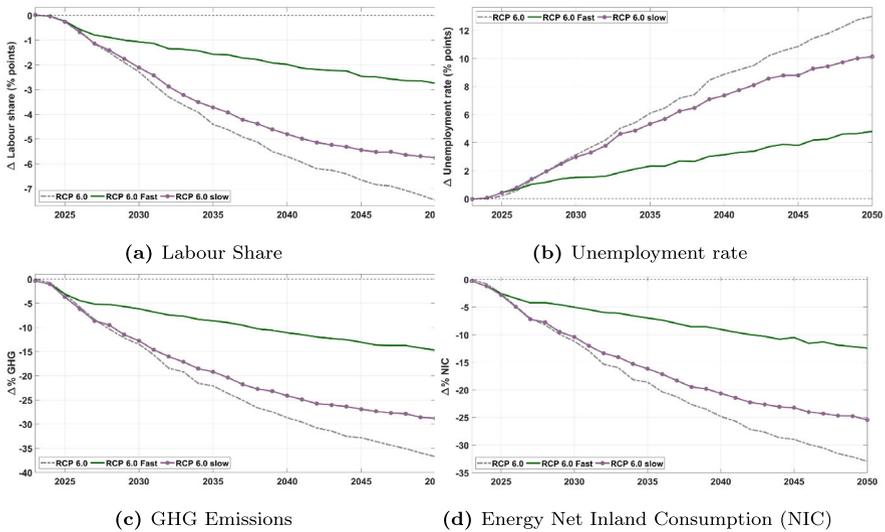


Fig. 6 Social and environmental adaptation effectiveness. The lines represent the percentage difference* in medians between the Fast (green) and Slow (red) adaptation scenarios relative to the Benchmark. The horizontal dotted black lines indicate the ideal value under the reference scenario (BAU) with no climate change, while the grey dotted lines represent the impact of climate damage (RCP 6.0) with 'no policy interventions'. *For indicators already expressed as percentages, we plot the absolute difference in percentage points ($\Delta\% = x_1\% - x_0\%$). For absolute values, we compute the percentage difference as ($\Delta\% = 100 \cdot (x_1/x_0 - 1)$)

pensates for the reduction of total output. However, the ability of the Fast adaptation strategy to contain economic damages comes with a trade-off in terms of environmental impact. As shown in Fig. 6c, greenhouse gas (GHG) emissions remain higher under the Fast scenario compared to the Slow one, reflecting the increased economic activity and energy consumption necessary to sustain growth (Fig. 6d). In contrast, the Slow adaptation scenario results in lower emissions and reduced net inland energy consumption, as the overall economic slowdown leads to a decline in energy demand. These findings suggest that while adaptation policies are crucial for mitigating economic and social damages, they are not sufficient on their own. To ensure a sustainable transition, adaptation must be complemented by broader strategies aimed at decarbonization and energy system transformation—an aspect beyond the scope of the present study but essential for future research and policy design.

6 Discussion

6.1 Limitations

Although the study combines a rigorous analytical framework with a complex and established model like EUROGREEN, grounded in actual data to test alternative scenarios, we acknowledge the main limitations.

First, our assumption that climate change affects the economy solely through reductions in industries' productivity overlooks other critical channels through which climate change can impact people's well-being and economic stability. However, even under this conservative framework, our simulations indicate that adaptation policies play a crucial role in preventing unchecked debt accumulation driven by climate-related damages. While mitigation remains essential, it is equally important to assess who benefits from climate policies and to identify the winners and losers in the energy transition. For instance, the Italian government has subsidized the purchase of electric vehicles—typically expensive—and the energy efficiency of buildings. Data from the Italian Parliament's research offices indicate that these subsidies disproportionately benefited wealthier households, exacerbating inequalities in living standards. This highlights a key distinction between adaptation and mitigation policies: while adaptation measures directly address climate-induced economic disruptions, mitigation policies currently implemented in many European countries often favor affluent groups (see, e.g., Owen and Barrett 2020; Sovacool 2021). Moreover, since the study focuses on aggregate macroeconomic sectors, it does not account for micro-level impacts at the firm level (Lamperti et al. 2018, 2019). Future studies could incorporate this perspective to assess how private actors respond to climate change, particularly in terms of innovation and investment.

Second, while our study emphasizes the importance of timely adaptation investments, it does not explicitly incorporate the concept of *low-regret adaptation pathways* (Haasnoot et al. 2013, 2024). Unlike dynamic adaptation planning frameworks that account for uncertainty by sequencing measures flexibly over time, our model evaluates only pre-defined adaptation strategies without a proper evaluation of cost-effective strategies. As a result, while we highlight the macroeconomic trade-offs of early versus delayed adaptation, our approach does not provide an optimal sequencing of adaptation investments in response to evolving climate and economic conditions. Future research could integrate adaptive decision-making frameworks into macroeconomic modeling to better reflect the complexities of climate adaptation policies.

Finally, although Italy provides a compelling case to explore the interplay between debt, climate change, and adaptation policies, the generalizability of our findings is subject to country-specific factors. A nation with lower debt levels, for example, may experience different trade-offs, and the timing of climate impacts on fiscal dynamics may vary. However, our model remains flexible enough to incorporate additional relevant factors and can be adapted to different national contexts, depending on data availability. Future research will extend this analysis to other countries, allowing for comparative assessments that can further inform robust, data-driven policy decisions.

6.2 Concluding Remarks

This study investigates the fiscal and macroeconomic implications of climate adaptation policies within the evolving economic landscape of the European Union. In light of increasing concerns about a potential return to austerity, the study explores

how relaxing stringent fiscal constraints could strengthen governments' ability to effectively contain climate damages. The analysis begins with a simple theoretical model that examines the relationship between public adaptation spending and macroeconomic outcomes. The model suggests that well-designed adaptation policies can drive GDP growth and ensure fiscal sustainability, as long as investments are both timely and strategically implemented.

Building on this foundation, the second part of the study extends the EUROGREEN model to incorporate climate damages under the RCP 6.0 scenario, simulating key macroeconomic indicators for Italy from 2010 to 2050. Italy is chosen as a case study due to its combination of high public debt and significant climate vulnerability, making it an ideal context for assessing the trade-offs between fiscal constraints and adaptation strategies. The findings reveal that while GDP reductions under the RCP 6.0 scenario are projected to remain moderate through 2050, there is a significant increase in the debt-to-GDP ratio—approximately 20%—driven by declining tax revenues and rising public expenditures. These results underscore the financial risks of climate inaction and emphasize the need for proactive adaptation strategies. Additionally, climate-induced damages are shown to worsen inequality, as reflected by an increase in the Gini coefficient, further exacerbating income disparities. This is compounded by a rise in unemployment, suggesting a deterioration in economic conditions.

This research develops a comprehensive framework for evaluating the long-term fiscal risks associated with various climate adaptation policies, with a particular focus on the timing of these strategies. The key findings are as follows: while climate change negatively affects GDP, its most notable fiscal consequence is the sharp rise in the debt-to-GDP ratio. This increase, driven primarily by falling government revenues—especially from value-added and income taxes—intensifies the risk of insolvency and underscores the need for proactive adaptation measures. The study compares two adaptation strategies. The *Fast* adaptation scenario—allocating 10 billion euros annually over three years to restore sectoral productivity—proves highly effective in mitigating the socio-economic impacts of climate change. In contrast, the *Slow* adaptation scenario—spending 1 billion euros per year over thirty years—yields significantly weaker outcomes. Overall, the Fast adaptation approach bolsters resilience and fiscal sustainability, while delayed action exacerbates fiscal and economic vulnerabilities.

These findings suggest that rigid fiscal rules could create a lose-lose situation, undermining both climate adaptation efforts and debt stability. Austerity measures may prevent highly indebted countries from making the necessary investments to stabilize their debt trajectories, paradoxically threatening the very fiscal sustainability they aim to preserve. The analysis, supported by both a theoretical model and an extensive set of simulations, shows that imposing strict limits on public adaptation spending significantly increases the likelihood of a public debt crisis in the coming decades. Further simulations in the Appendix demonstrate that similar conclusions hold under the milder RCP 4.5 scenario. This reinforces the idea that early and decisive intervention acts as an insurance policy, reducing future risks without imposing significant long-term trade-offs. However, while the Fast Adaptation strategy yields economic benefits, it also results in higher greenhouse gas (GHG) emissions and

increased energy consumption, highlighting the need for complementary policies that support both climate adaptation and the energy transition. This suggests that adaptation alone is insufficient and must be integrated with broader mitigation efforts—a topic outside the scope of this study but crucial for future research.

Simulation outcomes highlight the urgent need to rethink fiscal policies in the face of climate change. The results suggest that delaying adaptation efforts not only exacerbates economic losses but also increases the risk of fiscal instability, ultimately undermining debt sustainability in the long term. In contrast, proactive and well-targeted adaptation policies can act as a powerful tool to safeguard both economic resilience and public finances. This calls for integrating climate adaptation into broader fiscal frameworks to ensure long-term sustainability. However, adaptation alone is insufficient without a complementary energy transition strategy; higher resilience may come at the cost of increased emissions and energy consumption. This reinforces the need for policies that align adaptation with mitigation efforts, addressing both climate change and its socio-economic repercussions simultaneously. Hence, a broader policy approach is required to integrate adaptation strategies with ambitious mitigation efforts while ensuring social equity. Effectively addressing climate change requires not only financial resources but also a fundamental shift in policy priorities—one where fiscal rules support long-term resilience rather than obstructing the necessary actions.

In conclusion, our methodology can be extended to other countries, particularly those with different economic structures or varying levels of climate vulnerability, allowing for a broader understanding of fiscal and adaptation dynamics in diverse contexts. Future research could also explore alternative adaptation pathways, enabling a more flexible allocation of public investments to maximize the effectiveness of climate adaptation efforts. This approach would allow for a more nuanced response to climate damage, facilitating targeted interventions that balance economic resilience with sustainable fiscal management. By testing different adaptation pathways, future studies could provide valuable insights into optimizing the allocation of resources and improving long-term fiscal resilience.

Appendix A: Tables

See Tables 2, 3 and 4.

Table 2 This table presents the 19 macro-sectors used in the Italian EUROGREEN model, indicating which NACE sectors are grouped within each aggregated category

Sector no	Sector name	Nace Rev. 2 code
1	Agriculture, forestry and fishing	<i>A</i>
2	Mining and quarrying	<i>B</i>
3	Manufacturing	<i>C</i> (excl. <i>C19</i>)
4	Coke and refined petroleum products	<i>C19</i>
5	Electricity, gas, steam and air conditioning supply	<i>D</i>
6	Water supply	<i>E</i>
7	Construction	<i>F</i>
8	Wholesale and retail trade	<i>G</i>
9	Transportation and storage	<i>H</i>
10	Accommodation and food service activities	<i>I</i>
11	Information and communication	<i>J</i>
12	Financial and insurance activities	<i>K</i>
13	Real estate activities	<i>L</i>
14	Professional, scientific, technical, administrative	<i>M, N</i> and support service activities
15	Public administration and defence	<i>O</i>
16	Education	<i>P</i>
17	Human health and social work activities	<i>Q</i>
18	Arts, entertainment and recreation	<i>R</i>
19	Other	<i>S, T, U</i>

Table 3 Exogenous percentage changes in the main components of aggregate demand between 2019 and 2020 as a result of the Covid-19 pandemic

Covid shocks	$\Delta\%$
Investments	– 12.40
Consumption	– 8.84
Export	– 15.4
Import	– 17.3

Authors' own elaboration. Data are provided by the EUROSTAT [GDP and main components](#)

Table 4 Temperature projections under the Representative Concentration Pathways 4.5 and 6.0.

Temperature Projections	RCP 4.5				RCP 6.0			
	Mean	10th	90th	Std	Mean	10th	90th	Std
2024	13.8	13.0	14.6	0.6	13.8	13.0	14.6	0.6
2025	13.9	13.1	15.1	0.9	13.9	13.0	14.7	0.8
2026	14.1	13.3	15.1	0.8	13.8	12.9	14.7	0.7
2027	13.9	13.4	15.0	0.8	14.0	13.1	14.6	0.5
2028	14.0	13.4	15.2	0.9	13.8	13.0	14.8	0.8
2029	14.1	13.4	15.0	0.7	14.0	12.9	15.2	0.9
2030	13.9	13.3	14.8	0.7	13.9	13.0	15.3	1.1
2031	13.9	13.0	15.0	0.9	14.1	13.0	14.9	0.6
2032	14.3	13.4	15.0	0.6	14.0	13.3	15.3	1.0
2033	14.1	13.3	14.9	0.6	14.2	13.2	15.0	0.6
2034	14.2	13.3	15.1	0.7	14.1	13.4	15.2	0.9
2035	14.3	13.6	15.3	0.8	14.1	13.0	15.6	1.2
2036	14.4	13.6	15.3	0.8	14.0	13.3	15.4	1.1
2037	14.4	13.4	15.0	0.5	14.4	13.5	15.4	0.8
2038	14.4	13.6	15.3	0.7	14.3	13.4	15.2	0.7
2039	14.3	13.6	15.1	0.6	14.5	13.2	15.2	0.6
2040	14.2	13.5	15.3	0.8	14.4	13.3	15.8	1.1
2041	14.1	13.6	15.1	0.8	14.4	13.6	15.5	0.9
2042	14.4	13.7	15.2	0.6	14.3	13.4	15.7	1.1
2043	14.5	13.4	15.3	0.7	14.7	13.9	15.4	0.5
2044	14.3	13.4	15.4	0.8	14.6	13.5	15.6	0.8
2045	14.5	13.9	15.3	0.6	14.4	13.7	15.7	1.0
2046	14.5	13.4	15.3	0.7	14.4	13.4	15.5	0.9
2047	14.7	13.3	15.4	0.6	14.7	13.9	15.6	0.7
2048	14.7	13.8	15.7	0.8	14.8	13.9	15.6	0.7
2049	14.5	13.7	15.7	1.0	14.9	14.0	15.7	0.6
2050	14.8	14.0	15.7	0.7	15.1	14.1	16.0	1.1

The table reports, for each year from 2024 (year of the climate and policy evaluation) to 2050, the mean, top and bottom decile, and the standard deviation (std). Climate projection data are taken from the global climate model compilations of the Coupled Model Inter-comparison Projects (CMIPs), overseen by the World Climate Research Program, and provided by the World Bank (<https://climateknowledgeportal.worldbank.org/country/italy/climate-data-projections>)

Appendix B: Climate damage

Climate change affects the economy directly by multiplication with output. The Leontief production function reads as:

$$y_{j,t} = \min \left\{ \frac{z_{1,j,t}}{a_{1,j,t}}, \frac{z_{2,j,t}}{a_{2,j,t}}, \dots, \frac{z_{j,t}}{a_{j,t}} \right\}, \quad (22)$$

where y_j is the total output of sector j , $z_{i,j}$ represents inter-industry sales by sector i to sector j , and $a_{i,j}$ is the technical coefficient representing the relation between sector j 's output and its input from sector i . Introducing a sectoral climate damage multiplier $(1 - \Lambda_{j,t}) \in [0, 1]$ into Eq. 22 yields:

$$\begin{aligned}
 y_{j,t} &= (1 - \Lambda_{j,t}) \min \left\{ \frac{z_{1,j,t}}{a_{1,j,t}}, \frac{z_{2,j,t}}{a_{2,j,t}}, \dots, \frac{z_{j,t}}{a_{j,t}} \right\} \\
 &= \min \left\{ \frac{z_{1,j,t}}{(1 - \Lambda_{j,t})^{-1} a_{1,j,t}}, \frac{z_{2,j,t}}{(1 - \Lambda_{j,t})^{-1} a_{2,j,t}}, \dots, \frac{z_{j,t}}{(1 - \Lambda_{j,t})^{-1} a_{j,t}} \right\}, \tag{23}
 \end{aligned}$$

meaning that climate damage increases the input from sector i per output of sector j . A value of Λ equal to 0 implies no damage, whereas a value equal to 1 implies no production. As the initial observed $a_{i,j,0}$ already incorporates the effect of the contemporary temperature, subsequent technical coefficients are scaled not by the absolute value of $\Lambda_{j,t}$, but by its relative change with respect to the previous period: $a_{i,j,t} = a_{i,j,t}^{bd} \cdot \frac{\tilde{J}_{j,t-1}}{\tilde{J}_{j,t}}$, where $a_{i,j,t}^{bd}$ is the technical coefficient before climate damage has been taken into account and $\tilde{J}_{j,t} = 1 - \Lambda_{j,t}$ is the realised damage multiplier.

Damage is modelled following Desmet and Rossi-Hansberg (2015) with modifications to account for extreme climate events. Let T denote the annual mean temperature in °C. The average multiplicative effect of climate on production is:

$$1 - \mathbb{E}[\Lambda_{j,t}] \equiv J_{j,t} = \max \left\{ g'_j + g''_j T_t + g'''_j T_t^2; 0 \right\}, \tag{24}$$

where (g'_j, g''_j, g'''_j) is a triple of real-valued parameters with $g''_j > 0$ and $g'''_j < 0$, implying that the optimal temperature for economic activity in sector j is $T_j^* = -g''_j/2g'''_j$. Thus, sectoral production tends to decrease with temperature when $T > T_j^*$ and to increase with temperature when $T < T_j^*$ (this is consistent with studies suggesting that global warming will be associated with an increase in output at certain latitudes; see e.g. Burke et al. 2015). The percentage change in output due to warming from a base period b to a comparison period $t \geq b$ is given by $(J_{j,t} - J_{j,b})/J_{j,b}$.

On average, damages on agricultural production are therefore minimised when $T \approx 21.1^\circ$, whereas non-agricultural damages are minimised when $T \approx 17.4^\circ$. This also means that agricultural production is zero when mean temperature falls below 9.34° or above 32.85° , while non-agricultural production is zero when mean temperature is below -3.41° or above 38.20° .

The possibility of extreme events—such as droughts and floods—is accounted for by assuming that for each sector j and period t , $\Lambda_{j,t}$ is a random variable having a Beta distribution:

$$f(\Lambda_{j,t}; \varphi_{j,t}, v_{j,t}) = \frac{\Lambda_{j,t}^{\varphi_{j,t}-1} (1 - \Lambda_{j,t})^{v_{j,t}-1}}{\int_0^1 \Lambda_{j,t}^{\varphi_{j,t}-1} (1 - \Lambda_{j,t})^{v_{j,t}-1} d\Lambda}, \tag{25}$$

where

$$\varphi_{j,t} = \bar{\varphi} \left| T_j^* - T_t \right|, \quad (26)$$

whereas $v_{j,t}$ satisfies:

$$J_{j,t} = 1 - \frac{\varphi_{j,t}}{\varphi_{j,t} + v_{j,t}},$$

which gives:

$$v_{j,t} = \frac{\varphi_{j,t} J_{j,t}}{(1 - J_{j,t})}. \quad (27)$$

The parameter $\bar{\varphi}$ is set to 10 to ensure that Λ has a reasonably small variance. In the special (but unlikely) case where $T_j^* = T_t$, a small constant (10^{-9}) is added to the right-hand side of (26) and to the denominator of the right-hand side of (27) to avoid multiplication and division by zero. Similarly, when T_t is such that $J_{j,t} = 0$, a small constant is added to the numerator of the right-hand side of (27). Greater deviations from T^* result in higher average damages (relative to a world where temperature is at its optimal level) and a greater likelihood of extreme events on the right tail of the distribution.

B.1 Calibration

The empirical calibration of parameters and initial values for the Italian economy is based on official data, providing a consistent and coherent foundation for assessing the feasibility of carbon tax measures. To estimate the unknown parameters, we used official data from 2010 to 2020 (if available) and applied the optimisation function provided by Vensim SDD. We employed the multi-objective parameter optimization mode available in Vensim SDD, which automates the calibration process through repeated simulations. Technical details are available at: <https://vensim.com/optimization/#model-calibration>. The calibration process aimed to align the model outputs with observed data for key variables (Table 5).

Table 5 Main parameters for calibration and sensitivity analysis

Parameter	Value	Equation or definition	Note
p_0^{T2}	0.5	Probability of emergence of a labour productivity (λ) gains innovation	The innovation process is modelled in four steps. First, new technologies are discovered. Second, the magnitude of $\Delta\lambda$ and $\Delta a_{i,j}$ coefficients (i.e. the extent of the innovations) is determined. Third, a choice is made on whether to adopt one of the new technologies or not, based on a min cost rule. Fourth, the chosen technology is implemented. Calibration based on EU Klems and WIOD Rev. 1, 1995–2009 data for Italy
p_0^{T3}	0.5	Probability of emergence of a material efficiency gain innovation, which affects technical coefficients ($a_{i,j}$)	
p_0^{T4}	0.25	Probability of emergence of a win-win innovation, which improves labour productivity and material efficiency	
δ	0.3	$Div_i = \delta \cdot (\Pi_i - Inv_i)$	Total dividends as a residual of profits net to new investments. δ is defined as: (dividends + buybacks – stock issuances)/(net income + depreciation – capital expenditure + new debt – debt repaid). Data is available at: https://pages.stern.nyu.edu/~adamodar/pc/datasets/divfundEurope.xls (05/01/2021 update). Investment (Inv) is derived from OECD.Stat, Table 8A: capital formation by activity. Available at: https://stats.oecd.org/Index.aspx?DataSetCode=SNA_TABLE8A

Table 5 continued

Parameter	Value	Equation or definition	Note
$\bar{\eta}$	0.03	$\eta(t) = \eta(t-1) \cdot [1 - \bar{\eta}(uc - uc^N)]$	η is the markup and $\bar{\eta}$ is a measure of the sensitivity to capacity over-utilisation. Initial industry-specific markups ($m_{i,0}$) are approximated based on Christophoulou and Vermeulen (2012, Appendix C) using Eurostat correspondence tables (https://ec.europa.eu/eurostat/web/nace-rev2/correspondence_tables). The value for initial (2010) inflation is taken from OECD data (https://data.oecd.org/price/inflation-cpi.htm). Other parameters are calibrated to 2010–2019/20 data. Normal utilization capacity (uc^N) is taken from Setterfield and Avritzer (2020, p. 909)
uc^N	0.8	Eq. above	Normal utilization capacity values are approximated following Setterfield and David Avritzer (2020)
$(g'_{agr}, g''_{agr}, g'''_{agr})$	(-2.24, 0.308, -0.0073)	Eq. above, these values refer to the agricultural sector	In the model a distinction is made between agricultural and non-agricultural activity. Estimates are taken from Desmet and Rossi-Hansberg (2015).
(g'_j, g''_j, g'''_j)	(0.30, 0.08, -0.0023)	Eq. above, these values refer to all the other sectors $j \neq agric.$	

Appendix C: Figures

C.1 Trends under RCP60

See Fig. 7.

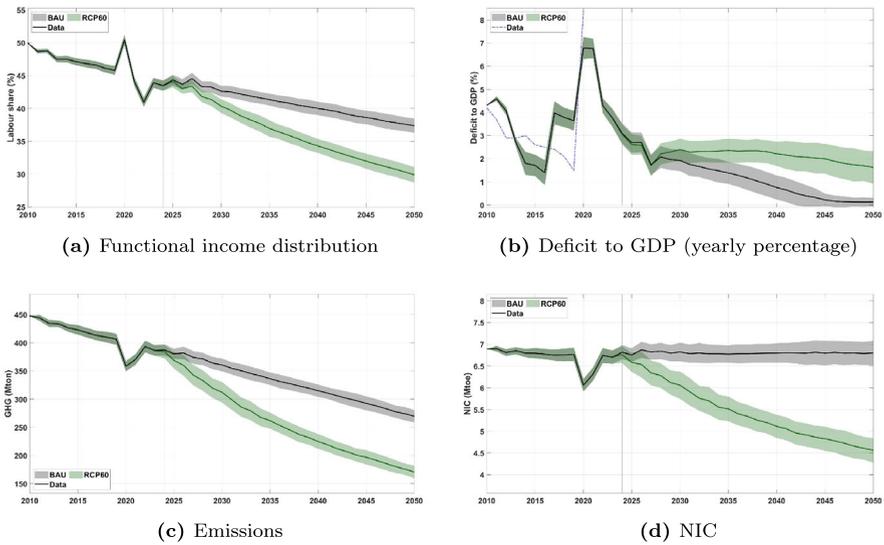


Fig. 7 Main socio-environmental indicators. The lines represent the median of 300 simulations for each scenario: Baseline (black) and Damage RCP 6.0 (green). The shaded areas indicate the 95% confidence interval. The vertical dotted line marks the starting year for calculating climate damage and policy adaptations (2024)

C.2 Comparison RCP60 with RCP45

See Fig. 8.

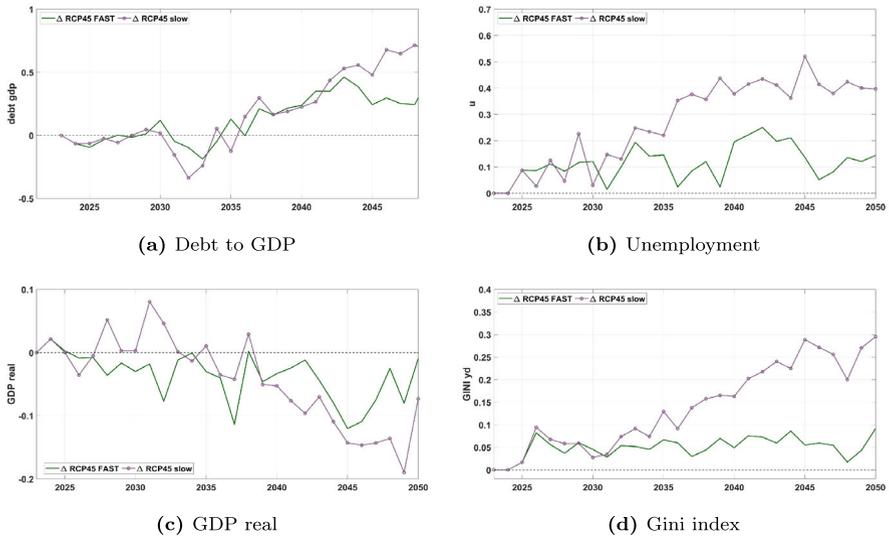


Fig. 8 Main socio-environmental indicators. Lines show the percentage difference between outcomes under the RCP 4.5 with respect to RCP 6.0 scenarios for key macroeconomic indicators, under Fast (green) and Slow (red) adaptation pathways

The plots illustrate the *differences* in outcomes under two climate scenarios—RCP 4.5 and RCP 6.0—relative to the baseline, comparing the effects of Fast and Slow adaptation strategies. While some variations emerge between the two climate pathways, the overall divergence in key economic and social indicators remains relatively modest. This indicates that, regardless of the specific climate trajectory or the speed of implementation, public intervention plays a crucial role in mitigating climate damages. These findings support a precautionary policy approach: given the low downside risks and the potential for substantial long-term gains, proactive adaptation policies constitute a no-regret strategy consistent with robust decision-making under uncertainty.

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Data Availability The full model and the data will be available upon request.

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