ITAGREEN MRIO: Towards a Multiscale Ecological Macroeconomic model

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Abstract

This study presents ITAGREEN-MRIO, a novel Multi-Spatial Integrated Assessment Model (MS-IAM) developed to explore the socio-economic impacts of climate change in Italy within the context of sustainability transitions. Rooted in Ecological Macroeconomics, the model is built on a modular system dynamics framework and extended to capture spatial heterogeneity across five macro-regions. Its design enables the analysis of complex socio-economic and ecological dynamics under alternative techno-climatic scenarios, with particular attention to the propagation of regional shocks and their aggregation at the national scale. The main methodological contribution lies in the explicit incorporation of a multi-regional input–output structure, region-specific household consumption, and spatially heterogeneous climate damage impacts. This configuration provides a detailed representation of how climate-induced productivity shocks affect intermediate goods flows, household demand, and value added across regions and sectors. The results show that neglecting regional heterogeneity leads to a systematic underestimation of long-run aggregate losses, as climate shocks propagate unevenly through interregional production networks and are amplified by regions with strong manufacturing centrality. The analysis further highlights the interaction between endogenous technological change and climate damages. While innovation supports output growth, it does not fully offset productivity losses and may amplify resource pressures through increased intermediate input requirements. Overall, ITAGREEN-MRIO provides a spatially explicit framework capable of capturing the intertwined economic, technological, and ecological dimensions of climate impacts, offering a robust tool for regionally informed policy design.

Keywords— Scenario Analysis, Integrated Assessment Models, Climate Change, Regional Heterogeneity, Ecological Macroeconomics, Multi-Regional Input-Output Analysis

JEL: E17, E61, Q54, Q57, R15

1 Introduction

The urgency of climate change-related emergencies is escalating daily. What was once considered a potential future threat has now become a pervasive and present reality (Gills et al., 2022). Across the globe, the tangible consequences of climate shocks are intensifying in both frequency and intensity, with rising sea levels, droughts, heavy precipitation, and other extreme meteorological events occurring (IPCC, 2023a,b; Mal et al., 2017; Trenberth et al., 2015). This global crisis manifests with regionally diverse consequences that are not spatially uniform (Rosenbloom, 2020). Its impacts are deeply stratified, revealing different dynamics across continents, nations, and even regions within countries (Intergovernmental Panel on Climate Change, 2023). This heterogeneity of shocks underscores the imperative for a more effective policymaking process (Rogge et al., 2024). A "one-size-fits-all" approach is not only inadequate but also risks exacerbating social vulnerability and existing inequalities (D'Alessandro, André Cieplinski, et al., 2020). In the European context, these asymmetries are particularly pronounced, as long-standing disparities in economic performance and institutional development have continued to reproduce inter- and intraregional divides, creating persistent development gaps that re-emerge across spatial scales (Camagni et al., 2020). The Italian case reflects this broader pattern, with structural divides between its macro-regions shaping both vulnerability to climate shocks and the capacity to respond effectively. Consequently, the call for climate action has never been more urgent, demanding a new generation of analytical tools capable of capturing the complex and multilevel nature of the issue (Andersen et al., 2023; Löhr et al., 2024).

Despite the increasing attention dedicated to the impacts of climate change, almost all economic Integrated Assessment Models (IAMs) have remained focused on either the national or global scale, often neglecting the role of spatial heterogeneity and multilevel linkages (Nykamp et al., 2023). While economic and environmental dimensions receive considerable attention, the connections across regional and national levels are rarely investigated, leaving a critical gap in understanding how local impacts propagate and how national policies are transmitted at the regional scale, both of which are crucial in understanding social vulnerability (Breil et al., 2018). Nonetheless, the literature indicates a growing interest in Ecological Macroeconomics and related interdisciplinary approaches, suggesting a shift toward more integrated perspectives for quantitative policy evaluation analyses (Hafner et al., 2020; Saltelli et al., 2023).

In this context, this study presents ITAGREEN-MRIO, a Multi-Spatial Integrated Assessment Model (MS-IAM) designed to investigate the local and national impacts of climate change in Italy from a regional perspective. Rooted in the framework of Ecological Macroeconomics, ITAGREEN-MRIO extends and updates the Italian EUROGREEN model (D'Alessandro, André Cieplinski, et al., 2020; Distefano and D'Alessandro, 2023), which employs a system dynamics simulation approach, by incorporating a central methodological innovation: the simultaneous integration of national and subnational dynamics within a coherent modelling structure. The subnational layer comprises five macro-areas of Italy, thus capturing the geographical heterogeneity of the Italian economy. A comprehensive review of the literature confirms that this multi-spatial configuration, which combines national and regional processes in an integrated framework, represents a novel contribution to the field.

Methodologically, the model is adapted to a multi-scale framework in which some blocks follow a bottom-up approach, being modelled at the regional level and subsequently aggregated to the national scale, while others are specified top-down, defined at the national level and then disaggregated across regions.

This design has both methodological and substantive implications. From a modelling perspective, it provides a flexible structure that can be adapted to different research objectives by varying the degree and locus of spatial disaggregation, while remaining consistent with the constraints imposed by data availability, which often limit the feasibility of fully regional specifications. In this sense, the allocation of model components across spatial levels is not fixed, but can be tailored to the specific research question, allowing different elements to be treated as bottom-up or top-down depending on their analytical relevance and empirical support. At the same time, by enabling the explicit interaction between national and regional dynamics, the model captures heterogeneous spatial outcomes that are central to the analysis of climate change and its distributional consequences. By combining bottom-up and top-down elements within a coherent structure, the model thus offers a tractable yet rich representation of multi-level interactions.

The ITAGREEN-MRIO model brings together three interlinked building blocks. First, the Input-Output (IO) block employs a multi-regional Input-Output (MRIO) framework comprising five regions and 19 industries. This block constitutes the core bottom-up component of the model, as it represents production at the regional level and explicitly captures interregional linkages through trade and input dependencies. Regional disaggregation also extends to household consumption by classification of individual consumption by purpose (COICOP), reinforcing the bottom-up representation of demand-side dynamics. Climate change is incorporated as a region-specific productivity shock. These bottom-up components are subsequently aggregated to the national level in a manner consistent with the broader model architecture. While alternative aggregation strategies are possible, the approach adopted here is designed to preserve coherence between regional dynamics and national outcomes, a feature that will be discussed in detail in the methodological section.

Second, the system-dynamics core captures the feedback loops, endogenous adjustments, and out-of-equilibrium processes that shape the interactions between prices, employment, investment, innovation, and emissions.

Third, the scenario analysis enables simulations of a wide range of environmental and social policies, including a carbon tax, fossil fuel phase-out, and wealth taxation, as well as broader scenarios such as climate damage pathways and exogenous shocks (e.g., energy price volatility). By integrating regional and national dynamics within a coherent modelling framework, preliminary simulations reveal heterogeneous regional responses and identify key sectoral vulnerabilities. In the baseline scenario, the GDP divide between the northern and southern regions tends to widen over time, highlighting persistent territorial imbalances. Moreover, under a scenario aligned with Representative Concentration Pathway 6.0 (RCP 6.0), the activation of a climate damage coefficient shows that regions more reliant on agriculture—particularly in the South—experience more substantial adverse effects, suggesting that climate change could further exacerbate existing disparities. This modelling approach enables a nuanced assessment of climate mitigation strategies and provides a robust tool for designing just and regionally differentiated transition policies in the Italian context.

This article is structured as follows: Section 2 reviews the literature on IAMs and introduces the Ecological Macroeconomics framework; Section 3 presents the regional extension; Section 4 presents and discusses the model simulation results; And, lastly, we conclude and remark.

2 Extending the Ecological Macroeconomics and IAMs framework to a multi-regional setting

Most of the existing literature on Integrated Assessment Models (IAMs) relies on Computable General Equilibrium (CGE) and Dynamic Stochastic General Equilibrium (DSGE) approaches, with Nordhaus' DICE model representing the first and most influential example (Nordhaus, 1993). The case of DICE is emblematic: despite being awarded the Nobel Prize, it has been widely criticised for endorsing implausible assumptions and generating questionable policy guidance, such as treating global warming of more than 4°C as economically 'optimal' (Sterman, 2002).

While such models have shaped climate policy debates for decades, they rest on highly restrictive assumptions, including perfect competition, full employment, representative agents, and utility maximisation. These simplifications not only misrepresent the complexity of real-world economies but also systematically bias results toward 'optimal' equilibrium solutions, often neglecting transitional processes, structural rigidities, and the instabilities inherent to large-scale socio-ecological transformations. Criticisms have also been articulated by proponents of mainstream economics, such as Blanchard (2017), who argued in his critique of DSGE models that these approaches must *"become less imperialistic and willing to share the scene with other modelling approaches."* Likewise, Stiglitz (2018), another neoclassical economist, emphasised that mainstream macroeconomic frameworks fail to capture essential behavioural and institutional dimensions because of their flawed microfoundations.

Ecological Macroeconomic Models (EMMs) have emerged as a promising alternative over the past decade (Fragio et al., 2024; Victor et al., 2015). These models integrate insights from Stock-Flow Consistent (SFC) modelling and Environmentally Extended Input-Output (EEIO) analysis within a post-Keynesian framework (Fontana et al., 2016; Hardt et al., 2017). They are demand-driven, assuming excess economic capacity, and focus on non-equilibrium dynamics and aggregate demand fluctuations (Lavoie, 2014). They use various indicators and System Dynamics methods to model interdependencies between economic, social, and environmental systems, incorporating feedback loops, delays, and path dependencies (Mediavilla et al., 2025; Sterman, 2001). This methodology enables the capture of interconnections and feedback mechanisms between socio-economic and environmental components (Costanza et al., 1993; Rezai et al., 2013). Often structured as Integrated Assessment Models (IAMs), they analyse long-term policy impacts through scenarios (Nieto et al., 2020; Rezai et al., 2013). By incorporating lagged responses and feedback effects, EMMs offer a more realistic portrayal of transitions, thereby aiding informed policy decisions.

In this study, we refer to a model specifically developed within the field of Environmental Macroeconomic Modelling (EMM), known as EUROGREEN. The model is primarily designed to generate reliable scenarios that can be used to evaluate the effects of different policy options. In doing so, it helps identify potential trade-offs and unintended consequences that may arise from the implementation of isolated policy measures, given the interconnected nature of the real economy. While the foundational paper was originally designed for France (D'Alessandro, André Cieplinski, et al., 2020), subsequent studies have adapted it for application in Italy, by evaluating different low-carbon transition pathways (Cieplinski et al., 2021), social labour policies (D'Alessandro, Distefano, et al., 2023), a new carbon tax (Distefano and D'Alessandro, 2023), the responses to energy price shocks (Morlin et al., 2025), and the interactions between public finance and climate change (Campigotto, D'Alessandro, et al., 2025). Given the model's modular design, versatility, and capacity to capture complex socio-economic and ecological characteristics under different techno-climatic policy scenarios, we have chosen to expand this model by incorporating spatial differences in production, consumption, and climate-related damages.

The path towards a climate-resilient future depends on the ability to design and implement policies that are both effective and equitable. This, in turn, hinges on the sophistication of the analytical tools used to comprehend the problem. Nevertheless, the solutions currently offered by the literature remain limited, constrained by an over-reliance on aggregate national models that obscure critical regional realities and by a lack of attention to the complex social dimensions of climate change. These shortcomings are highlighted not to dismiss past efforts, but to underscore the challenges ahead. For example, regional production interactions and local government interest may increase the degree of challenges for policy coordination (Markard et al., 2020; Rogge et al., 2024), pointing towards regional downscaled (or even place-based) perspectives (Biggeri et al., 2014). They represent a call to action for the research community: to advance multi-regional, multi-level, and dynamic models capable of capturing the intricate geography of climate change in a world marked by deep disparities.

To fill this gap, ITAGREEN-MRIO builds upon the modelling architecture of EUROGREEN, maintaining its core structure while introducing significant innovations. For the reader's convenience, the main features of EUROGREEN are summarised in Table A1.1 in the Appendix. The following Section provides a detailed description of the logic and assumptions behind the model.

3 The ITAGREEN-MRIO model

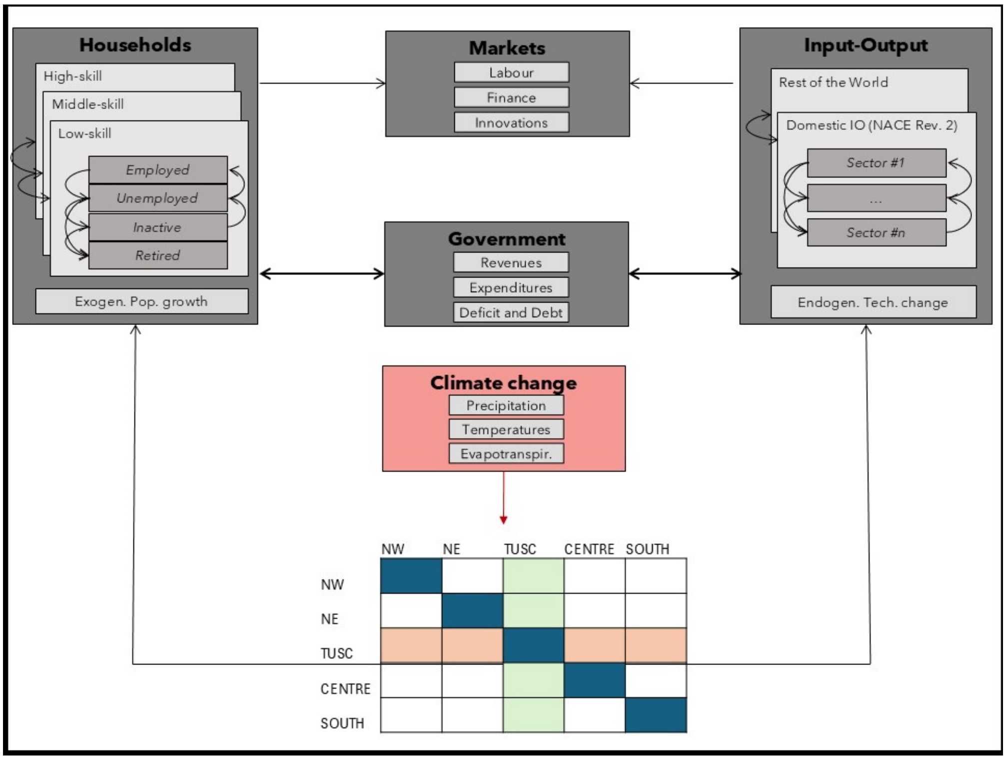


Figure 1: Macroview of the ITAGREEN-MRIO model structure. This figure illustrates the core components and feedback mechanisms of the ITAGREEN-MRIO model, which extends the Italian EUROGREEN framework (Distefano and D'Alessandro, 2023) by incorporating spatial dimensions of production (through multi-regional input-output MRIO tables), consumption, and climate damages. The lower matrix depicts the regional disaggregation*: blue diagonal blocks represent intra-regional trade flows, while the off-diagonal rows and columns indicate inter-regional exchanges. For example, the row (column) corresponding to Tuscany shows the volume of goods sold to (purchased from) other regions.
*Northwest (NW), Northeast (NE), Tuscany (TUSC), Centre (excluding Tuscany), and South (including islands).

Figure 1 provides a concise overview of the novel Multi-Spatial IAM, known as *ITAGREEN-MRIO*, which updates and extends the EUROGREEN model, as described below. In line with the EMM literature, ITAGREEN-MRIO employs a system dynamics approach to policy analysis and design, which is particularly well-suited to studying complex systems (Richardson, 2013). At its core, the model employs an environmentally extended multi-regional input-output (EE-MRIO) framework, dividing the whole economy into 19 macro-sectors (see Appendix Table A1.2). This structure enables the integration of monetary flows, energy and water use, and labour inputs within a consistent framework aligned with official national accounts, facilitating the analysis of inter-industry linkages. In the current version, ITAGREEN-MRIO includes five macro-regions—Northwest (NW), Northeast (NE), Tuscany (TUSC), Centre (excluding Tuscany), and South (including islands)—enabling a more granular spatial representation of production, consumption, and emissions in Italy.[1] The current development of a Multi-Spatial version enhances the model's capacity to capture the heterogeneous effects of national policies across Italy's territory. This advancement also enables the exploration of regionally tailored policy options, providing a more detailed and nuanced framework to analyse economic-environmental interactions that vary significantly across the Italian territory.

Compared to standard EMMs, ITAGREEN-MRIO is designed as a modular,[2] multi-system, multi-dimensional, and multi-spatial model, integrating socio-economic and ecological processes within a unified framework. It simultaneously accounts for multiple, often incommensurable, indicators across alternative scenarios and incorporates a spatial disaggregation into five interconnected geographical areas. This structure enables the model to capture both the complexity of economic-ecological interactions and the heterogeneity of regional dynamics. In what follows, we first outline the key assumptions inherited from EUROGREEN, before turning to a detailed discussion of the novel extensions introduced in ITAGREEN-MRIO in the following subsections.

Technological change is modelled as an endogenous, industry-specific process through which firms adopt innovations aimed at reducing intermediate input requirements—this affects the matrix A of technical coefficients, as described below—and/or increasing labour productivity. Investment dynamics are driven by demand and depend on the level of capacity utilisation, but they are constrained by internal financial resources and the ability to take on private debt. At the same time, investment contributes to improvements in labour productivity and energy efficiency, which subsequently affect wages, profits, and environmental outcomes. Additional central features of the model include the representation of energy flows disaggregated by source—renewables, gas, coal, and oil—enabling the evaluation of environmental sustainability and associated greenhouse gas emissions. On the demand side, households are modelled as heterogeneous agents, classified by economic status (employed, unemployed, inactive, retired, and capitalists). Employed workers are further distinguished by three skill levels, defined according to their highest educational attainment. The model also incorporates a detailed representation of the macroeconomic welfare system, including taxes and transfers, enabling the simulation of the fiscal and distributive

[1]Italy is administratively divided into 20 regions (NUTS-2). For statistical purposes, the National Institute of Statistics (ISTAT) commonly aggregates them into five NUTS-1 macro-regions: North-West (ITC), North-East (ITH), Centre (ITI), South (ITF), and Islands (ITG). These groupings include, for example, Lombardy and Piedmont in the North-West; Veneto and Emilia-Romagna in the North-East; Tuscany and Lazio in the Centre; Campania and Puglia in the South; and Sicily and Sardinia in the Islands. This work is carried out in the context of the project "Regional Models for Human and Sustainable Development in Tuscany", so Tuscany is separated from the Centre. Finally, the Islands are merged with the South.

[2]The model is organised into 14 interconnected sub-modules: Population, Input-Output and GDP, International Trade, Innovation, Investment and Profits, Finance and Wealth Distribution, Labour, Government, Prices, Consumption, Energy, Climate Damage, Time Use, and Water Use.

implications of public policies on public deficit and debt.

In what follows, we describe the Multi-Spatial extensions introduced by ITAGREEN-MRIO, which comprise production (3.1), household consumption (3.2), and climate damage (3.3).

3.1 Multiregional Input-Output extension

In a Multiregional Input-Output (MRIO) framework, the total output y_{ir} by industry i and region r is given by:

$$y_{ir} = \sum_j \sum_s z_{ir,js}^{dom} + f_{ir}, \tag{1}$$

where $z_{ir,js}^{dom}$ represents the flow of intermediate domestic goods from industry i in region r to industry j in region s, and f_{ir} is the final demand for domestically produced goods by industry i in region r, constituted of households consumption expenditures by households, gross fixed capital formation (i.e. investments), government expenditures, and exports.

Based on the NACE Classification, industries were aggregated into nineteen categories, as listed in Table A1.2 in the Appendix. Given $i = 19$ and $r = 5$, the resulting intermediate goods matrix $\boldsymbol{Z}$ has dimensions 95×95, while the sum of final demand components results in 95×1 a final demand for domestically produced goods and services vector. Using data from the MRIO table for Italy provided by the Regional Institute for Economic Planning in Tuscany (IRPET) for 2019, the technical coefficients $(a_{ij,rs})$ are calculated as:

$$a_{ij,rs} = \frac{z_{ij,rs}^{dom}}{y_{ir}}, \forall a_{ij,rs} \in \boldsymbol{A}. \tag{2}$$

These coefficients represent the share of intermediate inputs from industry j in region s required per unit of output in industry i in region r, with all values expressed in basic prices.

Following standard MRIO methodology, total output $\boldsymbol{Y}$ is obtained in the model by multiplying the vector of final demand for goods and services $(\boldsymbol{f}^{dom})$ by the Leontief matrix $(\boldsymbol{L})$, derived from the technical coefficients matrix $(\boldsymbol{A})$.

$$\boldsymbol{Y} = \boldsymbol{L} \cdot \boldsymbol{f}, \tag{3}$$

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}, \tag{4}$$

where $\boldsymbol{I}$ stands for the identity matrix and the Leontief inverse $\boldsymbol{L}$ denotes the total requirements matrix given final demand. This structure provides a demand-side approach to determine total output across industries and regions. On the supply side, production is constrained by the full capacity output (y_{ir}^{FC}), namely the maximum output that each industry can produce depending on its total stock of fixed capital. Therefore, the actual output in the model is determined as:

$$\boldsymbol{Y} = \min\{\boldsymbol{Lf}, \boldsymbol{y}^{FC}\}. \tag{5}$$

Imports are determined using constant coefficients calculated from the multiregional input-output table for the initial period and held fixed over time. For intermediate goods imports ($z^{imp}_{ir,j}$) of industry i in region r from industry j in the rest of the world, the coefficients are expressed as ratios relative to the corresponding domestic input demand:

$$\gamma^z_{ir,j} = \frac{z^{imp}_{ir,j,t=0}}{z_{ir,j,t=0}}. \tag{6}$$

In contrast, for final demand imports, import shares are computed for each component $\delta \in C, G, I$, respectively household consumption, government expenditures, and investment, so that overall demand of each component ($\hat{f}^{\delta}_{ir}$) is given by domestic plus imported demand:

$$\gamma^{\delta}_{ir} = \frac{f^{\delta,imp}_{ir,t=0}}{\hat{f}^{\delta}_{ir,t=0}}. \tag{7}$$

$$\hat{f}^{\delta}_{ir} = f^{\delta}_{ir} + f^{\delta,imp}_{ir}. \tag{8}$$

This distinction arises from the structure of the input-output tables: while intermediate trade is calculated based on the domestic technical coefficients matrix—requiring the addition of imports to compute total inputs—data on final demand is available only in aggregate form for domestic agents, and must be split between domestic goods and imports using the calculated shares.

3.1.1 Technological Progress

An input–output matrix, and in particular the associated technical coefficients matrix **A**, represents a snapshot of the production technology prevailing in a given period. It captures the structure of inter-industry relationships at a specific point in time. In a purely static setting, this technological structure would remain fixed. However, the model includes a technological module that allows technical coefficients and labour productivity to evolve endogenously over time (if activated), thereby enabling structural transformation beyond the initial MRIO configuration.

Technological change modifies the production structure by altering intermediate input requirements and/or labour productivity. Since the **A** matrix embodies the production technology of the economy, any variation in its coefficients reflects a shift in underlying production methods and implies a reallocation of output shares across sectors. The dynamics of innovation contain a stochastic component affecting both the availability and the efficiency gains of new technologies. For each industry, firms adopt the most cost-effective available technique, generating potential savings in labour and/or intermediate inputs. Technological change therefore determines the evolution of the Leontief technical coefficients, labour productivity, and associated efficiency gains.

Technological change is modelled as an industry-specific process calibrated using national data. Since the MRIO table is available for a single benchmark year, the innovation mechanism and the calibration of productivity and input-saving dynamics are derived from national input–output series. Technological progress therefore operates at the sectoral level and is applied uniformly across regions, maintaining coherence within the multiregional framework while preserving structural heterogeneity across industries.

The innovation process unfolds in four steps.

Step 1: Discovery. In each period and for each industry, the model determines whether new technologies become available. Four technological scenarios are considered. The baseline case (T1) follows a Kaldor–Verdoorn mechanism: in the absence of new discrete innovations, productivity increases when output and capital expand, reflecting dynamic increasing returns. If expansion does not occur, productivity remains unchanged.

In addition to T1, three stochastic innovation types may become available: labour-saving (T2), intermediate-input-saving (T3), and win–win (T4). The discovery process of T2–T4 is probabilistic and depends on the relative evolution of unit labour and intermediate input costs. Their probabilities are calibrated using historical data and evolve endogenously with cost dynamics.

Step 2: Magnitude of innovation. Conditional on discovery, the model determines the extent of technological improvement. For each available technology, changes in labour productivity and in intermediate input coefficients are drawn from calibrated distributions based on historical evidence. Labour-saving innovations primarily increase labour productivity; intermediate-input-saving innovations primarily reduce average intermediate input requirements; win–win technologies improve both dimensions. The magnitude of these changes is industry-specific.

Step 3: Choice of technique. Firms select among the available techniques according to a Classical–Sraffian rule (Kurz and Salvadori, 1995). For each technological option, they compute unit labour costs and unit intermediate input costs, and then adopt the cost-minimising technique. Innovations are therefore not automatically implemented: they are adopted only if they reduce unit full production costs relative to the existing technique.

Step 4: Implementation. If a new technique is adopted, technical coefficients and labour productivity adjust accordingly. Implementation is gradual and linked to capital turnover: productivity gains and input-saving effects materialise progressively as new capital replaces depreciated capital. Even in periods without new discoveries, diffusion effects may lead to incremental improvements in efficiency.

3.2 Household consumption

Household consumption data is originally available on ISTAT for six macro regions—Northwest, Northeast, Tuscany, Central (excluding Tuscany), South, and Islands—and is disaggregated by 2-digit COICOP categories[3]. In the model, South and Islands are aggregated into a single macro-region, resulting in the five-region structure. Note that consumption (COICOP) and production (NACE) official categorization follows different classification criteria, hence a COICOP-NACE bridge matrix is required to make them compatible and to run the Leontief inverse. The bridge matrix is based on data elaborated from Eurostat and subsequently is balanced with respect to the MRIO structure using the bipartitive balancing RAS algorithm (for a full explanation, see Distefano and D'Alessandro (2023)).

Household consumption in real terms (i.e., net of price inflation) is formalised as a behavioural equation linking expenditure on each good to three components: regional heterogeneity (captured by regional fixed effect), the income effect (disposable income deflated by the price of the good), and the substitution effect (relative prices across goods). The estimation relies on a panel dataset comprising 6 household groups—across six regions—and panel fixed effect regressions are applied separately to each COICOP consumption category.

The estimated consumption equation uses the following notation: $c_{i,r,t}$ denotes real household consumption of good i in region r, and time t; $YD_{r,t}$ is net disposable income; $P_{i,r,t}$ is the price of good i in region r; and $\frac{P_{i,r,t}}{P_{j,r,t}}$ represents the relative price of good i to other goods j.[4]

$$\begin{aligned}\Delta \ln c_{i,r,t} = \beta_{i1} \Delta \ln \frac{YD_{r,t}}{P_{i,r,t}} \\ + \sum_{j\neq i}\left(\phi^s_{ij} \Delta \ln \frac{P_{i,r,t}}{P_{j,r,t}}\right) + \beta_{i2}\Bigg[\ln c_{i,r,t-1} - \beta_{i3} - \sum_r (\alpha_{i,r} Dum_r) \\ - \beta_{i4} \ln \frac{YD_{r,t-1}}{P_{i,r,t-1}} - \sum_{j\neq i}\left(\phi^l_{ij} \ln \frac{P_{i,r,t}}{P_{j,r,t}}\right)\Bigg], \quad (9)\end{aligned}$$

Where $i = fo, at, cf, hb, fe, he, tr, co, rc, ed, rh, ot$ denotes the index of consumption classifications, $r = NW, NE, Tuscany, Centre, South, Islands$ denotes the index of regions, $\alpha_{i,r}$ denotes

[3]COICOP Consumption categories include: 1) food and non-alcoholic beverages (fo), 2) alcoholic beverages, tobacco and narcotics (at), 3) clothing and footwear (cf), 4) housing, water, electricity, gas and other fuels (hb), 5) furnishings, household equipment and routine household maintenance (fe), 6) health (he), 7) transport (tr), 8) communications (co), 9) recreation and culture (rc), 10) education (ed), 11) restaurants and hotels (rh), and 12) miscellaneous goods and services (ot).

[4]The replication dataset and STATA do-file are available upon request.

the regional fixed effect, $\beta_{i1} > 0$ and $\beta_{i4} > 0$ denotes the short-run and long-run elasticity of consumption to disposable income, respectively, ϕ^s_{ij} and ϕ^l_{ij} denotes the short-run and long-run substitution effect, respectively, $-1 < \beta_{i2} < 0$ denotes the long-run correction parameter of household consumption, β_{i3} denotes the propensity to consume in average.

Regional household disposable income is derived by allocating national disposable income across regions in proportion to their value added,

$$YD_{r,t} = \frac{VA_{r,t}}{VA_t} YD_t, \tag{10}$$

where $VA_{r,t}$ denotes the value added of region r.

Prices of consumption goods are obtained from national industry prices using a consumption–industry bridge matrix and are assumed to be homogeneous across regions. The same bridge matrix is applied to convert real household consumption by COICOP categories into real household consumption by industry. For consistency with the regional input–output module, household consumption of the South and Islands is aggregated into a single regional account.[5]

3.3 Climate damage

To capture the differentiated impacts of climate change across macro-regions, we incorporate regional temperature projections into the model. This extension allows us to derive region-specific damage coefficients. Within this framework, rising temperatures reduce productivity by directly affecting the technical coefficients matrix **A** of the MRIO. Increasing temperatures lead to a decline in productive efficiency, which in turn generates higher demand for intermediate inputs to offset damages caused by extreme events. To account for these impacts, we adopt the methodology proposed by Distefano, D'Alessandro, et al. (2025), whereby the intermediate input matrix is updated under conditions of climate damage as follows:

$$\mathbf{Z} = \mathbf{Y}^T \mathbf{A} \mathbf{D}, \tag{11}$$

where **D** denotes the climate damage matrix (95×95),

$$\mathbf{D} = \begin{bmatrix} \mathbf{D}_{NW,NW} & \mathbf{D}_{NW,NE} & \cdots & \mathbf{D}_{NW,South} \\ \mathbf{D}_{NE,NW} & \mathbf{D}_{NE,NE} & \cdots & \mathbf{D}_{NE,South} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{D}_{South,NW} & \mathbf{D}_{South,NE} & \cdots & \mathbf{D}_{South,South} \end{bmatrix}. \tag{12}$$

For each pair of inter-regional intermediate good transactions from region r to region s, $\mathbf{D}_{r,s} = diag(\frac{1}{1-\Lambda_{1,s,t}}, \frac{1}{1-\Lambda_{2,s,t}}, \cdots, \frac{1}{1-\Lambda_{19,s,t}})$, the industry-specific climate damage multiplier,

[5]The consumption–industry bridge matrix is a weight matrix indicating, for each unit of a specific good, the percentage contribution of each industry producing it.

$\Lambda_{j,s,t}$, depends on the temperature of the intermediate good destination region, which is governed by a Beta distribution to account for extreme climate events (Desmet et al., 2015 and Burzynski et al., 2018) as in Campigotto et al. (2022). In particular, the agriculture sector is more sensitive to temperature change than the other sectors, which makes the south region more vulnerable to climate change in the model, because they are mainly specialised in agricultural production.

Expected climate damages are based on the temperature–productivity relationship proposed by Desmet and Rossi-Hansberg (2015), who model sectoral productivity as a concave quadratic function of temperature. For non-agricultural sectors, expected productivity is given by

$$\phi_{s,t}^{\text{ind}} = \max\left(0.3 + 0.08\,T_{s,t} - 0.0023\,T_{s,t}^2,\, 0\right), \tag{13}$$

while for the agricultural sector it is defined as

$$\phi_{s,t}^{\text{agri}} = \max\left(-2.24 + 0.308\,T_{s,t} - 0.0073\,T_{s,t}^2,\, 0\right). \tag{14}$$

These functions attain their maximum at sector-specific optimal temperatures and are interpreted as expected no-damage productivity factors.

To account for regional climatic heterogeneity, we depart from the use of absolute temperature levels and evaluate the damage functions using temperature deviations relative to a counterfactual baseline without climate change. Specifically, regional temperature is expressed as

$$T_{s,t} = \Delta T_{s,t} + T^*, \tag{15}$$

where $\Delta T_{s,t}$ denotes the deviation of temperature under the climate scenario from its historical average over the period 1995–2014 in region s, and T^* corresponds to the sector-specific optimal temperature implied by the original calibration. This re-centering ensures that, in the absence of climate change, expected productivity is at its normal level in all regions.

Expected productivity is then normalised by its sector-specific peak value and transformed into a damage measure as

$$\Lambda_{j,s,t} = 1 - \frac{\phi_{j,s,t}}{\max(\phi_j)}, \tag{16}$$

so that $\Lambda_{j,s,t} = 0$ in the baseline scenario and increases monotonically with warming. In line with the empirical evidence, productivity losses are assumed to arise only from temperature increases, while potential gains from cooling are ruled out.

The temperature of the five macro regions are computed as the average (size weighted) of the projections of 20 Italian regions based on the data from the Copernicus Climate Data Store (CDS). The temperature under alternative emission scenarios are constructed using projections from the CMIP6 ensemble, obtained via the World Bank Climate Change Knowledge Portal.

4 Results

Following the presentation of the model structure and its multiregional extensions, this section reports the results of a simulation exercise based on four scenarios combining two key dimensions: climate damages and technological progress. The objective is to isolate the economic effects of climate impacts, distinguish them from those associated with structural technological adjustment, and assess their interaction. The analysis focuses primarily on the economic implications for Tuscany, examining both direct impacts and indirect effects transmitted through interregional production linkages and supply chains. Selected multiregional results are presented for comparison in order to contextualise Tuscany's performance within the broader national framework.

The scenario design allows for a transparent assessment of the transmission mechanisms embedded in the model. The development of the ITAGREEN-MRIO framework required extensive work, including data harmonisation, extension of the architecture to five macro-areas, regional calibration of behavioural components, and the construction of spatially differentiated climate projections. The exercise therefore serves to illustrate the model's operational capacity and its relevance for regionally informed policy analysis.

In the *Baseline* scenario, climate damages are not considered and regional temperatures are fixed at the twenty-year average observed in the reference period (2003–2022). Technological change follows the calibrated national dynamics of the technical coefficients matrix $\mathbf{A}$, applied uniformly across industries.[6]

The *Climate Change* scenarios introduce damages consistent with the Representative Concentration Pathway 6.0 (RCP 6.0), starting from 2025. RCP 6.0 represents a medium-to-high emissions trajectory developed by the IPCC, characterised by delayed and moderate mitigation efforts and stabilising radiative forcing at 6.0 W/m^2 above pre-industrial levels by 2100. Atmospheric temperature projections are generated for each macro-region following RCP 6.0, as described in Section 3.3. These projections affect precipitation patterns and activate a climate damage coefficient that reduces productivity in exposed sectors.

Lower productivity implies that more inputs are required to produce a given level of output. This increases the relative weight of intermediate goods in production, raises firms' costs, and reduces revenues, value added, and ultimately gross domestic product (GDP). Climate damages are activated from 2025 onwards and capture the adverse effects of extreme weather conditions on sectoral productivity.

The technological dimension of the analysis is introduced through two additional scenarios. In the *Technological Progress* scenario, endogenous innovation operates in the absence of climate

[6] This choice reflects the scarcity of consistent multi-regional input–output time-series for Italy, which prevents estimating region-specific technological trends. Regional heterogeneity is nevertheless preserved through region- and industry-specific initial technical coefficients.

damages. In the *RCP 6.0 + Technological Progress* scenario, climate damages and endogenous technological change interact, allowing us to assess the extent to which structural adjustment can mitigate or amplify climate-induced economic losses. In all scenarios, technological progress is active up to 2022, reflecting the calibrated historical trajectory considering the available data. From 2023 onwards, in the scenarios without technological progress, the technical coefficients remain fixed at their 2024 configuration.

For a robustness check and sensitivity analysis, we run 500 simulations in which selected parameters affecting technological innovation and climate damage are treated as stochastic. When active, technological innovation remains endogenously determined, but its parameters are varied according to a Normal distribution, influencing the intermediate-input and labour-saving technology (D'Alessandro, André Cieplinski, et al., 2020). Climate change parameters follow a Beta distribution and increase the required amount of intermediate inputs across industries for a given output. From these simulations, we compute the median trajectory and a confidence interval to reduce the influence of stochastic noise and avoid arbitrary outcomes associated with numerical simulations (Distefano, D'Alessandro, et al., 2025). The simulations start from 2019, consistent with the MRIO data described in Section 3.1, and incorporate two exogenous shocks: the COVID-19 pandemic in 2020 and 2021 (see Table A1.3 in the Appendix) and the Italian National Recovery and Resilience Plan (PNRR) in 2022. The former is constructed based on the Bank of Italy's projections for variations in consumption, investment, exports, and imports.[7] The latter increases government expenditure and subsidies to firms by sectors in six mission plans.[8]

4.1 Atmospheric temperature and climate-related damage

We begin by presenting the projected temperature dynamics under the RCP 6.0 scenario relative to the Baseline. Figure 2 reports the evolution of average annual temperature deviations for the five Italian macro-regions. As expected, temperatures remain constant in the Baseline scenario, while under RCP 6.0 they display a persistent upward trajectory from 2025 onwards. Although the magnitude of the increase differs across macro-regions, reflecting spatial heterogeneity in climate projections, the overall pattern is characterised by a gradual and sustained rise in average temperature.

[7] Further information available on https://www.bancaditalia.it/pubblicazioni/proiezioni-macroeconomiche/2020/index.html. Accessed 30/08/2025.

[8] Further information available on https://www.italiadomani.gov.it/content/sogei-ng/it/it/home.html. Accessed 30/08/2025.

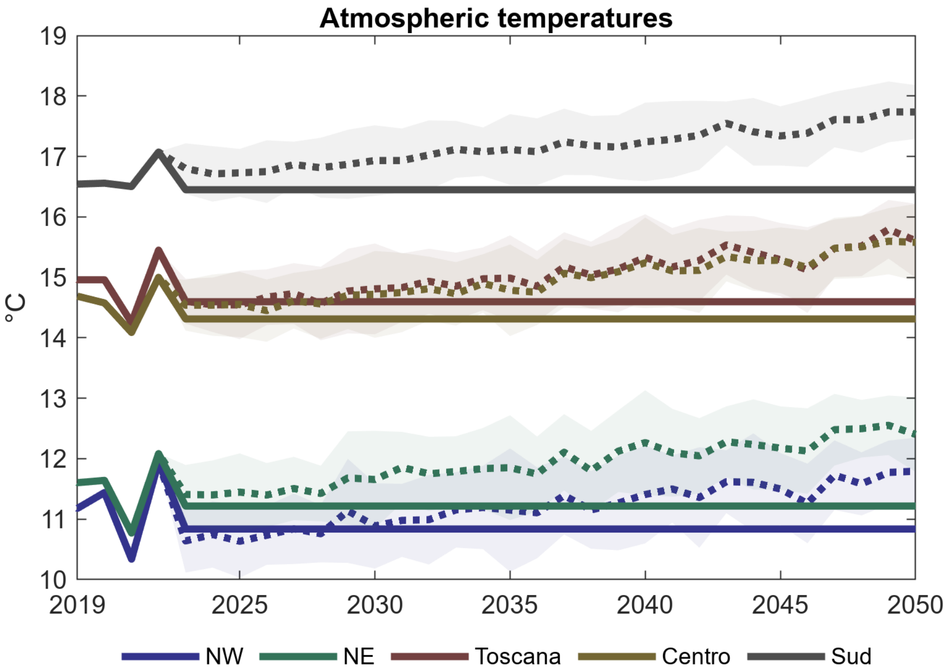
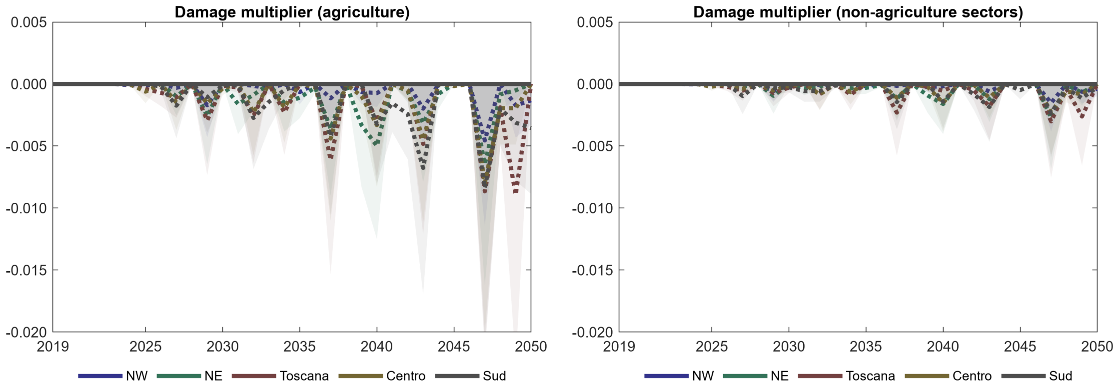


Figure 2: Projected average annual temperature deviations under RCP 6.0 relative to the Baseline for the five macro-regions.

The projected trajectory follows the same increasing pattern observed across regions, though the magnitude and timing of the temperature rise are region-specific. This confirms the importance of incorporating spatially differentiated climate projections within the modelling framework, as local temperature dynamics directly influence sectoral productivity through the damage function described in Section 3.3.

The increase in temperature translates into productivity losses through the climate damage multiplier. Figure 3 reports the evolution of the damage coefficients for agricultural and non-agricultural sectors across the five macro-regions. The agricultural sector exhibits higher sensitivity to temperature increases, reflecting its direct exposure to extreme weather conditions and changes in precipitation patterns. Non-agricultural sectors also experience productivity reductions, although the magnitude is comparatively smaller and more gradual.



(a) Agricultural sectors

(b) Non-agricultural sectors

Figure 3: Climate damage multipliers across the five macro-regions under RCP 6.0.

4.2 On spatial disaggregation

To assess the role of regional climate damages, we compare aggregate output losses under the RCP 6.0 scenario with those under the baseline, both in the multi-spatial and national models (i.e., using the EUROGREEN model). The results, reported in Figure 4, illustrate that incorporating regional heterogeneity leads to marked under-estimation of production losses. This difference highlights the importance of spatial granularity. By revealing how uneven regional impacts accumulate into amplified national damages, the multi-spatial framework provides a more accurate and robust basis for assessing climate impacts.

The trajectories shown in Figure 4 correspond to the median across the 500 simulation runs, with confidence intervals constructed from the median absolute deviation scaled by a factor of 1.5. In 2030, aggregate output losses in the multi-spatial model already exceed those of the national model (approximately 3% versus 2%), although the confidence intervals still overlap. Thereafter, the trajectories diverge progressively. From around 2040 onwards, the confidence intervals no longer overlap, indicating that in virtually all simulations the multi-spatial framework generates larger aggregate losses than the national model. By 2040, the median loss reaches approximately 8% in the multi-spatial model, compared to about 4% in the national specification. By 2050, the gap widens further, with cumulative median losses of roughly 17% under the multi-spatial approach versus about 10% in the national model. This widening divergence reflects the cumulative amplification of uneven regional shocks over time, which are progressively internalised in the multi-spatial framework but smoothed out under national aggregation. The results therefore confirm that neglecting regional heterogeneity leads to a systematic underestimation of long-run production losses.

The aggregate findings therefore reinforce the need to move beyond a purely national perspective, motivating a closer examination of the spatial distribution of GDP losses across macro-regions. This is addressed in the following maps of GDP losses by macro-region, shown in

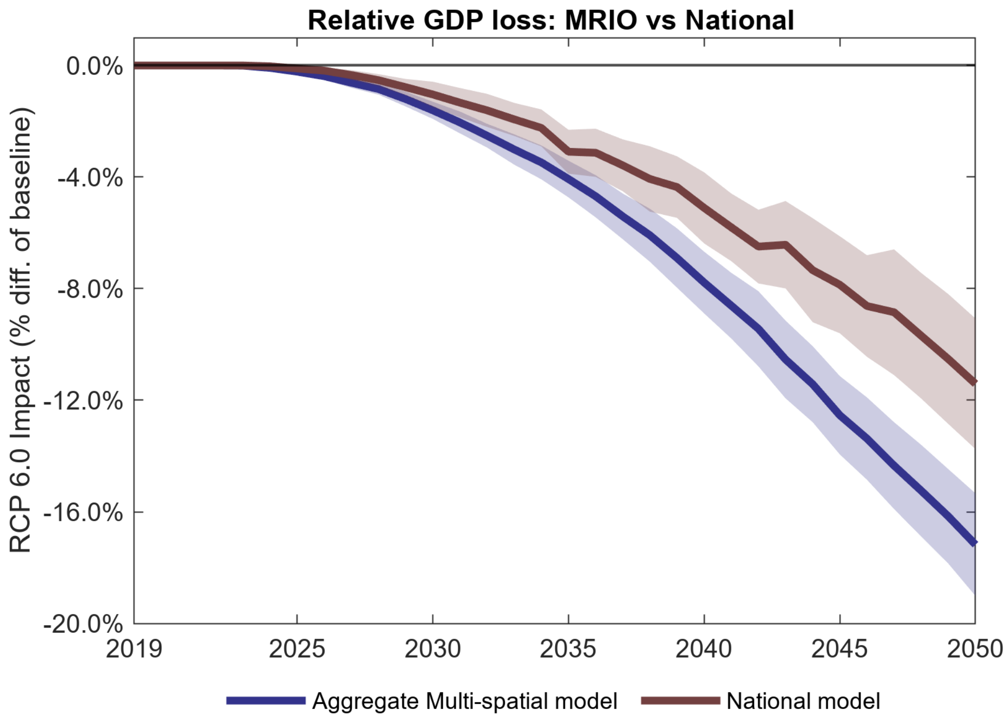
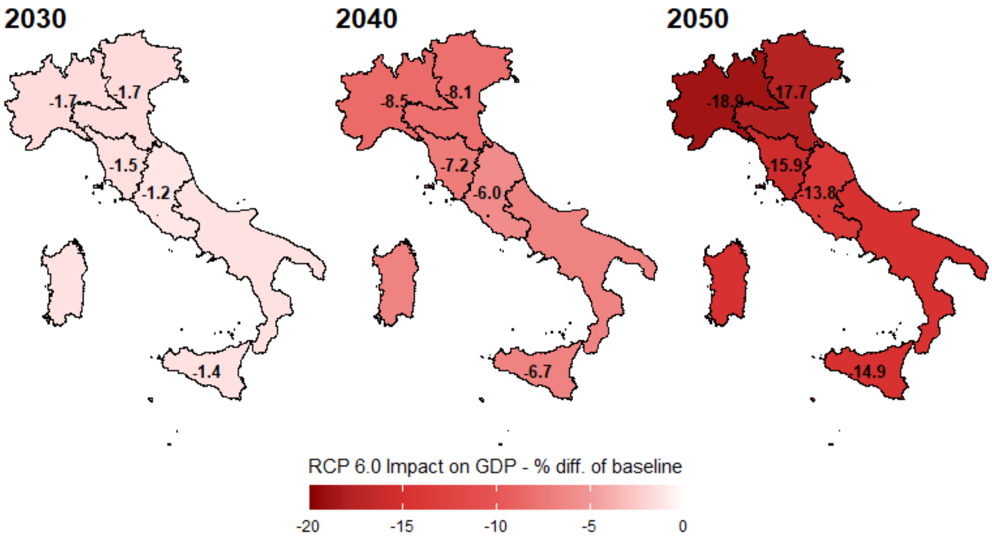


Figure 4: Aggregate Output loss: Multi-Spatial vs National. Yearly percentage difference of national output under the climate scenario RCP 6.0 with respect to the Baseline. The red line refers to the national-scale EUROGREEN model, while the blue line refers the the Multi-Spatial ITAGREEN-MRIO model in which the national output is given by the sum of macro-regional output.

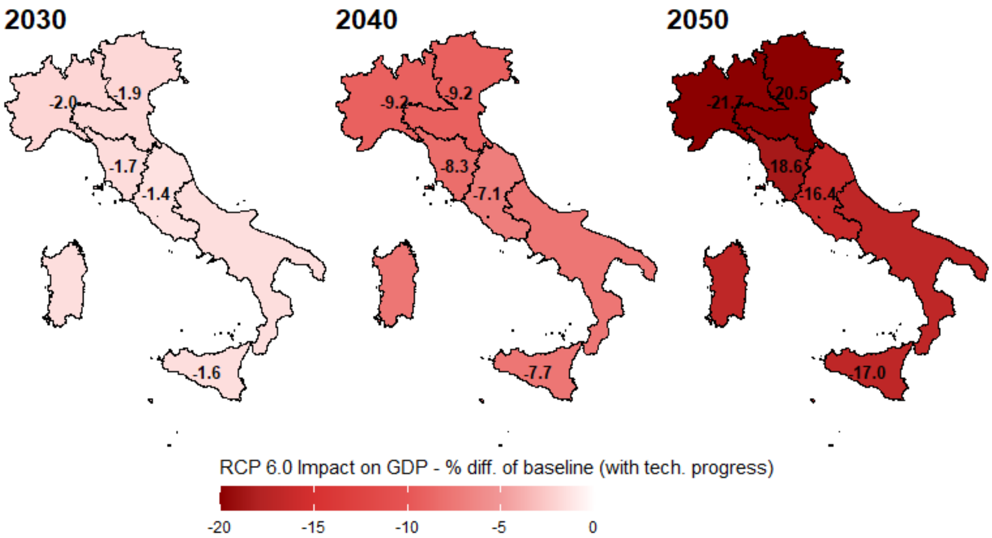
Figure 5.

Figure 5 reports the regional distribution of GDP losses under the RCP 6.0 scenario, without and with technological progress. Consistent with the aggregate results, all macro-regions experience increasingly severe contractions over time. However, the magnitude of the impact differs across territories, revealing clear spatial heterogeneity.

In the absence of technological progress (upper panel), the Northwest and North-East display the largest percentage losses by 2050, followed by Tuscany, the South, and the Centre. These differences reflect variations in productive structure and economic centrality. The Northern regions, characterised by a large manufacturing base and dense interregional linkages, do not necessarily experience the strongest direct productivity shocks. Rather, although climate damages are more intense in agriculture, the propagation of these shocks through input–output linkages disproportionately affects regions where manufacturing is concentrated. Given that manufacturing represents the largest share of national value added and is deeply embedded in interregional supply chains, the Northern regions absorb a substantial portion of the shocks transmitted from climate-sensitive sectors. As a result, contractions in these highly interconnected production hubs generate larger aggregate losses, despite the initial shock originating elsewhere. Tuscany and the Centre exhibit intermediate dynamics, while the South's losses reflect its higher exposure to climate-sensitive sectors but lower centrality in national value chains.



(a) Without technological progress.



(b) With technological progress.

Figure 5: GDP loss by macro-region. Percentage difference in value added due to climate damages under the RCP 6.0 scenario, by macro-region, relative to the Baseline.

When technological progress is introduced (lower panel), the overall ranking remains broadly unchanged, but the magnitude of losses increases across all regions. The amplification observed under endogenous innovation confirms that structural interdependencies and growth dynamics interact with climate-induced productivity shocks, reinforcing regional divergences over time. The slightly larger percentage GDP loss under the technological progress scenario may reflect a growth–input interaction effect. When endogenous innovation is active, the economy follows a higher growth path, implying a progressively larger volume of intermediate input requirements. Although productivity improvements partially offset input needs, climate damages operate as a productivity wedge that increases the quantity of intermediate inputs required per unit of output. In a faster-growing economy, this wedge interacts with a larger and expanding production base, generating stronger cost pressures and, consequently, a slightly larger relative contraction of GDP. When climate pressures operate through input constraints, a larger and more dynamic production system can remain, or even become, comparatively more exposed to such shocks.[9]

Finally, we report the GDP trajectories by macro-region. Figure 6 presents the evolution of GDP under the four scenarios.

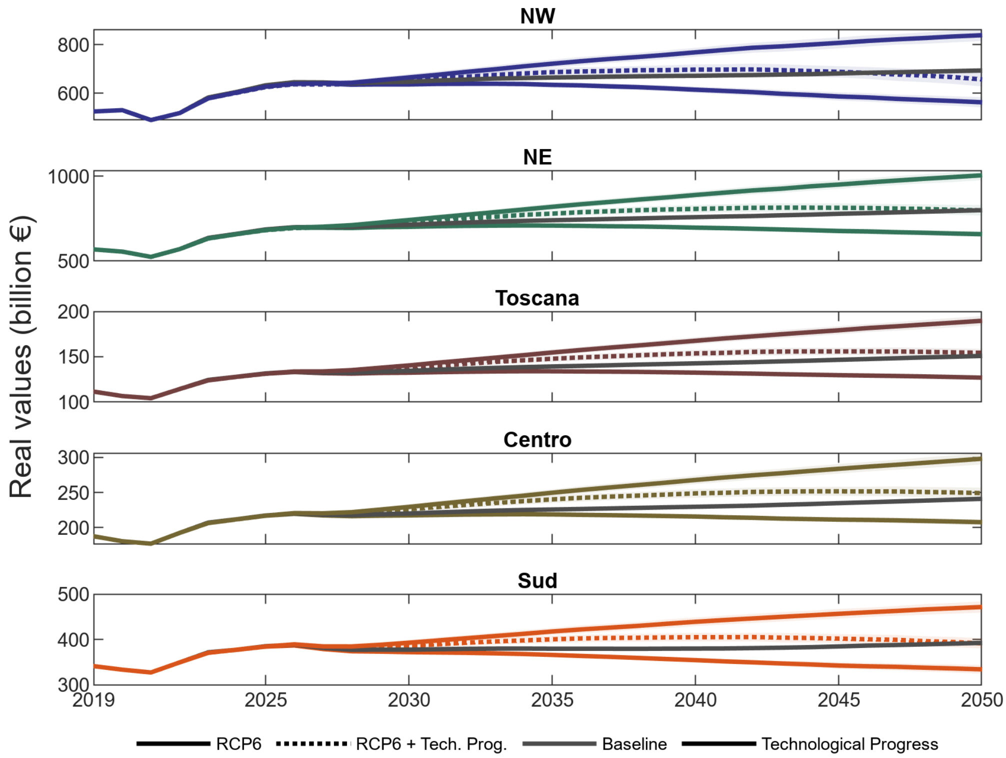


Figure 6: GDP in the five macro-regions under the four scenarios.

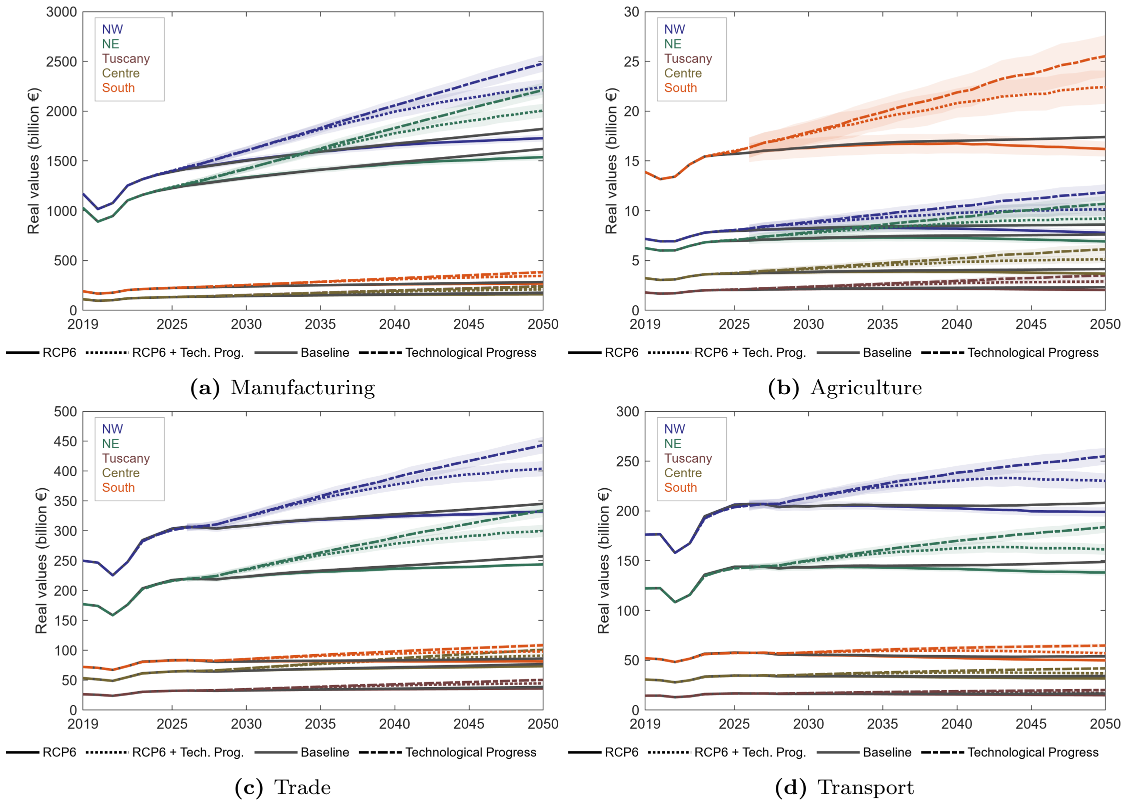
The comparison highlights three key mechanisms. First, climate damages reduce GDP relative to the Baseline when technology is held fixed. Second, endogenous technological progress

[9] A caveat is that higher labour productivity may also affect labour demand, as fewer workers may be required to produce a given level of output. At this stage of the analysis, however, regional labour market dynamics are not explicitly modelled.

supports output growth in the absence of climate shocks. Third, when climate damages and technological progress interact, innovation partially offsets productivity losses, although it does not fully neutralise their effect. The divergence across trajectories emerges from 2023 onwards, reflecting the forward-looking counterfactual design of the exercise.

4.3 Multi-sectoral and multi-spatial focus

The regional patterns discussed above motivate a closer analysis of the temporal dynamics of output at the sectoral level. Figures 7a–7d depict the evolution of real output under the four scenarios across the five macro-regions for selected sectors. In particular, manufacturing (Panel 7a), agriculture (Panel 7b), trade (Panel 7c), and transport (Panel 7d) allow us to disentangle how sectoral composition interacts with regional vulnerability to climate impacts. This sectoral perspective sheds light on the mechanisms through which climate damages propagate within and across regions, ultimately shaping the distribution of aggregate losses in the Italian economy.



(a) Manufacturing **(b)** Agriculture **(c)** Trade **(d)** Transport

Figure 7: Real output for selected sectors. Spatial comparison of sectoral output, by macro-area, under the four scenarios for four selected sectors: (a) Manufacturing, (b) Agriculture, and (c) Trade. Panel (d) Transport.

The behaviour of output closely mirrors that observed for GDP. Under the RCP 6.0 scenario, output is lower than in the Baseline both with and without technological progress, while endogenous innovation partially offsets the level of economic losses. However, the relative contraction in total output is smaller than that observed for GDP. One possible interpretation lies in the role of intermediate goods. Since climate damages operate by increasing the input–output technical coefficients—reflecting a productivity loss in intermediate inputs—a larger quantity of inputs is required per unit of final output. As a result, although overall production declines, the share of intermediate goods in total output increases relative to final goods. This mechanism moderates the relative reduction in gross output compared to value added.

Consistent with the previous results, the Northwest and the Northeast show the largest output levels and climate losses. These regions also grow the fastest, reflecting their manufacturing intensity and higher productivity, characteristic of more industrialised areas. However, for the same reasons, they register the largest climate-related losses, as productivity shocks propagate through interregional and intersectoral linkages and affect demand. This pattern echoes the aggregate results discussed above, while the regional breakdown now reveals how these mechanisms unfold across space and sectors. It is necessary to note, however, that since many mechanisms continue to follow national-level dynamics, the emphasis here is less on the absolute values of the simulations and more on the dynamics they reveal. This aspect becomes accessible precisely through the multi-spatial structure.

Turning to the sectoral dimension, the South stands out with the largest agricultural output. Given agriculture's direct exposure to climate shocks, damages in this sector exert strong spillover effects on the rest of the regional economy, which helps explain why aggregate value added in the South is among the most affected. In manufacturing, the figures highlight the wide distance separating the Northwest and Northeast from the other regions. This gap underscores not only the tendency for the north-south divide in Italy to widen, but also its role as a shock absorber of value-added losses originating elsewhere in the economy. Finally, services—here represented by trade—are also most affected in the Northwest and Northeast, reflecting the contraction in household demand following the decline in productivity and income.

The productivity shocks induced by climate damages call for a closer examination of how intermediate goods flows are reshaped across regions. Tables 1 and 2 report percentage differences in intermediate transactions for selected sectors—agriculture, manufacturing, and trade—across the five macro-regions in 2030, 2040, and 2050. For expositional clarity, the origin of intermediate goods is restricted to Tuscany (aggregating all sectors), while destination sectors are identified separately for each macro-region. This choice serves as an illustrative case of how climate-induced productivity losses affect regional positions within interregional supply chains and how these effects propagate across territories over time.

The selected sectors reflect their structural relevance within the regional economy. Agriculture is the most sensitive to climate damages, manufacturing represents the core productive sector in terms of output and inter-industry linkages, and trade is the largest service sector.

Table 1: Intermediate goods transaction for selected sectors. Percentage difference of intermediate demand under climate scenario RCP 6.0 with respect to the Baseline.

	NW			NE			TOSC			CEN			SOUTH		
Year	*agri*	*manuf*	*trade*	*agri*	*manuf*	*trade*	*agri*	*manuf*	*trade*	*agri*	*manuf*	*trade*	*agri*	*manuf*	*trade*
2030	0.6%	1.0%	0.5%	2.3%	1.5%	0.9%	2.1%	1.0%	0.5%	1.9%	1.1%	1.0%	4.3%	2.1%	1.3%
2040	2.3%	1.1%	0.7%	7.4%	2.5%	1.5%	5.5%	0.8%	0.5%	5.1%	0.8%	1.3%	11.1%	3.3%	2.1%
2050	1.4%	-1.6%	-0.4%	9.5%	0.8%	0.4%	5.9%	-2.6%	-1.1%	5.9%	-2.3%	0.5%	16.7%	2.3%	1.8%

Table 2: Intermediate goods transaction for selected sectors. Percentage difference of intermediate demand under the Technological Progress scenario with respect to the RCP 6.0 (Climate Damages) + Technological Progress scenario.

	NW			NE			TOSC			CEN			SOUTH		
Year	*agri*	*manuf*	*trade*	*agri*	*manuf*	*trade*	*agri*	*manuf*	*trade*	*agri*	*manuf*	*trade*	*agri*	*manuf*	*trade*
2030	0.0%	0.7%	0.5%	1.8%	1.3%	0.6%	1.1%	0.8%	0.2%	1.3%	0.7%	0.6%	3.8%	1.8%	1.0%
2040	-0.8%	-1.2%	-1.5%	4.5%	0.5%	-0.5%	2.1%	-1.5%	-1.3%	2.1%	-1.5%	-0.6%	7.2%	1.1%	0.2%
2050	-4.3%	-6.1%	-5.7%	3.4%	-3.8%	-4.7%	-1.2%	-6.9%	-6.2%	-0.1%	-6.5%	-4.7%	9.8%	-2.2%	-3.1%

The results highlight two opposing mechanisms shaping intermediate demand. On the one hand, climate-induced productivity losses increase input requirements for a given level of output, generating an upward pressure on intermediate demand. On the other hand, the contraction in value added reduces the overall scale of production, eventually lowering total transaction volumes (a scale effect). The interaction between these forces governs the evolution of interregional intermediate flows.

Three stylized patterns emerge [too raw, give better flow and naturality]. First, agriculture exhibits a persistent increase in intermediate demand across all regions, reflecting its high sensitivity to climate damages. Second, manufacturing and trade display an initial increase followed by a decline over time, as the reduction in value added and output increasingly offsets the higher input requirements per unit of production. Third, the magnitude and timing of these adjustments varies across regions, reflecting differences in sectoral composition and highlighting the role of structural heterogeneity.

The comparison with the technological progress scenario highlights the interaction between climate damages and endogenous efficiency improvements. Productivity gains from technological progress alter the balance between increasing input requirements and the contraction of economic activity induced by climate change. In agriculture, intermediate demand often remains positive, particularly in regions where the sector plays a larger role, indicating that the increase in input requirements associated with climate damages is only partially offset. In manufacturing and trade, by contrast, intermediate demand tends to decline over time in several regions, reflecting the combined effect of efficiency gains and the contraction in value added.

These results do not point to a uniform mitigating role of technological progress, but rather to a reconfiguration of intermediate demand across sectors and regions. The interaction between climate-induced productivity losses and technological change reshapes production processes and input structures, with outcomes depending on sectoral composition and regional economic structure. In this sense, the model captures how the joint dynamics of climate damages and innovation propagate through interregional input-output linkages, modifying transaction patterns and, ultimately, regions' positions within supply chains.

Building on this, we turn to household consumption, another dimension explicitly modelled at the regional level. Figure 8 mirrors the structure of the output analysis, reporting total consumption by region (Panel 8d) as well as consumption in agriculture (Panel 8b), manufacturing (Panel 8a), and transport (Panel **??**). This parallel structure allows us to examine how climate damages, transmitted through output and income, ultimately translate into regional consumption patterns across sectors.

Household consumption is disaggregated by region and COICOP categories, as described in Section 3.2. Region- and COICOP-specific consumption coefficients were estimated and subsequently mapped into NACE industries through a bridge matrix, ensuring consistency between final demand and sectoral production. This procedure provides household consumption by industry and by region, allowing for a detailed sectoral representation of demand.

In the current framework, disposable income is modelled as a fixed share of national value added. As regional labour income dynamics are not yet explicitly represented, disposable income follows the aggregate national trajectory, implying that consumption levels adjust proportionally to national income fluctuations.

The pattern mirrors that observed for GDP and output. Under the RCP 6.0 scenario, consumption levels are lower relative to the Baseline. Endogenous technological progress partially offsets these losses by supporting higher income and production levels. As a result, the scenario with technological progress and no climate damage exhibits higher consumption levels than the Baseline without technological progress.

The transmission channel from productivity shocks to household consumption operates primarily through income: regions with larger losses in value added tend to experience more substantial reductions in consumption. However, in a multi-spatial setting, interregional consumption flows diffuse these impacts across space, making the relative intensity of the climate shock on consumption more uniform across regions. What remains differentiated are the absolute levels of consumption, which mirror the distribution of output and value added—highest in the Northwest and Northeast, followed by the South, Central, and Tuscany. While these results largely reproduce the output patterns, the regional consumption structure provides a foundation

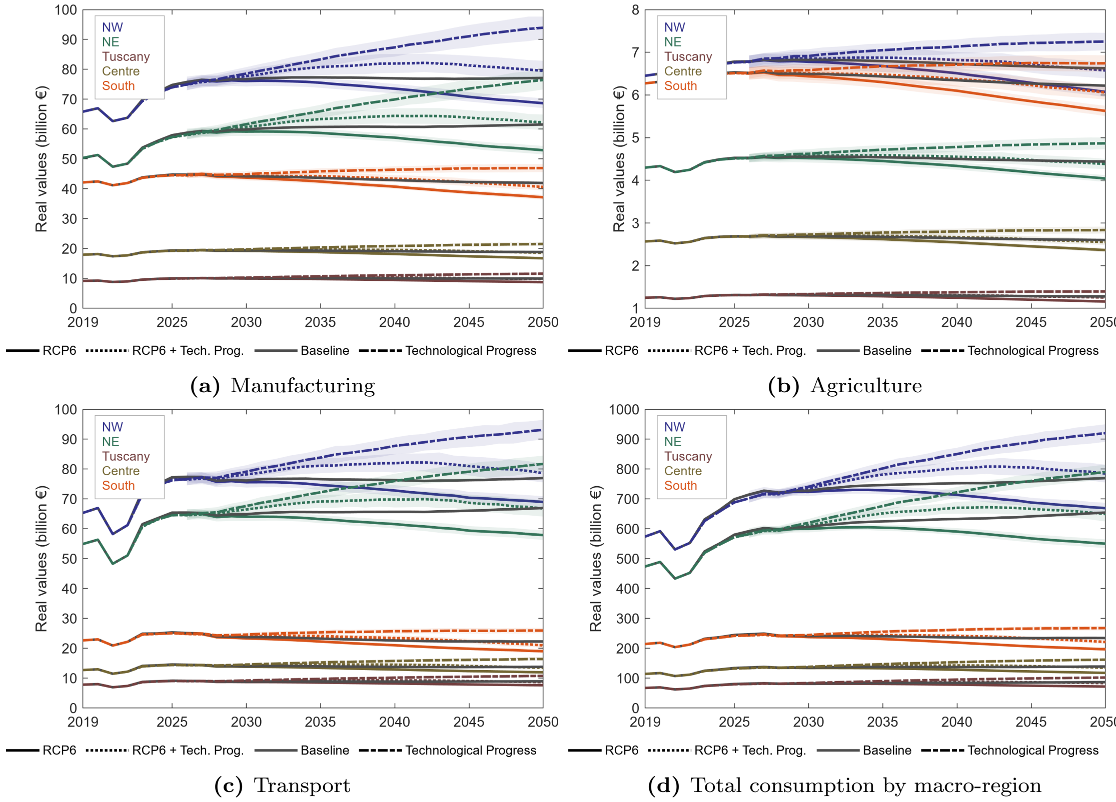


Figure 8: Real household consumption for selected sectors. Spatial comparison of total consumption, by macro-area, under the four scenarios for three selected sectors: (a) Manufacturing, (b) Agriculture, and (c) Transport. Panel (d) shows the overall output at the regional level under the two scenarios.

for future extensions, where incorporating region-specific demographic, labour market and price system dynamics will allow for a more complete assessment of how climate shocks transmit from production to household demand.

While these results largely reproduce the output patterns, the regional consumption structure provides a foundation for future extensions. Incorporating region-specific demographic, labour market, and price system dynamics would allow for a more complete assessment of how climate shocks transmit from production to household demand.

Figure 9 shows how emission trajectories differ across scenarios, reflecting the interaction between climate damages and technological change. Emissions are modelled through sector-specific coefficients applied to regional output, implying a simplified representation of environmental processes. Within this structure, technological progress can sustain higher levels of economic activity by partially offsetting climate-induced economic losses, but this also entails higher input use and material throughput, which in turn leads to higher emissions and ecological pressures. In this sense, the results point to a limitation of relying on efficiency and productivity gains to mitigate environmental impacts through innovation. This contrasts with standard modelling approaches in which technological progress is assumed to offset climate damages while enabling decoupling between production and emissions, and underscores the importance of explicitly accounting for production structures and biophysical constraints in multi-regional frameworks.

Finally, we report the estimated greenhouse gas (GHG) emissions by macro-region under the four scenarios in Figure 9. The model includes sector-specific GHG emission intensities. By applying these national sectoral intensities to sectoral output trajectories in each region, we obtain an approximate measure of total regional emissions under the four scenarios. While this approach does not account for potential regional differences in production technologies or energy mixes, it allows for a consistent comparison of emission dynamics across scenarios within the existing modelling framework.

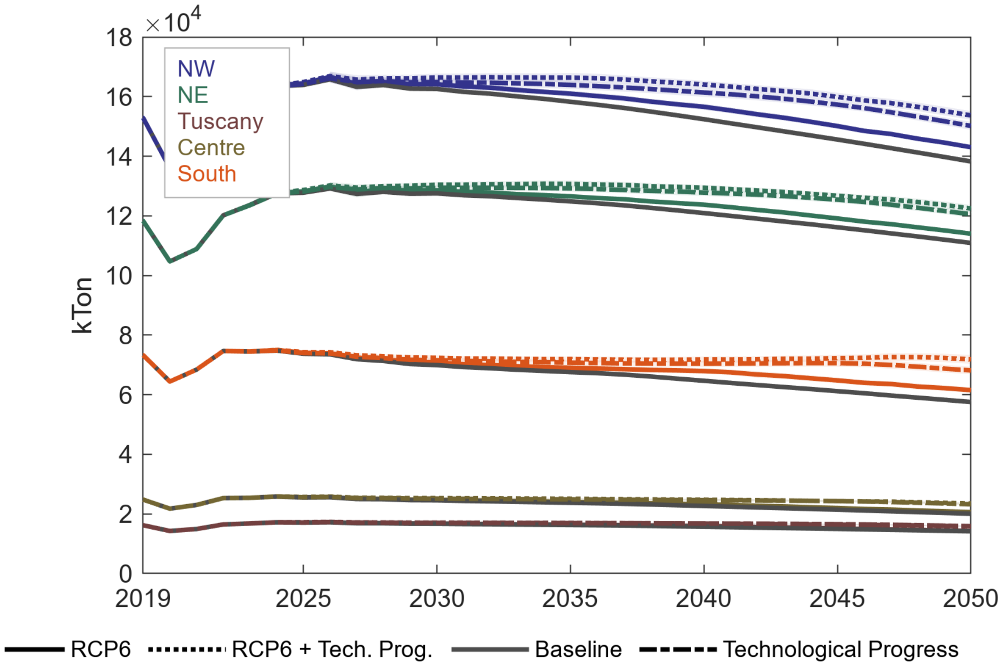


Figure 9: Estimated GHG emissions by macro-region. Evolution of total greenhouse gas emissions under the four scenarios.

Figure 9 shows how emission trajectories differ across scenarios, reflecting the interaction between climate damages and technological change. Emissions are lowest in the Baseline scenario and increase progressively across scenarios, with the highest levels observed when technological progress and climate damages are combined. The RCP 6.0 scenario exhibits relatively low emissions, consistent with lower output levels, although climate-induced declines in productivity increase input requirements. The technological progress scenario, by contrast, is associated with higher output and improved efficiency, resulting in moderately higher emissions despite the absence of climate pressures on input use.

The highest emission levels emerge in the combined scenario, where technological progress sustains economic activity while climate damages increase input requirements. This interaction results in higher material throughput and intensified environmental pressures. These results point to a limitation of relying on efficiency and productivity gains to mitigate environmental pressures through innovation. This contrasts with standard modelling approaches in which technological progress may offset climate damages while enabling decoupling between production and emissions, and underscores the importance of explicitly accounting for biophysical constraints in ecological macroeconomics modelling frameworks.

5 Concluding remarks

This study contributes to the literature by incorporating a central methodological innovation: the simultaneous integration of national and subnational dynamics within a coherent modelling structure. The model combines a national layer with a regional disaggregation into five macro-areas of Italy, capturing geographical heterogeneity while preserving consistency with aggregate dynamics. This is achieved through a multi-scale framework in which some components are specified bottom-up—modelled at the regional level and aggregated nationally—while others are defined top-down and disaggregated across regions.

The model builds on the tradition of Ecological Macroeconomics while advancing a line of research that has so far received limited attention, namely the development of multi-spatial integrated assessment models. Despite growing interest in climate change impacts, most existing IAMs operate at the global or national level, thereby overlooking spatial disparities and the interactions between local and aggregate dynamics. This leaves an important gap in understanding how climate damages propagate across regions, how regional vulnerabilities compound at the national scale, and how national policies may generate uneven effects across space. By explicitly incorporating subnational dynamics, ITAGREEN-MRIO takes a step toward closing this gap and contributes to the development of tools capable of capturing the geography of climate impacts with greater accuracy and policy relevance.

The multi-spatial structure allows us to trace how regional and sectoral trajectories evolve, highlighting differences in both growth patterns and climate-induced impacts. The comparison between the regionalised and national versions of the model underscores the importance of spatial granularity. Aggregate models, by construction, smooth over localised variations in climate impacts, thereby limiting their ability to represent the uneven geography of damages. By contrast, the MRIO framework captures how heterogeneous regional shocks interact through inter-industry and interregional linkages. The results show that ignoring spatial heterogeneity leads to a systematic underestimation of long-run losses. Regions characterised by dense manufacturing bases and strong network centrality absorb shocks propagated from climate-sensitive sectors, amplifying aggregate effects at the national level. In this way, regionalisation does not simply refine the detail of the analysis but enhances its robustness and explanatory power.

The results also highlight the role of natural resource constraints, which cannot be expanded through economic activity. Whether under climate damage scenarios (lower productivity) or technological progress scenarios (higher growth), the findings point to the limits of relying on efficiency gains to address environmental pressures, and to the asymmetry between growth dynamics and natural resource constraints. This interaction underscores the importance of embedding environmental limits within macroeconomic modelling frameworks.

It should be emphasised that, at this stage, several mechanisms in the model continue to follow national-level dynamics. At the same time, the allocation of mechanisms across spatial levels is not fixed, but can be adapted to the research question and data availability, allowing the model to balance empirical feasibility with analytical flexibility. These modelling choices help reduce the number of free parameters and ensure consistency with observed macroeconomic patterns, while acknowledging the limits of representation inherent in any modelling exercise.

Building on this multi-spatial structure, the model provides a foundation that can be progressively expanded. Beyond the economic core, it already incorporates energy and environmental modules, opening the possibility of extending the analysis to capture how climate shocks and transition policies reverberate not only through production, income, and household demand, but also across labour markets, resource use, technological change, and ecological pressures. While some modules may be extended to a multi-spatial setting in future work, others—such as finance and government—are appropriately retained at the national level, provided they remain fully integrated with regional dynamics. In this way, the model offers a platform on which a wide range of policies and scenarios can be analysed within a genuinely multi-systemic perspective.

Developing the ITAGREEN-MRIO model required an extensive effort in data collection, harmonisation, and calibration to ensure internal consistency across submodules. Despite its detailed structure and broad variable coverage, the model remains a stylised representation of the real economy. Given its complexity and the number of parameters involved, some mechanisms are treated as exogenous to preserve tractability and robustness. These challenges are further amplified in the multi-spatial setting, where the inclusion of five regions increases the number of equations, parameters, and interdependencies. The model should therefore be interpreted as a structured analytical tool rather than a predictive device, and is best employed in combination with complementary quantitative approaches and qualitative insights, including stakeholder engagement.

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A Appendix

A.1 Tables

Table A1.1: EUROGREEN model in a nutshell. List of all the modules together with a recap of the main assumptions and feedback effects. The full documentation is available at doi.org/10.1038/s41893-020-0484-y.

Module	*Main assumptions*	*Feedback*
Demography	Four age cohorts and three skill groups by education (low, middle and high). Demographic exogenous trends provided by ISTAT projections.	It affects labour force participation rate and educational skill composition.
Prices	Prices depends on the markup and unit cost of production, which include unit labour cost, unit intermediate cost, unit capital depreciation cost. The price markup depends on the difference between current capacity utilisation rate and normal capacity utilisation rate.	Generates an upward slopping Philips curve. Technological improvements reduce prices.
Profits and VA	Accounting equations follow SNA.	It affects the maximum level of private indebtedness and then the level of future investments.
Consumption	Average propensity to consume extrapolated by non-linear algorithm into household income categories by income level, gender, skill, employment status, pensioner and capitalist. Consumption share between COICOP depends on price elasticity and income elasticity.	Consumption depends on income and substitution effects between goods. Final demand determines the overall sectoral output through the Leontief inverse.
Input-Output	The Input–Output module follows a demand-led framework with no substitutability between inputs, unlike neoclassical models based on optimization and flexible factor use. Technical coefficients define inter-sectoral input requirements and evolve endogenously over time, reflecting changes driven by innovation. The model also allows for output to be constrained by capacity utilisation.	It affects labour demand and employment, VA, emissions, GDP growth and public revenues (via taxation).

Table A1.1 continued from previous page

Module	*Main assumptions*	*Feedback*
Investments	Demand-led determination of investment based on deviations from the capacity utilisation from the desired rate (Post-Keynesian/Sraffian). Financial constraint to investment based on the Equity-to-Liabilities Ratio (ELR) is rooted in Post-Keynesian/Kaleckian/Minskyan macroeconomic theory of investment behaviour and financial fragility.	It affects final demand, capital stock accumulation, and financial indebtedness.
International Trade	Imports are computed using constant import share coefficients derived from historical real data. Exports are modelled based on a constant price elasticity and an exogenous, industry-specific growth rate.	Gross domestic product and trade balance.
Finance	The value of total national wealth is divided depending on the skill level, used as a proxy of propensity to make financial investments. Also, capitalists are included. Low-skill individuals hold only bank deposits, middle-skill individuals hold also public bonds, while high-skill individuals and Capitalists make also investments in Equities. Allocation of assets according to a simplified Tobin's portfolio choice depending on the rate of return.	It impacts income distribution, inequality and wealth taxation.
Labour	Wage evolution depends on labor productivity growth rate, employment levels, and inflation. Since it depends on prices, it is affected by the markup. Employment by industry is determined by how much labour is required to produce the planned output, and hence depends on labour productivity, as well as hours worked.	It has an impact on income distribution, working hours, (un)employment, consumption and inequality.
Energy	Five main energy sources: solid, liquid, gas, nuclear and renewable. Exogenous share composition depending on scenarios.	Energy demand depends on total output and technological innovations (which affects energy efficiency). It determines the level of GHG emissions.

Table A1.1 continued from previous page

Module	*Main assumptions*	*Feedback*
Carbon Emissions	Coefficient of CO2 emissions are calculated for each fossil source and GHG is derived in proportion to CO2 levels.	It does not have feedback in the economy but is influenced by innovations and energy efficiency changes.
Technology	The dynamics of innovation contain a stochastic element influencing the accessibility and efficiency advancements of novel technologies. Each industry will adopt the most cost-effective technology, resulting in savings in labour and/or intermediate resources.	It determines the dynamics of the Leontief technical coefficients, labor productivity, and energy efficiency gains.
Government	It includes all the sources of revenue (income tax, corporate income and financial tax, VAT, labour and carbon tax) and expenditures (subsidies, wages, investments, and consumption) to determine the public deficit and debt, also considering the interest rate on bonds.	It impact production and consumption through taxes and subsidies and via direct policy intervention under given scenarios.

Table A1.2: List of sectors of ITAGREEN-MRIO Model

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

Table A1.3: Exogenous shocks from the Covid-19 pandemic from 2019 to 2020.

Covid shocks	Δ%
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.

A.2 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 A2.1: 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	

Table A2.1 continued from previous page

Parameter	***Value***	***Equation or definition***	***Note***
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.
$\overline{\eta}$	*0.03*	$\eta(t) = \eta(t-1) \cdot [1 - \overline{\eta}(uc - uc^N)]$	η is the markup and $\overline{\eta}$ is a measure of the sensitivity to capacity over-utilisation. Initial industry-specific markups ($m_{i,0}$) are approximated based on Christopoulou 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 **setterfield2020hysteresis**.
$(g'_{agr}, g''_{agr}, g'''_{agr})$	*(-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 et al., 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.*	