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Summary

In this work we update the regionalization and the calibration of the Regional dynamic Integrated model of Climate and the Economy (RICE) in its 1999 version developed by Nordhaus and Boyer (2000), with a focus on the Mediterranean countries. Our aim is to assess the impact of climate change damages on their main macroeconomic variables in a context where all economies are fossil fuel based. In addition, we extend the model by introducing the uncertainty associated with a possible future catastrophic event, triggered by the temperature increase and variation over time, following the approach of Castelnuovo et al. (2003). We then develop an empirical exercise to asses the impact of climate change on the agricultural sector at country level. In this framework, we implement the traditional IAMs scenarios, namely the Business As Usual, the Social Optimum and the Temperature Limit, where population dynamics is calibrated according to the IIASA SSP2 projections. Among our findings, we show that, in the absence of renewable energy sources and break-through technologies, meeting the limit of a temperature increase of less than 2°C requires a carbon tax of more than 700 USD/tC by 2050, doubling by the end of this century. When uncertainty is introduced, the higher the probability of a possible catastrophic event and the greater the associated utility loss, the more society is willing to pay for a rising cost of carbon. The upward trend of the carbon tax relative to the no-uncertainty model is reduced by the end of the century in the temperature-limit scenario, due to the benefits associated with this policy and the inclusion in the model of societal awareness of the potential risks of climate change. In both versions of the model, the agricultural sector in the Southern Mediterranean countries is severely affected, and stringent policies can partially mitigate these impacts and reduce damages by 2100.

Keywords: IAMs, climate change, carbon tax, carbon price, emissions, temperature, energy, Mediterranean region, Mediterranean countries

JELClassification: Q54, H23, R13.

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Abstract

In this work we update the regionalization and the calibration of the Regional dynamic Integrated model of Climate and the Economy (RICE) in its 1999 version developed by Nordhaus and Boyer (2000), with a focus on the Mediterranean countries. Our aim is to assess the impact of climate change damages on their main macroeconomic variables in a context where all economies are fossil fuel based. In addition, we extend the model by introducing the uncertainty associated with a possible future catastrophic event, triggered by the temperature increase and variation over time, following the approach of Castelnuovo et al. (2003). We then develop an empirical exercise to asses the impact of climate change on the agricultural sector at country level. In this framework, we implement the traditional IAMs scenarios, namely the Business As Usual, the Social Optimum and the Temperature Limit, where population dynamics is calibrated according to the IIASA SSP2 projections. Among our findings, we show that, in the absence of renewable energy sources and breakthrough technologies, meeting the limit of a temperature increase of less than 2°C requires a carbon tax of more than 700 USD/tC by 2050, doubling by the end of this century. When uncertainty is introduced, the higher the probability of a possible catastrophic event and the greater the associated utility loss, the more society is willing to pay for a rising cost of carbon. The upward trend of the carbon tax relative to the no-uncertainty model is reduced by the end of the century in the temperature-limit scenario, due to the benefits associated with this policy and the inclusion in the model of societal awareness of the potential risks of climate change. In both versions of the model, the agricultural sector in the Southern Mediterranean countries is severely affected, and stringent policies can partially mitigate these impacts and reduce damages by 2100.

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LIST OF ACRONYMS

Abbreviations

AT	Atmosphere
AC	After the catastrophic event
BAU	Business as usual
BC	Before the catastrophic event
CCS	Carbon capture and storage
CES	Constant elasticity of substitution
CO2	Carbon dioxide
GDP	Gross domestic product
CGE	Computable general equilibrium model
DICE	Dynamic integrated climate-economy
GHG	Greenhouse gases
GTC	Gigatonnes of carbon
HR	Hazard rate
IAM	Integrated assessment models
IPCC	Intergovernmental panel on climate change
MED	Mediterranean
OPT	Pareto optimal
RICE	Regional dynamic integrated model of climate and the economy
RM	RICE-MED model
RM-U	RICE-MED model under uncertainty
SCC	Social cost of carbon
TFP	Total factor productivity
TL	Temperature limit
WEFE	Water, energy, food and ecosystems

1 Introduction

The adverse effects of climate change on the water-energy-food-ecosystems (WEFE) nexus, and its components, have increased over the years. A recent work of Han et al. (2022) reports that for any additional increment of 1°C of the average temperature, the food yield will diminish by 1.6%.[1] Climate variability trends affect future changes in monthly heavy-precipitation events (van der Wiel and Bintanja, 2021), rising the exposure of agriculture to floods risk. In addition to that, agricultural yield anomalies are found to be linked to temperature-related extremes (Vogel et al., 2019), increasing the potential damage to the sector if no effective climate change policies are adopted. Water is the first channel through which the consequences of climate change will appear, since changing precipitation patterns already alter agronomic productivity (Miralles-Wilhelm, 2022). Energy and ecosystems play a central role on temperature trend and variation overtime, because of their close relation with greenhouse gases (GHG) emissions and carbon cycle dynamics.

The understanding of this complex framework, and underlying interactions, requires an integrated macroeconomic approach to assess effectively the relation between the climate and the economy, which are both affecting, and affected, by human choices and behaviors overtime. We try do so with our RICE-MED model, which aims to study the effects of climate change in one of the world's hot-spots of global warming, namely the the Mediterranean region.

The analytical framework of the RICE-MED model is based on the Regional dynamic Integrated model of Climate and the Economy (RICE) in its 1999 version developed by Nordhaus and Boyer (2000). As in its original form, all the countries of the world are grouped into different regions, whose sole purpose is to maximize their respective social welfare, in a context where their economies are all fossil fuels based.[2] The main feature of this '99 version is the presence of energy as an explicit input in the production of the GDP of the economies.. A climate module is integrated with the economic one, allowing the identification of the optimal global carbon tax needed to compensate for the negative environmental externality induced by a changing climate. The introduction of such a fee (per tonne of carbon emitted) serves also as a lever to reduce carbon emissions. After having analytically formalized the initialization rules of the original RICE-99 model, we update the calibration to the base year 2015 and revise the regionalization to consider the Mediterranean countries at a finer spatial scale. In addition we modify the damage function following Golosov et al. (2014), which allows us to relate the economic damage directly to the concentration of CO2 in the atmosphere.

Within this work, after presenting the analytical framework and the calibration background of the RICE-MED model, we discuss the possible effects of climate change, and associated policies, for all the regions included in the model, with a special focus to the Mediterranean countries. For the latter, an additional analysis is then carried out for the agricultural sector. This framework is also extended incorporating uncertainty associated to the probability of future climate-related catastrophic events, following the approach of Castelnuovo et al. (2003). We call such extension the RICE-MED-U model.

In the following sections, after describing the general context and the state of the art of the

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[1] This outcome yields from a systematic review and meta-analysis based on 97 studies (1253 observations) published before September 2021 to evaluate the effects of climate change factors on food yield and irrigation water, as well as the influence of socioeconomic development on energy production and water (Han et al., 2022).

[2] We acknowledge that this is stringent assumption in terms of reality. However, in 2015, primary energy world consumption by source was as follows: coal 29.33%, oil 33.32%, gas 23.15%, nuclear 4.43%, hydropower 6.95%, wind 1.49%, solar 0.49%, other renewable 0.37% (*Source:* Our World in data - Primary energy consumption by sources, access Feb, 2023). In 2020 only 16% of world energy came from low-carbon sources (*Source:* Our world in data - Webpage sources-global-energy, access Feb, 23). We leave to future research the introduction in the model of energy produced with renewables sources and technologies capable of offsetting carbon emissions from fossil fuels, such as carbon capture and sequestration (CCS).

scientific literature (subsections 1.1 and 1.2), we provide an overview concerning the general macroeconomic modeling framework of RICE-MED (section 2) and its extension in an uncertain framework (RICE-MED-U version, section 2.1). The calibration task is presented in section 3 and numerical results are discussed in section 4. Section 5 concludes. Appendix reports: variables list, equations, analytical description of model initialization conditions, tables summarizing calibration and model outcomes, which are also presented in figures.

1.1 The context

Climate change is a phenomenon originating from several interconnected aspects, ranging from natural dynamics to human behaviors. While it is recognized as a world issue, it is also important to acknowledge that its causes and consequences are characterized by spatial heterogeneity.[3]

The increase of GHG emissions has been driven overtime by some countries more than others, with different and shifting degrees of intensity.[4] It is known that GHG emissions path increases with industrial development (Mardani et al., 2019), but nowadays, what is even more clear then ever, is that some regions and some sectors will be more adversely affected than others by the rise in temperatures caused by climate change.

Governmental and civil society awareness of the climate crisis, and its negative impacts, has increased in recent decades, not only regarding the general issue itself, but also in terms of regional effects. This calls the need of investigating more in depth the relation between climate change and economies, with a finer level of spatial detail.[5]

In this work we try to discuss these issues by revising the regionalization and updating the calibration to the base year 2015 of the Regional dynamic Integrated Climate and Economy (RICE, hereafter) model developed by Nordhaus and Boyer (2000): the RICE-99 version. This model is one of the most known in the field of integrated assessment analysis of the relationship between climate and the economy. Its analytical framework introduces carbon-energy from fossil fuels as an input factor into each country's production function, allowing economies to be modelled as fossil-fuel based.. Countries of the world are grouped in several regions enabling the disaggregation of the economic damages associated to climate change at a finer spatial scale. This peculiarity is relevant because, while the world climate is changing as a result of the behavior of all economies, its economic impacts are characterized by spatial heterogeneity. Among the outcomes of this model is the the social cost of carbon (SCC), representing the economic cost of emitting an additional tonne of carbon (Nordhaus, 2017). However, it is worth acknowledging that the optimal assessment of this outcome is affected by the degree of regionalization in the model (Schumacher, 2018). Further efforts are therefore needed in this research field to investigate such an effect and its implications for governments and policy.

In such a framework, we focus our attention towards two different perspectives: the original regional structure of RICE-99 is revised to disaggregate and study the Mediterranean countries and then a specific analysis is devoted to the economic damage to the agricultural sector. For these reasons, we call this model *RICE-MED*. In addition, an extension is also presented with the aim to incorporate the uncertainty associated to a possible climate driven catastrophic event. This extension is called *RICE-MED-U* model.

The need to assess the economic impacts of climate change in the Mediterranean region arises

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[3] Ganti et al. (2023) discuss equitable contributions to emissions reductions and the entitlement of developing regions to a greater share of the remaining carbon budget due to their historically low contribution to global warming.

[4] A visualization of this issue can be found the Our World in Data Webiste: *Who has contributed most to global CO2 emissions?*

[5] Temperature change is not uniform across the globe. Some regions will experience greater increases in the temperature of hot days and cold nights than others (FAQ 3.1 in IPCC (2022)).

from the evidence, as also highlighted by the Sixth Assessment Report of the IPCC, which includes, for the first time from its set up, a specific focus on it (Ali et al., 2022b). Before going into the details of our model, it is worth defining which are the main characteristics of the *Mediterranean climate*. It is true that the name may immediately conjure up associations with the Mediterranean region, however Seager et al. (2019) list several areas across the planet characterized by such type of climate.[6] These territories share same temperature paths, wet winters, hot or warm dry summers. Natural vegetation and agricultural uses are also similar, raging from areas devoted for vineyards and to the cultivation of fruits, olives and wheat, among others. However, while all these regions face the same source of winter precipitation variability in the internal atmospheric variability, only in the Mediterranean region this is clearly related to annular mode variability (Seager et al., 2019), defining its uniqueness with respect to the others. Furthermore, among the main outcomes of their study, we find that all the regions of this *climate type*, except for the case of North America, have dried and will continue to do so as the time passes. A recent analysis on the Mediterranean basin is provided also by Kutiel (2019). In this work, the climate of the region, assessed through atmospheric pressure, temperature and precipitation levels, is found to be characterized by a huge degree of spatial and temporal variability.

Going back to the *climate and economy issue*, a good perspective on the current and future state of art on the side of the Mediterranean climate, and related macroeconomic effects, is provided by Galeotti (2020), reporting also some of the most relevant studies in this field, namely Ciscar et al. (2011), Galeotti and Roson (2011), Bosello and Eboli (2013) and Szewczyk et al. (2018). Among the most relevant findings of this work we have that the Mediterranean region rainfalls are expected to decrease from 4% to 27% during the 21st century. Periods of drought and extreme events will increase in frequency and intensity, while air temperature could change between +2.2°C and +5.1°C in the Mediterranean region over the period 2080-2099, with respect to the period 1980-1999 (Galeotti, 2020). In such a framework, the welfare loss for the southern part of Europe is valued around 1.4% under the +5.4°C scenario till 2080 and 0.25% for the +2.5°C one, while production loss for the agricultural sector in the area is 0.5% in 2050 (Ciscar et al., 2011; Bosello and Eboli, 2013).[7]

In terms of sectors, agriculture and tourism are the two main economic activities in the Mediterranean economies (Kutiel, 2019). The former is important not only concerning GDP but also for employment, the food supply chain and global food security.[8] It is very likely that the worsening of the climate conditions will have dramatic impacts not only on different economic layers, but also on geopolitical balances.

In such a context, our work contributes to the literature of the IAMs characterized by a regional approach, with the aim of also assessing the impact on the agricultural sector in the Mediterranean basin and incorporating the uncertainty associated to a future climate-driven catastrophic event. By updating the RICE-99 model of Nordhaus and Boyer (2000), we provide new results on the impact of climate change damages on the key economic variables by the end of this century, such as consumption and production levels, across regions, and assess the evolution of CO2 emissions under three different scenarios. The first is the Business As Usual (BAU), in which the negative environmental externality associated with climate change is not internalized, i.e. governments do not take active policy measures against the effects of global warming and

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[6] The authors identify four other regions, apart of the Mediterranean region itself, from which the definition originates, describing them as they exists at the western edges of five continents in locations determined by the geography of winter storm tracks and summer subtropical anticyclones(Seager et al., 2019), that are: the west coast of North America from northern Mexico to Washington State, central Chile, the far southwest tip of southern Africa, and southwest Australia.

[7] Such overview can also be complemented with the report developed by Woetzel et al. (2020).

[8] For the sake of brevity, we suggest the analysis provided in (Ali et al., 2022b), collecting the most relevant scientific references of the last decades in this field.

associated climate change. The second is the Social Optimum one (OPT), where instead this negative externality is considered. The final one is the Temperature Limit (TL) scenario, under which the social welfare optimization is solved with the objective of binding the temperature increase below 2°C with respect to the pre-industrial level by the end of the century. Moreover, we consider the latest projections provided by the International Institute for Applied Systems Analysis (IIASA, hereafter) on population,[9] as the dynamic of such a variable is of key relevance to evaluate current policies.

On the side of the regionalization, let us recall that the original RICE-99 comprises the following regions: USA, China, Europe, Other High-Income countries (OHI), Europe, Russia and Eastern Europe (EE), Middle Income countries (MI), Lower Middle Income countries (LMI) and Low Income countries (LI). We modify the original structure considering as regions 20 new countries belonging to the Mediterranean basin.[10]

Regarding the modelling part, we provide an analytical formulation of the RICE-99 model initial conditions (Appendix C),[11] based on the economic equilibrium in each country/region, taking into account also a specific disaggregation of the energy sector with respect to different energy sources. This calibration relies on the solution of a system of equations that gives four initial unknown parameters, namely Total Factor Productivity (TFP), physical capital stock, elasticity of output towards energy services and, lastly, the regional mark up on the price of energy services. The system is settled to match the historical values of population, production, net marginal productivity of capital, CO2 emissions as well as their reduction due to the imposition of a carbon tax. The base year is 2015.

Once the model is fed with these updated data, each region is solved under the different scenarios showing the projections of some key macroeconomic and climate variables, such as consumption, output, emissions, concentration and temperature. We then exploit the regional heterogeneity, to discuss the possible regional climate impact and economic damages, with the aim to answer the following research questions: (i) what are the economic and climate effects of the current climate targets on the regions included in RICE-MED? (ii) how the increase in temperature affects the Mediterranean region in terms of production, specifically on the side of the agricultural sector? iii) what are the implications for the model's results if society internalizes the uncertainty associated with the probability of surviving a possible climate-related disaster?

Overall, our main motivation is to understand how climate policies should be designed to meet current climate targets, such as limiting the temperature increase with respect to pre-industrial level up to 2°C by the end of the century, while focusing on the impacts on a primary sector such as agriculture and considering the adverse effects of a changing climate, such as in the case of natural disasters.

In addition to that, the structure of the RICE-MED model allows also to account for the role of energy as a production factor, which is a crucial feature of the traditional RICE-99 developed by Nordhaus and Boyer (2000), serving as key element to model the economies in a more realistic way. Since our RICE-MED model considers not only the global externality of climate change, but also the regional effects, we hope that it will provide new useful insights into the carbon price and the expected damages due to climate change in a fully fossil-fuels based world. The results of the model can also help policy makers understand how Mediterranean countries could implement policies to mitigate and adapt the the impacts of climate change.

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[9] Specifically data are sourced from the IIASA SSP Database (Shared Socioeconomic Pathways) - Version 2.0 (available at this link: IIASA online database).

[10] Specifically we refer to: Albania, Algeria, Croatia, Cyprus, Egypt, Ethiopia, France, Greece, Israel, Italy, Lebanon, Libya, Malta, Montenegro, Morocco, Spain, Sudan, Syria, Tunisia, Turkey. See Table 2 for details.

[11] In Nordhaus and Boyer (2000) the conditions defining the initialization rules of the RICE-99 model were mostly presented descriptively by the authors. In our view, an analytical formalization can improve the understanding of the model and facilitate the replication process, as well as possible future extensions of it.

1.2 Review of the literature

In this subsection, we provide an overview of the most relevant literature in the field of the IAMs assessing the relation between the climate and the economy, and in particular those strands characterized by a multi-regional perspective, most of which originating from the seminal work developed by Nordhaus and Yang (1996). In addition, we show how we complement the state of the art on the side of the environmental macroeconomic analysis of the Mediterranean region as well as studies focusing on the negative impacts of climate change on the agricultural sector. For a comprehensive review of the literature on macroeconomic models and IAMs in the field of the WEFE nexus, the reader can also refer to Castelli et al. (2022).

1.2.1 Regional integrated models of climate and economy.

As far as the broadest scientific dimension is concerned, the field of IAMs has been expanding and evolving rapidly over the last decades. Several reviews map scientific contributions over time , also with respect to different fields. In terms of climate change and related economic impacts, among the most comprehensive we have Kelly et al. (1999), Nikas et al. (2019), Weyant (2020) as well as the review work of Yang et al. (2016b), which is constantly updated by the authors.[12] Regarding the SCC, among others, we find Wang et al. (2019), Tol (2023) and Rennert et al. (2022), discussing its estimates across different models and its changes overtime, whereas Moore et al. (2017) focus their attention specifically on the agricultural sector and SCC.
On the side of the *RICE-type* models, defined by Yang (2021) as those IAMs characterized by a structure similar to the first version of the RICE model developed by Nordhaus and Yang (1996) (RICE-96, hereafter), treating climate change as an externality phenomenon explicitly, there are all different versions developed by these authors themselves, as well as all the related extensions, together with IAMs characterized by same purposes and common analytical structures.
At the same time period in which RICE-96 was released, the MERGE model[13] developed by Manne et al. (1995) and the FUND[14] by Tol (1996) were also published. In the case of MERGE, we still have a regional structure, but with respect to RICE-96, its focus is on the management of climate change proposals and its CES production function is composed of three inputs, namely capital, labor and energy, while in RICE-96 energy was not included in the production function. As far as the FUND model is concerned, one of its main characteristics is the "possibility to link scenarios for economy and population which are perturbed by climate change and greenhouse gas emission reduction policy". Specifically, policy variables are energy and carbon efficiency improvements, and sequestration of carbon dioxide in forests (Tol, 1997). Again, the analytical structure is different, but since its release it has been recognized as one of the closest to RICE in terms of approach.
The first update of RICE-96 was the RICE-99 version by Nordhaus and Boyer (2000), consisting of a revised Cobb Douglas production function with three inputs, namely capital, labor and carbon-energy, and a further production layer related to the energy sector, fully dependent on fossil fuel inputs. In other words, this version of the model describes the world economy as being driven by fossil fuels. On the regional structure side, the world is divided into eight regions, grouped on the basis of economic/political similarities, whereas in RICE-96 there were 10 regions.[15]
The RICE-96 model, together with two other IAMs, was used by Bosello and Moretto (1999) to

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[12] Web page direct access at this this link.

[13] That is a "Model for Evaluating Regional and Global Effects" of GHG reduction policies.

[14] Which stands for climate "Framework for Uncertainty, Negotiation and Distribution". Related publications can be found in the FUND model webpage. Additional reference is also Tol (1997).

[15] This model was also presented in a shorten version in Nordhaus and Boyer (1999).

carry out an exercise aimed at investigating the impact of possible but uncertain future catastrophic climate events. Buonanno et al. (2001) developed ETC-RICE, extending the RICE-96 framework with endogenous environmental technical change and then Castelnuovo et al. (2003) introduced uncertainty into this structure, based on the approach of Bosello and Moretto (1999), creating the ETC-U-RICE model. A further extension of the RICE-96 was the one of Castelnuovo et al. (2005) embedding two different drivers of technological change, namely research and development and learning-by-doing, while Bosello (2010) focused on adaptation, mitigation and green R&D in the framework of Buonanno et al. (2001). A recent application at country level of this model can be found in Tamaki et al. (2019).

The RICE-99 structure was extended by Galeotti and Carraro (2004) starting from the intuition of Buonanno et al. (2001), implementing different specifications of exogenous and endogenous induced technical change, in which we find, among others, Bosetti et al. (2006c) and Bosetti et al. (2006a). Von Below and Persson (2008) provided an updated calibration of a revised version of RICE-99 while also implementing a part devoted to uncertainty. Other extensions include Nordhaus (2009), who released the RICE-2009 with a module dedicated to sea level rise,[16] while De Bruin (2014) developed the AD-RICE-99 model, where adaptation is considered as a policy variable. Schumacher (2018) discusses the aggregation dilemma using RICE-99 focusing on the effect of regional disaggregation on SCC, stating that country-level models would provide higher levels of SCC compared to fully aggregated frameworks, such as the case of the DICE-2013R model (Nordhaus, 2014).

It is worth acknowledging that, according to our current review, apart the work of Von Below and Persson (2008),[17] all other extensions of the RICE-99 model have focused on revising some parts of its analytical structure. To the best of our knowledge no further updates of the original model initialization have been developed so far. This is where one of our contributions fits in, together with the analytical formulation of the model initialization, the new regionalization and the updated calibration to the base year 2015. On the other hand, we have to acknowledge that the WITCH (World Induced Technical Change Hybrid) model developed by Bosetti et al. (2006b) can be considered, in our opinion, both an analytical and numerical evolution of the RICE-99 framework.

In 2010, a new version of RICE was presented in Nordhaus (2010) (RICE-2010, hereafter). This new structure, focusing on the abatement actions, is still characterized by a Cobb Douglas production function but only with two inputs, capital and labor, and the world is divided into 12 regions. In what follows we list some of the works related to this updated version. We start with Skoufias et al. (2011), who develop scenarios to assess the long-term climate change impacts on poverty. Dennig et al. (2015) focus on the impacts of climate change on the poor and inequality, which in turn is extended by Budolfson et al. (2017) discussing on discounting and catastrophes. Li et al. (2017) analyze and discuss predictions of historical responsibilities for carbon mitigation, while Adler et al. (2017) revise the analytical structure designing the social welfare function under the a prioritarian perspective and no time discount. Finally, in the RICE-2011 model of Nordhaus (2011) we find a detailed analysis of the SCC.

Recent contributions in the field of the *RICE-type* models are the RICE 50+ model of Gazzotti (2022), RICE-2020 provided by Nordhaus and Yang (2021)and discussed by Yang (2022), and

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[16] We were not able to recover the detailed structure of the model from the web pages provided in the publications, but the description and references in the paper suggest that this version is largely based on the RICE-99 framework.

[17] The work of Von Below and Persson (2008) refers to the RICE-99 framework, however, when modifications are presented, the authors state that the Total Factor Productivity (TFP) at the base year was estimated. The original RICE-99 setting is characterized by a specific initialization process, under which, at the base year, the TFP value is identified simultaneously with the capital stock, the markup on energy cost and the elasticity of output respect to the energy services.

Moore et al. (2017). In the first case we find an extension of the DICE structure,[18] which is then regionalized in 57 regions and EU is disaggregated at country level. The RICE-2020 model is in turn characterized by a high degree of flexibility in regional breakdowns (16, 12 and 6 regions) to allow the comparison with the previous versions of RICE (Nordhaus, 2010). It is presented as a climate externality model and it is designed with the aim to obtain solutions concerning pressing policy issues in climate change area (Yang, 2022).[19] The production function is the same of the RICE-2010 version. Finally, in Moore et al. (2017) we find a complex IAM framework with two new damage functions, to assess the adverse impacts of climate change on agriculture. The work builds on a meta-analysis of crop yield under climate change and adaptation (Challinor et al., 2014) and results from the AgMIP model,[20] which feed the GTAP CGE model. The latter is used to parameterize the damage functions, which are then incorporated into several IAMs to assess the effect on the SCC.

1.2.2 Environmental macroeconomic analysis for the Mediterranean region and agriculture

Moving to our regional focus, the Mediterranean basin has been studied over the years under a macroeconomic and environmental perspective using various models. In what follows we report on the most relevant for this work.
The JRC-PESETA model [21] dates back 2009, and focuses on the creation of an interdisciplinary and regional CGE model to assess the physical and economic impacts induced by climate change in the EU in the 21st century with bottom-up or sectoral approach, discussing the effects on agriculture, river basin floods, coastal systems, tourism, and human health.[22] The ENVISAGE model developed by the World Bank[23] is used by Galeotti and Roson (2011) to asses the economic impact of climate change in Italy and in the Mediterranean area, while Aaheim et al. (2012) study the impacts and adaptation to climate change in EU using the GRACE model[24]. Paroussos et al. (2013) design four alternative macroeconomic scenarios for the Southern and Eastern Mediterranean using the GEM-E3 model framework,[25] thus accounting for the environment and the energy system in the analysis of governmental and economic development issues

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[18] Specifically the framework of DICE-2016R2 (Nordhaus, 2018). This choice allows the authors to introduce empirically estimated climate impact functions at the country level (Gazzotti, 2022).

[19] This version allows the solution of different cooperative (efficient) solutions and non-cooperative (inefficient) Cournot-Nash equilibrium. In addition it is able to identify optimal solutions under exogenous policy constraints (Yang, 2022).

[20] Agricultural Model Intercomparison and Improvement Project (Rosenzweig et al., 2014).

[21] Specifically, PESETA stands for "Projection of Economic Impacts of Climate Change in Sectors of the European Union Based on Bottom-up Analysis". Among others, publications related to the fist stage of the project are Ciscar et al. (2009) and Ciscar et al. (2011). For the sake of brevity we do not list other related publications which can be found in the PESETA projects webpage.

[22] This model is considered the first regionally-focused, quantitative, integrated assessment of the effects of climate change on vulnerable aspects of the European economy and its overall welfare. The EU countries are grouped in 5 regions, namely Southern Europe, Central Europe South, Central Europe North, British Isles and Northern Europe (Ciscar et al., 2009).

[23] The "Environmental Impact and Sustainability Applied General Equilibrium" model is a standard recursive dynamic multi-sector multi-region CGE model with emissions and climate module. Also in this case, it links directly economic activities to changes in global mean temperature, incorporating a feedback loop that links changes in temperature to impacts on economic variables such as agricultural yields or damages created by sea level rise (Source: Technical reference guide for ENVISAGE model)

[24] Global Responses to Anthropogenic Changes in the Environment (GRACE model Webpage)

[25] The GEM-E3 model is characterized by a multi-regional and multi-sectoral approach. Under a recursive dynamic CGE framework, it provides insights at macroeconomic level and related interactions with the environment and the energy system. Further details are available at the GEM-E3 model webpage.

of the area.[26] Bosello and Standardi (2018) present a regional version of the ICES model,[27] to assess economically the climate change impacts for the European Mediterranean countries, with a finer spatial resolution compared to that offered by standard CGE models.

We now review in brief the most relevant literature dealing with the analysis of agriculture at macroeconomic level, with respect to our work. Among the earlier work on the side of the IAMs we find Fischer et al. (2005), who develop an integrated ecologicaleconomic modelling framework including climate scenarios, agro-ecological zoning information, socio-economic drivers, world food trade dynamics. Hermann et al. (2012) use the Climate, Land, Energy and Water (CLEW) modelling framework, developed by the International Atomic Energy Agency (IAEA), to assess the importance of a coordinated approach to increase water, energy and food security, with a specific application in Burkina Faso concernig agricultural policies. Then Dono et al. (2013) focused on the physical, technical and economic factors connecting climate change and agriculture using the EPIC model,[28] a discrete stochastic programming framework to incorporate uncertainty connected to all mentioned factors, to represent the Mediterranean area where limited water is supplied from a reservoir. One of their main focus was the role of collective irrigation systems as tools to support adaptation to climate change. Yang et al. (2016a) integrated an hydro-agro-economic module with an agricultural energy use one. Bonsch et al. (2016) is an example of an application of the MAgPIE integrated framework[29] in the field of the large-scale bioenergy cultivation and related effect s on agriculture, on the side of land exploitation and water consumption. Blanc et al. (2017) used the MIT Integrated Global System Modelling (IGSM),[30] incorporating humans and earth system relations in the field of crop yield reduction. The Global Change Analysis Model (GCAM)[31] is used by Kim et al. (2016), Miralles-Wilhelm and Munoz-Castillo (2018) and de Vos et al. (2021) with different aims. In the first case, the focus was scarcity of fresh water, which is seen as a crucial factor in agricultural sector. In the second case, the authors design emissions mitigation on the basis of the Paris Climate Agreement to asses the effects on energy and food sectors. Finally, in de Vos et al. (2021) we find a study on the effect of competing water demands between food production, freshwater eco-systems and utilities (energy, industries and households). Veerkamp et al. (2020) employ two different types of IAMs, the IMAGE-GLOBIO[32] and the CLIMSAVE IAP one,[33] to study the environmental consequences of human activities on biodiversity and ecosystems, with a multi-sectoral perspective concerning impacts, vulnerability and adaptation to climate and socio-economic change across Europe, among which we find the agricultural sector. CLIMSAVE IAP was used also by Kebede et al. (2021) to provide insights on agriculture and land use allocation.

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[26] A specific focus on south Mediterranean is provided in Paroussos et al. (2015).

[27] The ICES model grounds on the structure of the GTAP-E model developed by Burniaux and Truong (2002) (ICES model webpage).

[28] The "Environmental Policy Integrated Climate" model is designed to simulate crop systems, estimate the soil productivity and study the relation with the erosion (EPIC webpage).

[29] MAgPIE stands for"Model of Agricultural Production and its Impacts on the Environment" (MagPIE webpage).

[30] Further information on the modelling framework can be found on the IGSM webpage.

[31] This model allows to explore the behavior and interactions, between the energy system, water, agriculture and land use, the economy, and the climate. (GCAM webpage)

[32] The Integrated Model to Assess the Global Environment (IMAGE) is simulates the environmental consequences of human activities worldwide, specifically between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being (IMAGE webpage). Its outcomes are then incorporated in the framework of GLOBIO model (Global Biodiversity Model for Policy Support) to calculates local terrestrial biodiversity intactness, accounting for six human pressures: land use, road disturbance, fragmentation, hunting, atmospheric nitrogen deposition and climate change (GLOBIO webpage).

[33] The CLIMSAVE Integrated Assessment Platform (IAP) allows the assessment and quantification of the impacts of climate change adaptation policies in several sectors: urban environment, coasts, water, forests, biodiversity and agriculture (CLIMSAVE IAP webpage).

We conclude this subsection with some contributions in the field of agriculture and a focus on the Mediterranean basin. Palatnik et al. (2011) incorporates in the climate and economy framework of the ICES model[34] inputs from VALUE,[35] a partial equilibrium model for the agricultural sector, to improve the agricultural production structure, providing an application to Israel and Italy. A similar objective is pursued by Palatnik and Lourenço Dias Nunes (2015), but this work also considers the role of biodiversity for the agricultural sector. Specifically, the economic impacts of climate change are estimated in terms of changes in the productivity of agricultural land. The overall framework consists of first identifying the role of biodiversity in agro-ecosystems, then assessing of the climate change-induced impacts on crop productivity, including the effect on biodiversity, which in turn is studied in a CGE framework. Comprehensive results are presented for all European countries. In Parrado et al. (2019) agricultural water management is studied, assessing the relation between policies that ration irrigation at the farm level and related macroeconomic effects caused by the associated changes in agricultural output. The Mediterranean area is considered with an application to the Murcia Region in Spain. Finally the work of Teotónio et al. (2020) shows how several models can be integrated with the aim of deepening the water-energy nexus, accounting for water competition in a context where climate change impacts are taken into account and studying such a complex framework with real data from Portugal.

1.2.3 Novelties of the RICE-MED model

In what follows, we briefly highlight our contribution to the scientific literature, based on current knowledge, while also including other works that are closer to our aims. The main novelties of the RICE-MED model are:

- new calibration of the RICE-99 model developed by Nordhaus and Boyer (2000) to the year 2015, based on their original initialization approach. The latter is also formalized analytically to facilitate future replication and improvements;
- new regionalization, where all the Mediterranean nations are considered at country level, allowing the study of climate change economic impacts at a finer spatial level with respect to the original version;
- revision of the analytical structure of the original damage function according to Golosov et al. (2014) and implementation of an extension of the RICE-MED model with uncertainty (RICE-MED-U), following the approaches of Castelnuovo et al. (2003), allowing us to include in the model the societal awareness towards a possible future catastrophic event, triggered by the temperature increase and variation over time;
- application of the model for the study of the economic damages linked to climate change to the agricultural sector for the Mediterranean countries.

Considering the IAMs literature, the most relevant existing studies for our work at the time of writing, especially in terms of alignment on the side of calibration timing, are: the RICE 50+ model of Gazzotti (2022) and the RICE-2020 provided by Nordhaus and Yang (2021) and discussed by Yang (2022). Our novelties, with regard to the first, are mainly related to the decision to follow the RICE-99 framework. By choosing such a version, our RICE-MED model is able to explicitly account for the carbon-energy factor in the production function. In addition

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[34] ICES, Intertemporal Computable Equilibrium System, consists of a recursive dynamic multiregional CGE model to assess impacts of climate change on the economic system and to study mitigation and adaptation policies. (Webpage link ICES Model)

[35] The "Vegetative Agricultural Land Use Economic" model adaptation of vegetative agriculture to changes in various exogenous variables through reallocation of land and water sources among crops(Palatnik et al., 2011)

to that, the original initialization approach accounts for the disaggregation of the energy sector of each region included in the model. Furthermore, to the best of our knowledge, this is the first updated calibration following the original RICE-99 framework. Concerning RICE-2020, it also represents a model closer to ours, although also in this case, energy is not included in the production function of the model.

Considering our regional focus, Paroussos et al. (2013) and Bosello and Standardi (2018) covers several Mediterranean countries, but not the entire region as we do in RICE-MED. The widest regional coverage for the Mediterranean is provided by Palatnik and Lourenço Dias Nunes (2015). With reference to our general objective on agriculture, the work of Moore et al. (2017) is among the closest to our approach. Our exercise on the agricultural sector is characterized by a lower degree of complexity and does not require integration with other models, except for the calibration of some parameters for which we rely on to the work of Roson and Sartori (2016).

2 The RICE-MED model

Integrated Assessment Models (IAMs) allow for the study of the impact of human economic activity on natural systems, at both global and regional scales. In recent decades, they have supported researchers and policy-makers to assess -in economic and environmental terms- the damage caused by climate change. In particular, the structure characterizing the models developed by Nordhaus (1994), DICE, and then, together with Yang, RICE (Nordhaus and Yang, 1996), are able to connect the effect of GHG emissions with climate change (Yang, 2021). In a macroeconomic framework characterized by a long run time horizon,[36] the global externality of climate change is incorporated, allowing the study of its impacts on the socio-economic environment of humans, taking into account the changes in population dynamics, technological change, temperatures and energy use, while also providing insights into the design of effective economic policies.

Following the existing literature, we update the regionalization, calibration and initialization of the RICE-99 model developed by Nordhaus and Boyer (2000) up to 2015, extending it with a specific focus on the Mediterranean area (MED region, hereafter) and its agricultural sector, while also chaining the analytical structure of the damage function according to Golosov et al. (2014).

In our new regionalization, the world is divided in 8 regions plus the countries of the MED Region.[37] In what follows, we briefly recall the structure of the RICE-99 model while also highlighting our novel contributions at the analytical level.[38]

As already mentioned, in this model the world is composed of different regions, where each of them (j) is a single decision maker, whose aim is the inter-temporal maximization of its own social welfare W_j.

Each economic system produces a unique commodity[39] $Q_j(t)$, with a specific level of technology $A_j(t)$, employing three production factors, namely capital $K_j(t)$, labor $L_j(t)$ and carbon-energy $ES_j(t)$, [40] in a framework where international trade across regions is not allowed, except for the exchange of carbon emissions permits, defined as $\prod_j(t)$.[41] Population growth and technological

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[36] This is done because the effect of increasing emissions is generated out over millennium (Mendelsohn, 2020).

[37] See detail in Table 2 in Appendix D.

[38] Detailed list of all the variables is provided in Appendix A while equations in Appendix B.

[39] Nordhaus and Boyer (2000) defines it as an *all-inclusive commodity* to be allocated either for consumption or investment.

[40] Carbon-energy is seen as the energy services provided for the production of $Q(t)$.

[41] Regions are organized in emissions trading blocks. Each trading block is characterized by its own level of carbon tax. In line with RICE-99 framework, each region is a trading block and within it the emissions

change are assumed to be exogenous, while labor market is characterized by full-employment.[42] Respective dynamics are described by Eq. (12) and Eq. (13).
The welfare optimization problem of each region j is then:

$$\max_{c_j(t)} W_j = \sum_t U\left[c_j(t), L_j(t)\right] R(t) \tag{1}$$

where the control is $c_j(t)$, the per-capita consumption, $R(t)$ is the pure time preference discount factor, as per Eq. (18),[43] and $U\left[c_j(t), L_j(t)\right]$ is the utility function characterizing the society of agents of each economy, which takes the functional form described by Eq. (17). The society is willing to reduce the wealth of high-consumption generations in favor of low-consumption ones,[44] therefore the utility function becomes:

$$U\left[c_j(t), L_j(t)\right] = L_j(t)\, log\left[c_j(t)\right]. \tag{2}$$

Since the model assumes a one-sector closed economy the optimization problem is subject to the following budget constraint:[45]

$$Q_j(t) = C_j(t) + I_j(t) \tag{4}$$

where $C_j(t)$ is the aggregate consumption of the $j-th$ region and $I_j(t)$ are the investments, while $Q_j(t)$ is the regional aggregate GDP. The latter is represented on the side of production as:[46]

$$Q_j(t) = \Omega_j(t)\left[A_j(t)\, K_j(t)^{\gamma}\, L_j(t)^{1-\beta_j-\gamma}\, ES_j(t)^{\beta_j} - c_j^E(t)\, ES_j(t)\right], \tag{5}$$

incorporating the environmental damage with coefficient $\Omega_j(t)$, revised following Golosov et al. (2014), that is:

$$\Omega_j(t) = 1 - D_j\left(M_{AT}(t)\right) = exp\left(-\theta_j\left(M_{AT}(t) - \bar{M}_{AT}\right)\right). \tag{6}$$

Eq. (6) depends on the damage function $D_j\left(M_{AT}(t)\right)$, which in turn is affected by $M_{AT}(t)$ and $\bar{M}_{AT}$, that are respectively, the stock of carbon dioxide (CO2) concentration in the atmosphere (AT) and the corresponding pre-industrial level.[47] As per Golosov et al. (2014), the function

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permits market is cleared. Furthermore, the world is then assumed to be a unique trading block, so that the *where-efficiency* condition (see Nordhaus and Boyer (2000)) is satisfied, thus emissions reductions allocation is performed in a cost minimizing way and a common carbon tax across regions is identified.

[42] Labor force equals population Nordhaus and Boyer (2000).

[43] Specifically, $R(t)$ represents the social time preference across different generations (Nordhaus and Boyer, 2000).

[44] Meaning that in Eq. (17) the parameter α is assumed to tend to 1. This parameter represents a measure of the social valuation of different levels of consumption. Specifically, Nordhaus and Boyer (2000) associate it as the measure to which a region is willing to reduce the welfare of high-consumption generations to improve the welfare of low-consumption generations. See (Nordhaus and Boyer, 2000) for further details.

[45] Let us recall from above that regions are allowed to trade only carbon emissions permits $\Pi_j(t)$, thus the budget constraint on regional expenditures is:

$$Q_j(t) + \tau_j(t)\left[\Pi_j(t) - E_j(t)\right] = C_j(t) + I_j(t) \tag{3}$$

where $\tau_j(t)$ represents the price of each emissions permit (and the carbon tax as well), while $\Pi_j(t)$ is the number of carbon emissions allowances allocated to region j and $E_j(t)$ the carbon emissions. The term $\tau_j(t)\left[\Pi_j(t) - E_j(t)\right]$ represents the net revenues a region receives from its trade of emission permits. Eq. (4) yields combining eq. (3) with the following assumptions: i) the world is a unique trading block, thus all the region are subject to the same carbon tax ii) for any positive value of the carbon tax, the emissions permits market is cleared.

[46] The Cobb-Douglas function is characterized by constant-returns-to-scale.

[47] The term $M_{AT}(t) - \bar{M}_{AT}$ is always positive, since the stock of CO2 concentration in the atmosphere AT has been always increasing overtime respect to pre-industrial level. Further detail on this side, among others, can be found in Hofmann et al. (2009).

D enables the mapping between the concentration of CO2 to the economic damage, measured as percentage of the final output. The structure of the climatic module remains the same of Nordhaus and Boyer (2000). The parameter θ_j allows to incorporate the region specific damage cost. The higher is θ_j, the more is the negative impact of a changing climate on the economy.[48] Back to Eq. (5), the term $c_j^E(t)\, ES_j(t)$ is the cost of producing carbon-energy, which is subtracted from the overall output produced by the economy. The production function of carbon-energy, Eq. (22) in Appendix B, is a function of $\varsigma_j(t)$, which is the level of carbon-augmenting technology[49] and carbon services $E_j(t)$, provided by fossil fuels.Such consumption of inputs translates into industrial emissions of CO2 in the atmosphere. Overall emissions of the model yield from the sum between the latter and the exogenous land use emissions.

2.1 The RICE-MED model under uncertainty

In this subsection, we then present an extension of the RICE-MED model, which is revised with the aim of incorporating the uncertainty associated with a possible climate-induced catastrophic event. To this end, we follow the approaches developed by Castelnuovo et al. (2003). The rationale behind this approach is that the temperature increase can trigger a catastrophic event at any point in time. Based on this assumption, we consider two possible states of the world: one in which the catastrophic event is yet to occur (BC) and the other in which a catastrophe occurs and agents must deal with its direct consequences (AC). Uncertainty arises from society's inability to identify the global temperature level at which the catastrophic event may occur. Such ignorance leads agents to guess their probability of survival and the probability of a climate-driven disaster at any point in time.

Specifically, we define as $SP(t)$ the survivor probability associated with the absence of a catastrophic event, while $1 - SP(t)$ is that one of facing it. Following Eq.7 shows the dynamics of $SP(t)$ overtime:[50]

$$SP(t) = \exp\left[-HR(t)\right], \tag{7}$$

where $HR(t)$ represents the hazard rate (HR) function relating the survivor probability with the endogenous temperature variation. The functional form of $HR(t)$ is:

$$HR(t) = \begin{cases} HR(t-1) + \left[\varphi_0 + \varphi_1 \dot{T}(t)\right] \eta \left[\max\left(0; T(t) - T_0\right)\right]^{\eta - 1} & \text{if} \quad \dot{T}(t) > 0, \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

$$\text{and } \dot{T}(t) = \frac{\Delta T(t)}{T(t-1)} \qquad \text{with } \frac{\partial HR(t)}{\partial T(t)} > 0. \tag{9}$$

If the temperature change overtime $\dot{T}(t)$ is not positive, then $HR(t)$ is nil, while otherwise it depends on its value at the previous time step, $HR(t-1)$, and three exogenous terms, namely φ_0, φ_1 and η. The first is a scaling parameter, the second a coefficient defining the relevance of the temperature growth rate $\dot{T}(t)$, while η weights the temperature variation, $T(t) - T_0$, with T_0 being the temperature level at the base year.

We now explain how such a catastrophic event affects the analytical framework of the model. As mentioned above, the agents ignore the temperature level that triggers the adverse event, but

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[48] Its maximum value can be associated to a catastrophic damage.

[49] The term $\varsigma_j(t)$ can also be interpreted as the ratio between carbon-energy $ES_j(t)$ and carbon services provided by fossil fuels inputs $E_j(t)$. The higher the ratio, the higher is the carbon-energy generated per unit of fossil fuels inputs and the lower the emissions of CO2 produced in such a process.

[50] Detailed mathematical background can be found in Bosello and Moretto (1999) as well as in Kiefer (1988).

they are aware of its possibility at all times. The utility function given in Eq. 1 is therefore decomposed into two separate elements, which are multiplied by their respective probabilities, namely the survival probability $SP(t)$, in the BC scenario, while they refer to $1 - SP(t)$, in the case of a catastrophic event (AC scenario). The new utility function is then:

$$U\left[c_j(t), L_j(t), SP(t)\right] = SP(t)\, U\left[c_j(t), L_j(t)\right]_{BC} + \left[1 - SP(t)\right] U\left[c_j(t), L_j(t)\right]_{AC}, \tag{10}$$

$$\text{with } U\left[c_j(t), L_j(t)\right]_{AC} = (1-b)\, U\left[c_j(t), L_j(t)\right]_{BC}, \tag{11}$$

where $U\left[c_j(t), L_j(t)\right]_{BC}$ is the utility level before the catastrophe and $U\left[c_j(t), L_j(t)\right]_{AC}$ the one after it. In the BC scenario, the level of utility is the same as in the RICE-MED model, whereas in the AC one, the whole society faces a loss of utility, compared to the BC scenario, of the order of $bU\left[c_j(t), L_j(t)\right]_{BC}$, where b is the utility loss share. The higher the term b, the greater is the decline in utility due to the catastrophic event.

All other parts of the model remain the same as in the RICE-MED version, described in section 2.

3 The model calibration

The regional structure of our RICE-MED model is developed following the same rationale of Nordhaus and Boyer (2000),[51] except that the Mediterranean area is subdivided into twenty regions corresponding to the country spatial level, allowing us to study the economic impacts of a changing climate in the Mediterranean basin. Further details concerning regional aggregation and the Mediterranean area are provided in Table 2 in Appendix D.

The base year is 2015 and the model runs for more than thirty periods,[52] with a time step (Δt) of 10 years.[53] The model is initialized using the parameters described in Table 3 and then solving a set of equations assuring the alignment to the empirical observations at the base year. This involves, for each region j, the simultaneous calibration of the initial total factor productivity $A_j(0)$, the initial capital stock $K_j(0)$, the elasticity of output respect to the energy input β_j and the markup on the energy costs $Markup_j$. These parameters have been calibrated to reflect regional GDP, industrial emissions and interest rates levels. The analytical details of are provided in Appendix C with outcomes summarized in Table 6.[54]

Population is exogenous and it has been calibrated in order to follow the IIASA scenario SSP2.[55] In particular, the associated dynamic is described by logistic-type equations of the form 12. The population growth rate g_j^L matches the IIASA 2050 projections (Table 4) so that the regional demography approaches the estimated *plateu* by 2100. As a result, world population is coints 11 billion of people by 2100.

The parameters governing the carbon cycle and the temperature models have been updated following Nordhaus and Sztorc (2013) and Folini et al. (2021). Moreover, exogenous radiative forcings for 2015 and 2100 have been set to replicate, as much as possible, the latest IIASA RCP-4.5 projections. Exogenous land use emissions for each region refer to (Nordhaus and Boyer, 2000).

We finally describe the calibration of climate damages. The related existing literature is quite

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[51] Countries were grouped in regions according to economical and/or political similarities.

[52] This means that projections are made until 2305. Results are only shown up to 2105.

[53] This time step is in line with current climate change scientific literature. The effects of a small increase in the atmospheric CO2 concentration on temperature exhibit after several years. For this reason, such a time lag is identified in about 10 years (Pindyck, 2022).

[54] In Table 6 GDP and capital stock are expressed in trillions of USD, while labor in million and emissions in GtC.

[55] SSP Database (Shared Socioeconomic Pathways) - Version 2.0

mixed. Depending on the temperature increase compared to the pre-industrial era, the loss of GDP could be between 1%-7% (Tol, 2009; Howard and Sterner, 2017). However, recent works highlight that leading climate-economic models underestimate the impact of climate change on economic damages (Kalkuhl and Wenz, 2020; Roson and Sartori, 2016; Burke et al., 2015), especially due to the uncertainty surrounding the effects of temperature rise (Pindyck, 2022).

In the RICE-99 model, the mapping from the atmospheric CO2 concentration to the economic damages - measured as a percentage of final output loss - is modeled in two steps, namely from the atmospheric CO2 concentration to the temperature and from temperature to damages (see Appendix B). Thus, in order to simplify our framework, and to decrease the level of uncertainty, we follow the analytical formulation of Golosov et al. (2014), which directly maps the link between atmospheric CO2 concentrations and damages.[56] Given the regional structure of the RICE-MED model, we calibrate and incorporate the region specific damage cost θ_j of Eq. (6), following the work of Roson and Sartori (2016).[57]

Since the MED countries are highly exposed to the effects of climate change due to their geographical morphology, especially on the side of agriculture, we develop an application of the RICE-MED model with the aim to assess the economic damages for this sector. The original calibration of the RICE-MED model is then revised assuming that all regions account only for climate change induced damages on this side. Such an exercise still relies on the work carried out by Roson and Sartori (2016). Thanks to their outcomes at sectoral level, the economic damage parameter θ_j of Eq. (6) is duly re-calibrated for the share of the agricultural sector on the overall GDP for each region in the model. We thus revise the notation of the model defining it as θ_j^A (see Table 7).[58]

Concerning finally the extension of the model in an uncertain framework (RICE-MED-U model), Table 5 reports values for $HR(t-1)$ and parameters φ_0, φ_1, η, which are calibrated to obtain a survival probability, $SP(t)$, and a probability of a catastrophic event, $1 - SP(t)$, in line with Castelnuovo et al. 2003.[59] Three different scenarios are instead considered concerning the utility loss parameter b, namely 0.3, 0.5 and 0.7, in order to cover all possible states of the world. The higher the value, the greater the loss to society caused by the disaster.[60]

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[56] Notice that the exponential approximation by Golosov et al. (2014) is close to the one by Nordhaus and Boyer (2000).

[57] The regional damage cost parameter θ_j is calibrated on the basis of the following equation: $\theta_j = -\frac{\log\left(1-D_j\left(M_{AT}(t)\right)\right)}{M_{AT}(t)-\bar{M}_{AT}}$, where $D_j\left(M_{AT}(t)\right)$ represents the impact on the GDP of each country of an atmospheric temperature increase equal to 3°C, according to Roson and Sartori (2016), while $M_{AT}(t)$ is the value of the atmospheric CO2 concentration associated to the temperature increase of 3°C.

[58] The equation used to compute the damage cost parameter θ_j^A is the same of the regional damage cost, but in this case we account only for the share of agriculture on regional GDP. To this end, we introduce the additional variable π_j, as the ratio between the agricultural GDP and the overall one. The economic damage parameter θ_j^A yields from this ratio: $\theta_j^A = -\left[\log\left(1 - \frac{D_j\left(M_{AT}(t)\right)}{\pi_j}\right)\right] \setminus \left[M_{AT}(t) - \bar{M}_{AT}\right]$.

[59] Following Castelnuovo et al. (2003), φ_0, φ_1, η have been calibrated in order to have a catastrophe probability closer to 4,8% in year 2100 in the BAU scenario. The values of the parameters must be determined simultaneously. The hazard rate function depends on the rate of change of temperature, thus the parameter φ_1 has to be estimated together with φ_0. Detailed discussion on this side can be found also in (Bosello and Moretto, 1999).

[60] We refer to future research will be devoted to the empirical identification of parameter b on the basis of real data.

4 Scenarios and Results

We now use our models to assess the interaction between climate policies and economic outcomes. We consider three scenarios close to those traditionally used in the RICE-99 model. Specifically, we focus on the Business-As-Usual (BAU), the Social Optimum (OPT) and the Temperature Limit one (TL). Each of them is briefly described below:

- *Business as Usual (BAU).* It describes a world in which negative environmental externalities are not internalized, i.e. governments do not take active policy measures against the effects of global warming and associated climate change (model baseline).[61]
- *Social Optimum (OPT).* It represents the Pareto Optimal solution, where the social welfare is maximized, accounting for the damage induced by the climate change. The global carbon tax is exactly equal to the global environmental shadow price of carbon.
- *Temperature Limit (TL).* The maximization of the OPT scenario is constrained to a temperature increase limit below to 2 degrees Celsius, compared to pre-industrial levels, by the end of this century. This scenario can be adapted to test the results of our model considering temperature targets.[62]

The results are presented in the next subsections. Although the models run until 2300, we report results up to the end of this century.

4.1 Global and Regional Results

This subsection is dedicated to the discussion of the global and regional results of both the RICE-MED (RM, hereafter) and RICE-MED-U models (RM-U, hereafter). The outcomes will be presented by sub-themes, namely climate variables and economic-related ones, while also analyzing the impact of introducing uncertainty. Regarding this last part, it should be clarified that the RICE-MED-U model is run for three different values of the parameter b, namely 0.3, 0.5 and 0.7, and determines the utility loss associated with the occurrence of a climate-driven disaster.
Table 8 shows the results for the three global climate variables of our model, namely temperature increase with respect to pre-industrial level, atmospheric concentrations of CO2 and radiative forcings. For the last two, the variations from the baseline start from 2035 while significant temperature change appears after 2055, exceeding the 1.5°C increase in all policy scenarios.
When agents consider the uncertainty associated with a possible climate-induced disaster, all the climate-related variables decrease with respect to the RM model, and this magnitude of variation widens if the utility loss parameter b increases. As the temperature continues to rise, the probability of facing a disaster increases too (Table 9),[63] although its proportion is mitigated as the size of the utility loss increases. As we get closer to the end of the century, changes across scenarios become apparent: the more *environmentally binding* the policy scenario becomes, the smaller is the positive variation in this probability overtime. Furthermore, in the case of the highest utility loss scenario (RM-U0.70), the OPT scenario improves significantly in terms of temperature rise, approaching, but not reaching, the 2°C increase. This also shows us the differences in outcomes of the two versions of the model.

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[61] According a recent study of International Monetary Fund (link to access here), by June 2022, only 46 countries (24%) of the 195 in the world, are implementing schemes aimed at pricing emissions, i.e. carbon taxes and/or emissions trading schemes (ETS). This reflects the a situation in which 76% of the world's countries have yet to implement any kind of policy to reduce emissions. On average, we can say that the world is behaving as in the BAU scenario.

[62] Such as those of United Nations (2015) and United Nations Framework Convention Climate Change (2022)

[63] This is due to the relation between the HR function (part of Eq. 7) and the temperature increase.

Table 10 shows the results of the carbon tax up to 2105, while Table 11 its averages over two different time intervals, up to 2105 and up to 2305. In the RM model, the carbon tax dynamics over time increases in all policy scenarios. Same effect occurs within each time period as the policy become more tighter. The average values for the entire time horizon, i.e. until 2305, and in the 2015-2105 interval are respectively:[64] 806 (231) in the OPT and 53724 (1728) in the TL case. The goal of limiting the temperature increase to below 2°C above the pre-industrial level can be achieved only in the TL scenario, with a significant level of carbon tax. These values decrease when society is aware of the probability of a climate-related catastrophe, namely in the framework of the RM-U model, and with a wider magnitude if the associated utility loss parameter increases. In the case of its maximum level ($b = 0.70$), the carbon tax levels are: 1020 (681) in OPT and 46853 (1814) in the TL case. The RM-U results show significant variation respect to the ones of the RM model. Considering the highest utility loss scenario (RM-U0.70), the average values for the entire time horizon and the 2015-2105 interval vary as follows: in the OPT scenario with uncertainty, the carbon tax changes of 26,53% (194,68%) with respect to the RM framework, and of -12,79% (4,96%) in the TL one. If the utility loss parameter decreases to 0.30, the effects are quite mixed if the entire time horizon is considered: in the OPT scenario the average carbon tax decreases of -23,26% with respect to the RM framework and of -5,57% in the TL one. The effect changes in sign only for the OPT scenario. If the short time horizon in considered, the average carbon tax is always increasing in the parameter b.[65]

What is evident is that the economic effort required during this century in such a framework will be very high. We should also remember that the more time passes, the greater the likelihood of the catastrophic event as temperature continues to increase. Of course this can be mitigated by the implementation of policies.[66]

From these results, we can also learn more about the importance of the level of societal awareness towards climate change and a possible climate-driven disaster. The lower is the survivor probability perceived by the agents, the higher is the cost, in terms of a carbon tax, that they are willing to pay to reduce the temperature rise. This appears only in 2105, in the TL scenario under uncertainty, i.e. in RM-U. The carbon tax is always smaller than in the RM case and decreases further as the parameter associated with the utility loss increases.

In general, we can say that in a fossil-fuels driven world economy a better temperature rise performance at the end of the century can be achieved thanks to a mix of environmental binding policies, the identification of an appropriate carbon tax value, and actions aimed at rising society's awareness on the impact of a potential climate-driven catastrophic event. With regard to the latter, this can be done by getting agents to correctly recognize, and value, a survivor probability determined by the temperature change and a correct possible loss of utility associated with the disaster.

We now move to the discussion of the economic impact across scenarios and regions/countries.[67] In Table 12 we report RM results, whereas in Tables 13, 14 and 15 those of the RM-U model.

The BAU scenario assures the highest level of income, as production, and so output, can grow without limit, as do emissions, without considering climate impacts. However, the benefits of

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[64] Numbers in the brackets refers to 2015-2105 time interval. For the sake of brevity, we will not report in the text the unit of measure for each value of the carbon tax, which is USD/tC.

[65] Of course, most specific insights can be derived observing not the average value, but the entire time series of the carbon tax across models, utility loss and policy scenarios.

[66] For a comparison with the current literature on the social cost of carbon see, among others Moore et al. (2017); Wang et al. (2019); Rennert et al. (2022); Tol (2023).

[67] For the sake of clarity, let us recall that the regional economic impact of climate change yields from the relation between the regional GDP (Eq.5) and CO2 concentrations across the globe. The damage function described in Eq. (6) allows the mapping between these two different dimensions. Further details can be found in Nordhaus and Boyer (2000).

meeting stringent environmental targets to mitigate the effects of climate change come at a cost to society.

In Table 12 we report the variations in the output of the Mediterranean countries and all other regions. Among the advanced economies, in the USA in 2015 if the OPT or the TL policies were those implemented at that year, the costs in both scenarios are 0.05% of the output with respect the BAU case, while after 2055, the TL policy erodes 5% of the GDP. Notice that for some regions, the OPT and the TL policies guarantee a gain in terms of GDP. If we consider Europe, for example, the OPT policy increases output up to 1.5% by the end of the century, while the TL scenario guarantees economic gains up to 2035 and then reduces economic growth by less than 1.5% by the end of the century. LMI and LI regions, on the other hand, show different dynamics. Although these countries have not been major contributors to past emissions, their economies and populations are expected to grow steadily over the coming decades. Thus, looking at the OPT and TL scenarios, climate policies could cost, in both cases, from 9.5% to 12% of their GDP by the end of the century.

When uncertainty is considered, GDP loss/gain results are not affected in the first period. Starting with the OPT policy and looking at the few regions where we observe an increase in GDP, namely Europe and EE, we can see that the higher is b, the lower is the gain. Specifically, both face a economic gain shift in the OPT scenario from 1.5% of the RM model to 1% in the RM-U0.70. If temperature rise is limited (TL) all the regions suffer of a loss in GDP compared to BAU, but as the utility loss parameter b increases, this loss becomes smaller. The same cannot be said for the OPT policy, where the results are puzzling.

4.2 Climate damages in the Mediterranean agricultural sector

In this section, we focus on the Mediterranean basin, which comprises countries geographically belonging to Africa and Europe. Due to its morphology, the Mediterranean area is a "hotspot" of climate change, and suffers from a double warming-effect on its coastal and land areas (Tuel and Eltahir, 2020).[68]These include not only climate impacts such as sea level rise, temperature increases and more frequent heat waves, but also changes in precipitation, prolonged summer groundwater shortages and severe droughts, which in turn expose the entire basin to a range of risks, including threats to food security. Given that agriculture accounts for an average of more than 10% of GDP in many Mediterranean countries,[69] the projected loss of crop yields due to the above-mentioned disasters could have serious environmental and economic consequences for the agricultural sector (Ali et al., 2022a).

For the above reasons, we extend and adapt the RICE-MED model to try to disentangle such effects on the agricultural sector, focusing on the Mediterranean countries. We calibrate the damage function using data from Roson and Sartori (2016), and then we project the economic damage affecting agricultural output, under our policy scenarios. It should be recognized that this approach could lead to an overestimation of agricultural damage.[70] To get a better insight on this side, the temperature dynamics should be regionalized to take into account the differences between countries. This is a plan for future research.

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[68] Annual mean temperatures in the Mediterranean area are currently 1.4 degree above late 19th century levels and heat waves are frequent, and the intensity of droughts have increased since 1950. In particular, the surface of the Mediterranean Sea has warmed by around 0.40 degrees, and sea levels have risen by about 3cm per decade, a sharp increase if compared to the period 1945-2000 (+0.7mm/year) and to 1970-2006 (1.1mm/year) (Galeotti, 2020).

[69] while 36% is the share for Ethiopia, 33% for Sudan and 11% for Algeria.

[70] In calibrating of the economic damage parameter for the agricultural sector of each region we need to take into account the share of agriculture in regional GDP. This leads to higher values of θ_j^A with respect to θ_j . This is due to the fact of the importance of the agricultural sector on the total GDP.

In Table 16, we report the results expressed as a percentage variation in output with respect to the BAU scenario. Figures in Appendix E show models' outcomes in the from of maps.

The majority of countries show a sharp increase in output loss after 2025. This is the result of both the increasing climate damage and the extent of the mitigation effort, which subtract resources to production activities.[71] However, such forces are counterbalanced differently within countries. In particular, areas where agricultural activities are crucial for the economy, are projected to suffer significant losses. At the same time, the effects in the OPT and TL cases are puzzling. By the end of the century Egypt, Algeria, Lybia, Tunisia, Sudan and Syria show output losses in the OPT scenario ranging from -16% and - 10%. European countries, such as Albania, Croatia, Greece, Italy and Spain, face a contraction in production between -7.5% and -3% in the same time series. Such differences are mainly due to cross-country characteristics in terms of production, agricultural dependence and other macroeconomic factor such as the expected economic and population growth, that interact in the dynamic of the model. In the TL scenario, the implementation of a stricter climate policy which drastically reduces emissions and thus production, is not always offset by the positive effect of reduced damages, and depresses output by 22% in Syria, 21% in Algeria, and 16% in Egypt, respectively, by 2105.

South MED countries show a different path between OPT and TL scenarios. In particular, Cyprus, Malta, Ethiopia, Israel, Morocco, are characterized by losses in output in the OPT case ranging from -25% to -7%. When the TL policy is implemented, the mitigation of climate damage is reflected in a positive impact on economic growth, and lower damages guarantee a higher level of output compared to the OPT case by 2105. For example, by the end of the century Cyprus will lose more than 25% of the GDP with respect to BAU, while in the TL case is of 20%. Finally, France shows an output loss which varies from 0% in the OPT scenario to -1.5% in the TL scenario by 2105.

If we compare the results between the RM model and the RM-U one, we can observe that, Ethiopia faces a loss of GDP in the OPT scenario equal to 10.7%, whereas the loss reported for the highest level of b is 8.5%.The same occurs for all the Mediterranean countries, in the TL scenarios.[72]

Finally, we discuss the evolution of the climate policies and their effects through time. Figure 2 shows that the output loss in 2015 ranges from -2% to -7.4%. The picture changes drastically in Figure 6, where in 2055 losses are more serious in most countries, and the median value is close to -11%, with a peak at around -20% in Cyprus. Finally, Figure 10 suggests that the OPT policy cannot lower damages enough to prevent even further losses, especially in the North African countries. The TL scenario brings in further evidence. The first year in Figure 14 reports the same picture as for Figure 2. However, by the mid of the century, the output loss reported in 18, has a mean around -14%, up to -27% in Syria and Libya.

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[71] Moreover, some studies (ex. CLIMRISK Estrada and Botzen (2021)) show that mitigation efforts could not be enough to avoid climate damages. Adaptation measures should be included too. However, the RICE-MED mode does not include in this version any adaptation process.

[72] Due to Roson and Sartori (2016) data.

5 Conclusions

In this work we present the RICE-MED model, an updated version of the RICE-99 model developed by Nordhaus and Boyer (2000) in terms of calibration of the base year, which is now 2015, and regionalization, focusing on the Mediterranean countries, with an extension on the incorporation of uncertainty related to the probability of a possible climate-related disaster following Castelnuovo et al. (2003)and an application to the agricultural sector.
Compared to the current state of the art, the main contributions of our work are: (i) the updated calibration of the RICE-99 original model, while also the revision of the regionalization to better focus on the Mediterranean countries; (ii) we incorporate uncertainty to study the impact of societal awareness of the effects of climate change on the outcomes of the RICE-MED model, in the form of a new utility function weighted by a survivor probability and a probability of a catastrophic event, and call such an extension the RICE-MED-U model; (iii) we adapt the RICE-MED model to perform specific analysis on the agricultural sector in the Mediterranean basin to project, under several scenarios, the potential losses due to climate change for that specific sector. First, the resetting of the initial conditions and the key parameters allow for the incorporation of the global economic shocks that have occurred over the years, and were overlooked in the previous version of the model. This has led to new projections, in line with the latest available data. Second, the RICE-MED model is able to capture the heterogeneity of the Mediterranean countries, accounting for their different characteristics and level of resilience to systemic shocks. In particular, we contribute to the literature which study the effects of temperature increase in the Mediterranean countries, calibrating the damage function to consider the economic and agricultural damages due to climate change. Incorporating uncertainty shows the importance of societal understanding and perception of the impact of climate change. The results of the RICE-MED-U model show us that the more the survivor probability decreases, thus the one of a catastrophic event rises, and the utility loss due to the catastrophic event widens, the more society is willing to pay for a growing cost of carbon. However, under the TL policy scenario, such a trend is reversed at the end of the century. This suggests that if effective actions are immediately taken and agents recognize that their survival is closely linked to temperature dynamics, while at the same time being aware of the effective risk of a catastrophe and its consequences, the 2°C temperature increase target can be achieved by the end of the century with a lower average carbon tax over the entire model time horizon. On the other hand, the associated economic costs are significant in a society that is entirely dependent on energy produced from fossil fuels. As already acknowledged in the introduction, we are aware that this is stringent assumption in terms of reality. However, let us recall that in 2020 only 16% of world primary energy came from low-carbon sources.[73]
With this work we also want to draw attention to the fact that if no transition to a low-emission energy sector is achieved and the only policy instrument is the carbon tax, the economic costs will be high, in all of our scenarios. We leave to future research the introduction in the model of energy produced with renewables sources and technologies capable of offsetting carbon emission from fossil fuels, such as carbon capture and sequestration (CCS), together with the possibility to study other RCP-SSP frameworks. By 2100, our projections show that a few Mediterranean countries will benefit from adopting strong climate policies, while the majority will still suffer significant economic losses. Such results confirm the vulnerability of this area. Thanks to a finer spatial detail compared to the original framework, the RICE-MED model shows that the timing of intervention is more critical for some countries than others. In addition, our analysis of the agricultural sector emphasizes potential negative impacts on the food sector and related supply chain as well.

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[73] *Source:* Our world in data - Webpage sources-global-energy, access Feb, 23.

A Appendix - Variables list

Table 1: Variables description

Variable	Description
t	Time, where $\Delta t = 10$ and $t = 1, 2...10$
j	Region
i	Country
s	Energy source
$L_j(t)$	Population and labor stock (million people)
g_j^L	Population growth rate, rate per Δt
$C_j(t)$	Aggregate consumption (trillion USD2015)
$c_j(t)$	Per capita consumption (trillion USD2015)
$A_j(t)$	Technological change (Hicks-neutral)
$g_j^A(t)$	Technological change growth rate
δ_j^A	Constant rate of decline of $g_j^A(t)$
α	Social valuation of different levels of consumption
$\rho(t)$	Pure rate of time preference
g^ρ	Growth rate of $\rho(t)$, rate per Δt
$\prod_j(t)$	Carbon emissions permits
$I_j(t)$	Investments (trillion USD2015)
$K_j(t)$	Capital stock (trillion USD2015)
δ_K	Capital depreciation rate
$ES_j(t)$	energy services.
γ	Elasticity of output respect to capital
β_j	Elasticity of output respect to the energy services
$1 - \beta_j - \gamma$	Elasticity of output respect to labor
δ_K	Capital stock annual depreciation rate
$c_j^E(t)$	Cost per unit of carbon-energy (thousand USD2015 per tC)
$q(t)$	Wholesale price of carbon-energy exclusive of the Hotelling rent (thousand USD2015 per tC)
$Markup_j^E$	Mark up on energy costs, capturing regional differences in transportation, distribution costs and national energy taxes (thousand USD2015 per tC)
$\varsigma_j(t)$	Level of carbon-augmenting technology / Ratio of carbon to carbon-energy
$g_j^z(t)$	Growth rate of the carbon-augmenting technology, rate per Δt
δ_j^Z	Constant rate of decline of $g_j^z(t)$

Variable	Description
$E_j\left(t\right)$	Carbon-energy inputs / carbon services, measured as CO2 emissions (Gtc)
$E\left(t\right)$	World use of carbon-energy in period t / Sum of carbon-energy across regions
$\Omega_j\left(t\right)$	Damage coefficient
$D_j\left(M_{AT}\left(t\right)\right)$	Damage function
θ_J	Climate change damage parameter.
θ_J^A	Climate change damage parameter related to the agricultural sector
π_j	Share of agricultural sector production on the overall GDP of the $j-th$ region
$M_{AT}\left(t\right)$	End - of - period of carbon in the atmosphere (AT) (GtC)
$\bar{M}_{AT}$	Pre-industrial atmospheric carbon dioxide (CO2) concentration (GtC)
$M_{UP}\left(t\right)$	Mass of carbon in the upper reservoir (biosphere and upper oceans) / Atmospheric concentration of CO2 in billions of Carbon (GtC)
$M_{LO}\left(t\right)$	Mass of carbon in the lower oceans (Gtc)
$\phi_{i,j}$	Per-period transfer rate from reservoir i to reservoir j, with $i,j=AT,UP,LO$
$ET\left(t\right)$	Global CO2 emissions including those arising from land use changing(Gtc)
$LU_j\left(t\right)$	Land-use carbon emissions (GtC)
$CumC\left(t\right)$	Cumulative consumption of carbon-energy at the end of period t (Gtc)
$CumC^*$	Parameter representing the inflection point beyon which the marginal cost of carbon-energy begins to rise sharply(Gtc)
ξ_i	Parameters related to $q\left(t\right)$ path overtime, where $i=1,2,3$
$F\left(t\right)$	Radiative forcings:increase since 1990 in watts per square meter $\left(W/m^2\right)$
$\mathcal{O}\left(t\right)$	Forcings of other GHGs (CFCs, CH4, N20 and ozone) and aerosols
$T\left(t\right)$	Increase in the globally and seasonally average temperature in AT and UP since 1900 (°C)
λ	Feedback parameter
σ_i	Transfer coefficients reflecting the rates of flow and the thermal capacities of the different sinks, with $i=1,2,3$
$SP\left(t\right)$	Survivor probability. The probability of a catastrophic event not to occur up to time t
$HR\left(t\right)$	Hazard rate of the survival probability function $SP\left(t\right)$
$\dot{T}\left(t\right)$	Rate of change of the temperature level $T\left(t\right)$ (°C)
φ_0	Scaling parameter of $HR\left(t\right)$
φ_1	Relevance of temperature growth rate in $HR\left(t\right)$
T_0	Temperature level at the base year (°C)
b	Utility loss share due to a catastrophic event

B Appendix - Equations

In what follows we provide a detailed list of all the most relevant equations in the model.

Population dynamics

$$L_j\left(t+1\right)=L_j\left(t\right)\left(\frac{L_j\left(T\right)}{L_j\left(t\right)}\right)^{g_j^L} \tag{12}$$

Technological change dynamics

$$A_j\left(t+1\right)=A_j\left(t\right)e^{g_j^A\left(t\right)} \tag{13}$$

Technological change growth rate

$$g_j^A\left(t\right)=g_j^A\left(0\right)e^{\left(-\delta_j^A t\right)} \tag{14}$$

Social welfare

$$W_j\left(t\right)=\sum_t U\left[c_j\left(t\right),L_j\left(t\right)\right]R\left(t\right) \tag{15}$$

Per capita consumption

$$c_j\left(t\right)=\frac{C_j\left(t\right)}{L_j\left(t\right)} \tag{16}$$

Utility function

$$U\left[c_j\left(t\right),L_j\left(t\right)\right]=L_j\left(t\right)\frac{c_j\left(t\right)^{1-\alpha}-1}{1-\alpha} \tag{17}$$

Pure time preference discount factor

$$R\left(t\right)=\prod_{\nu=0}^{t}\left[1+\rho\left(\nu\right)\right]^{-10} \tag{18}$$

Pure rate of time preference

$$\rho\left(t\right)=\rho\left(0\right)exp\left(-g^{\rho}t\right) \tag{19}$$

Production function

$$Q_j\left(t\right)=\Omega_j\left(t\right)\left[A_j\left(t\right)K_j\left(t\right)^{\gamma}L_j\left(t\right)^{1-\beta_j-\gamma}ES_j\left(t\right)^{\beta_j}-c_j^E\left(t\right)ES_j\left(t\right)\right] \tag{20}$$

Capital stock dynamics

$$K_j\left(t\right)=K_j\left(t-1\right)\left(1-\delta_K\right)^{\Delta t}+\Delta tI_j\left(t-1\right) \tag{21}$$

Energy services production function

$$ES_j\left(t\right)=\varsigma_j\left(t\right)E_j\left(t\right) \tag{22}$$

Technological change in the energy production

$$\varsigma_j\left(t\right)=\varsigma_j\left(0\right)exp\left(\int_0^t g_j^z\left(t\right)dt\right) \tag{23}$$

Growth rate of technological change in the energy production

$$g_j^z\left(t\right)=g_j^z\left(0\right)exp\left(-\delta_j^Z t\right) \tag{24}$$

Cost per unit of carbon-energy

$$c_j^E\left(t\right)=q\left(t\right)+Markup_j^E \tag{25}$$

Wholesale supply price of carbon-energy

$$q\left(t\right)=\xi_1+\xi_2\left(\frac{CumC\left(t\right)}{CumC^*}\right)^{\xi_3} \tag{26}$$

Cumulative consumption of carbon-energy

$$CumC\left(t\right)=CumC\left(t-1\right)+\Delta tE\left(t\right) \tag{27}$$

World use of carbon-energy

$$E\left(t\right)=\sum_{j=1}^{n}E_j\left(t\right) \tag{28}$$

Global CO2 emissions comprehensive of land use ones

$$ET\left(t\right)=\sum_{j=1}^{n}\left(E_j\left(t\right)+LU_j\left(t\right)\right) \tag{29}$$

Damage coefficient

$$\Omega_j\left(t\right)=1-D_j\left(M_{AT}\left(t\right)\right)=exp\left(-\theta_j\left(M_{AT}\left(t\right)-\bar{M}_{AT}\right)\right) \tag{30}$$

End-of-period mass of carbon in the atmosphere (AT)

$$M_{AT}\left(t\right)=\Delta tET\left(t-1\right)+\phi_{11}M_{AT}\left(t-1\right)+\phi_{21}M_{UP}\left(t-1\right) \tag{31}$$

Mass of carbon in the upper reservoir (UP)

$$M_{UP}\left(t\right)=\phi_{12}M_{AT}\left(t-1\right)+\phi_{22}M_{UP}\left(t-1\right)+\phi_{32}M_{LO}\left(t-1\right) \tag{32}$$

Mass of carbon in the lower oceans (LO)

$$M_{LO}\left(t\right)=\phi_{23}M_{UP}\left(t-1\right)+\phi_{33}M_{LO}\left(t-1\right) \tag{33}$$

Radiative forcing

$$F\left(t\right)=\eta\left\{log\left[\frac{M_{AT}\left(t\right)}{\bar{M}_{AT}}\right]\frac{1}{log\left(2\right)}\right\}+\mathcal{O}\left(t\right) \tag{34}$$

Increase in temperature in atmosphere and upper level of the ocean

$$T\left(t\right)=T\left(t-1\right)+\sigma_1\left\{F\left(t\right)-\lambda T\left(t-1\right)-\sigma_2\left[T\left(t-1\right)-T_{LO}\left(t-1\right)\right]\right\} \tag{35}$$

Increase in temperature in the deep oceans

$$T_{LO}\left(t\right)=T_{LO}\left(t-1\right)+\sigma_3\left\{T\left(t-1\right)-T_{LO}\left(t-1\right)\right\} \tag{36}$$

Survivor probability

$$SP\left(t\right)=\exp\left[-HR\left(t\right)\right] \tag{37}$$

Hazard rate function

$$HR\left(t\right)=\begin{cases}HR\left(t-1\right)+\left[\varphi_0+\varphi_1\dot{T}\left(t\right)\right]\eta\left[\max\left(0;T\left(t\right)-T_0\right)\right]^{\eta-1} & \text{if }\dot{T}\left(t\right)>0,\\0 & \text{otherwise}\end{cases} \tag{38}$$

C Appendix - Initial conditions

In the base year (i.e. 2015 in our model, $t = 0$), for each region j the initial values of the total factor productivity $A_j(0)$, the initial capital stock $K_j(0)$, the elasticity of output respect to the energy input β_j and the markup on the energy costs $Markup_j$ are calibrated so that the model align with certain specific conditions. The first two refer to the matching with empirical observations of the GDP and industrial emissions respectively. On the side of the interest rates on capital, the third condition requires the matching of their historical values with the capital's net marginal productivity. Finally, the impact of a constraint on carbon emission is introduced considering the effect of carbon tax in a *disaggregated energy model.* Therefore, the required initial values are identified simultaneously as a solution of a four-equations system.
In what follows we provide an overview for each analytical aspect together with the final formulation of the system.

The production side. In equation (20) the term $c_j^E(t)\,ES_j(t)$ represents the cost of producing carbon-energy and the related production function is described by Eq (22), where $\zeta_j(t)$ is the level of carbon-augmenting technology, that is the capacity of society to squeeze more energy services per unit of carbon inputs. At time $t = 0$, this value is set to be equal to 1, so that analytically $ES_j(0) = E_j(0)$.
Concerning the cost per unit of carbon-energy $c_j^E(t)$, it yields from the sum of two terms: $q(t)$, the wholesale price of carbon energy, exclusive of the Hotelling rent $h(t)$, equalized across regions, and $Markup_j$ representing spatial heterogeneity on the side of transportation, distribution costs and national taxation in each energy market. As mentioned above, at time $t = 0$, the latter is identified so that the model satisfies specific conditions, while $q(0)$ is in line with the original RICE-99 framework.
Under this framework, the production function described by Eq. (5) becomes:

$$\begin{aligned} Q_j(0) &= A_j(0)\,K_j(0)^{\gamma}\,L_j(0)^{1-\beta_j-\gamma}\,ES_j(0)^{\beta_j} - c_j^E(0)\,E_J(0), \\ &\text{with} ES_j(0) = E_j(0), \end{aligned} \tag{39}$$

where labor $L_j(0)$, $Q_j(0)$ and $E_j(0)$ are set equal to their historical values at the base year.[74]

The capital market. The interest rate on capital at the base year must equal its net marginal productivity, which yields from the sum between the contribution of capital with respect to the output and to the capital next period's stock. To this end, we first define r as the targeted value matching the historical level for the interest rate and the condition is then:

$$(1+r)^{10} = \frac{\partial Q_j(0)}{\partial K_j(0)} + \frac{\partial K_j(1)}{\partial K_j(0)}, \tag{40}$$

where the the first element in the RHS is the contribution of capital to the output, while the second is the one respect to the next period capital stock, with capital stock dynamics presented in Eq. (21).

The industrial emission. The third condition requires the matching with the industrial emissions historical value. To this end, we need to account for the market of the carbon-energy, in which following condition must hold:

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[74] Specifically, the initial values of labor (i.e. population) and output are taken from World Bank, whereas carbon-energy, expressed in CO2 emissions terms, from Enerdata database.

$$\beta_j \Lambda_j(t) ES_j(t)^{\beta_j - 1} = c_j^E(t) + \frac{h(t)}{\zeta_j(t)} + \frac{\tau(t)}{\zeta_j(t)}, \tag{41}$$

with $\Lambda_j(t) = \Omega_j(t) A_j(t) K_j(t)^{\gamma} L_j(t)^{1-\beta_j-\gamma}$. The LHS of (41) is the marginal productivity of carbon-energy and the RHS its market price, seen as the sum of the cost of producing carbon-energy $c_j^E(t)$, the Hotelling rent $h(t)$, representing the effect of current extraction of carbon fuels on future extraction costs, and $\tau(t)$ the carbon tax. Since the carbon tax and the Hotelling rent are applied only to the carbon content of carbon-energy, they are adjusted by the ratio of carbon to carbon-energy $\zeta_j(t)$ (Nordhaus and Boyer, 2000). By substituting Eq. (22) in (41) we obtain the level of emissions:

$$E_j(t) = \left\{ \left[c_j^E(t) + \frac{h(t)}{\zeta_j(t)} + \frac{\tau(t)}{\zeta_j(t)} \right] \frac{1}{\beta_j \Lambda_j(t)} \right\}^{\frac{1}{\beta_j - 1}}. \tag{42}$$

At the base year the Hotelling rent $h(0)$ and the carbon tax $\tau(0)$ are assumed to be nil while, as already mentioned above, $\zeta_j(0) = 1$, $L_j(0)$ and $E_j(0)$ are equal to their historical values and $\Omega_j(0) = 1$, leading to the following functional form of previous Eq. (42):

$$E_j(0) = \left[\frac{c_j^E(0)}{\beta_j \Lambda_j(0)} \right]^{\frac{1}{\beta_j - 1}}. \tag{43}$$

The disaggregated energy model. The carbon emissions of each region j, $E_j(0)$, are determined by the sum of the consumption for each energy source s (i.e. natural gas, oil, coal and electricity generated by fossil fuels) $X_{j,s}(0)$, weighted by its corresponding carbon coefficient $\gamma_{j,s}$. Accordingly, this is defined as:

$$E_j(0) = \sum_s X_{j,s}(0) \gamma_{j,s} \tag{44}$$

Each carbon coefficient $\gamma_{j,s}$ is computed as the ratio of the industrial carbon emissions from a particular fossil fuel s over its industrial consumption.[75] Data are sourced from Enerdata (2022). The demand of each fossil fuel $X_{j,s}(0)$ is defined as:

$$X_{j,s}(0) = \omega_{j,s}(0) \left[\frac{P_{j,s}(0)}{P_{j,s}(0) + \tau(0) \gamma_{j,s}} \right]^{\eta_j}, \tag{45}$$

where $\omega_{j,s}(0)$ is the consumption of energy source s at the base year, $P_{j,s}(0)$ is the price of the energy source s and η_j is the price elasticity of demand for energy source s.[76] Both consumption and prices information are sourced by Enerdata (2022), whereas the distribution of electricity generation by fossil fuels, used to compute the corresponding consumption of electricity, is available at the International Energy Agency (IEA) website.[77] To deal with the presence of missing

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[75] For electricity, the corresponding value is calculated as the sum of the carbon coefficients of individual fossil fuels weighted by their share in the electricity generation.

[76] Following the original RICE-99 model, we assign a regional specific η_j equal to -0.7 for the United States, Europe, Australia,New Zeland, Canada, Japan and those countries in the Mediterranean belonging to EU, whereas a value of -0.84 is assigned to the remaining regions.

[77] See the IEA dedicated page to electricity.

data, the aggregation to the regional case is performed by selecting the subset of countries for which information is available.[78]
Once the equations are calibrated with real values, the disaggregated energy model is run under two different scenarios, following Nordhaus and Boyer (2000). In the first case, the carbon tax entering into Eq. (45)is set to be 0, i.e. $\tau(0) = 0$, which leads to the emission value $E_j(0, \tau = 0)$. In the second case, the carbon tax is assumed to be equal to 50 USD per metric ton of Carbon, i.e. $\tau(0) = 50$, which leads to the corresponding $E_j(0, \tau = 50)$. Finally, the difference between the two resulting values, i.e. $E_j(0, \tau = 0) - E_j(0, \tau = 50)$, is set to be equal to the same imposition applied to Eq. (42), so that the last constraint of the initial conditions system is identified.

The initial calibration system. The four above constraints are required to provide the initial calibration of the model, on the basis of which it is possible to determine the initial values of the unknown $A_j(0)$, $K_j(0)$, β_j and $Markup_j$. This is done analytically by solving the following system of equations:

$$\begin{cases} Q_j(0) = \Omega_j(0)\left[A_j(0)K_j(0)^{\gamma}L_j(0)^{1-\beta_j-\gamma}ES_j(0)^{\beta_j} - c_j^E(0)E_j(0)\right] \\ E_j(0) = \left\{\frac{q(0)+Markup_j}{\beta_j\Omega_j(0)A_j(0)K_j(0)^{\gamma}L_j(0)^{1-\beta_j-\gamma}}\right\}^{\frac{1}{\beta_j-1}} \\ (1+r)^{10} = \frac{\partial Q_j(0)}{\partial K_j(0)} + \frac{\partial K_j(1)}{\partial K_j(0)} \\ \underbrace{E_j(0, \tau = 0) - E_j(0, \tau = 50)}_{\text{Computed as in Eq.42}} = \underbrace{E_j(0, \tau = 0) - E_j(0, \tau = 50)}_{\text{Disaggregated energy model}} \end{cases} \tag{46}$$

A last remark should be made with respect to the last constraint in (46). That is, industrial carbon emissions need to be calculated under two scenarios: a first one where no carbon tax exists, i.e. $\tau(0) = 0$, and a second one where $\tau(0) = 50$. Accordingly, on the left hand side of the last equation, this is done following Eq. (43) (i.e. the industrial emission function), while on the right hand side, the same change is calculated following Eq. (44)(i.e. the disaggregated energy model).

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[78] Specifically, regional consumption of energy as well as industrial carbon emissions are given by the sum of the corresponding country-level data, whereas energy prices are taken as weighted mean at country level, taking GDP values as weights.

D Appendix - Tables

Table 2: Regional structure of the model.

Code	Description	Type[79]
USA	USA	Country
China	People's Republic of China	Country
Europe	Europe (Austria, Belgium, Switzerland, Germany, Denmark, Finland, UK, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Sweden)	Region
OHI	Other High-Income countries (Aruba, Australia, Bahamas, Canada, Guam, Hong Kong, Japan, New Zealand, Virgin Islands, Singapore)	Region
EE	Russia and Eastern Europe countries (Bulgaria, Bosnia Herzegovina, Belarus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Moldova, Republic of Macedonia, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, Ukraine)	Region
MI	Middle Income countries (United Arab Emirates, Argentina, Bahrain, Brazil, Barbados, Brunei Darussalam, Gabon, Kuwait, Saint Lucia, Macao, Martinique, Malasya, New Caledonia, Oman, Puerto Rico, French Polynasia, RÃ©union, Qatar, Saudi Arabia, Suriname, Trinidad and Tobago)	Region
LMI	Lower Middle Income countries (Belize, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, Fiji, Micronesia, Guadeloupe, Grenada, French Guiana, Iran, Jamaica, Kazakhstan, Mexico, Mauritius, Namibia, Panama, Perï¿œ^{1}, Papua New Guinea, Paraguay, El Salvador, Thailand, Turkmenistan, Tonga, Uruguay, Saint Vincent and Grenadines, Venezuela, Vunatu, South Africa)	Region
LI	Low Income countries (Afghanistan, Angola, Armenia, Azerbaijan, Burundi, Benin, Burkina Faso, Bangladesh, Bolivia, Bhutan, Botswana, Central African Republic, Cote d'Ivoire, Cameroon, Congo (Kinshasa), Congo(Brazzaville), Comoros, Cape Verde, Djibuti, Georgia, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Guatemala, Guyana, Honduras, Haiti, Indonesia, India, Iraq, Jordan, Kenya, Kyrgyzstan, Cambodia, Lao PDR, Liberia, Sri Lanka, Lesotho, Madagascar, Maldives, Mali, Myanmar, Mongolia, Mozambique, Mauritania, Malawi, Niger, Nigeria, Nicaragua, Nepal, Pakistan, Philippines, North Korea, Rwanda, Senegal, Solomon Islands, Sierra Leone, Somalia, Sao Tome and Principe, Swaiziland, Chad, Togo, Tajikistan, Tanzania, Uganda, Uzbekistan, Vientnam, Yemen, Zambia, Zimbabwe, Samoa)	Region

Table 2: Regional structure of the model.

Code	Description	Type[79]
Mediterranean countries		
ALB	Albania	Country
DZA	Algeria	Country
HRV	Croatia	Country
CYP	Cyprus	Country
EGY	Egypt	Country
ETH	Ethiopia	Country
FRA	France	Country
GRC	Greece	Country
ISR	Israel	Country
ITA	Italy	Country
LBN	Lebanon	Country
LYB	Libya	Country
MLT	Malta	Country
MNE	Montenegro	Country
MAR	Morocco	Country
ESP	Spain	Country
SDN	Sudan	Country
SYR	Syria	Country
TUN	Tunisia	Country
TUR	Turkey	Country

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[79] We define as region, the aggregation of economies of different countries

D.1 Calibration

Table 3: Parameters (Nordhaus and Boyer, 2000).

Parameter	Value
γ	0.3
$\rho(0)$	0.015
g^{ρ}	0
r	0.05
δ_K	0.1
$CumC^*$	6000 (GtC)
ξ_1	113
ξ_2	700
ξ_3	4
ϕ_{11}	0.88
ϕ_{12}	0.12
ϕ_{21}	0.196
ϕ_{22}	0.797
ϕ_{23}	0.007
ϕ_{32}	0.001465
ϕ_{33}	0.9985
η	3.6813
σ_1	0.1005
σ_2	0.088
σ_3	0.025
λ	1.47252
$\bar{M}_{AT}$	581 (GtC)
$M_{AT}(0)$	883.3599 (GtC)
$M_{UP}(0)$	460 (GtC)
$M_{LO}(0)$	1740 (GtC)

Table 4: Population parameters

Regions	Parameter $g_j^L(0)$	Regions	Parameter $g_j^L(0)$
USA	0.198	FRA	0.221
China	0.04276	GRC	0.106
Europe	0.345	ISR	0.143
OHI	-0.0866	ITA	0.006032583
EE	-0.069	LBN	0.132693623
MI	0.24050076	LYB	0.356554673
LMI	0.187260152	MLT	0.046467611
LI	0.305	MNE	0.069296345
ALB	0.000955658	MAR	0.115243936
DZA	0.278190755	ESP	0.094447986
HRV	-0.058597844	SDN	0.348
CYP	0.39	SYR	0.332
EGY	0.343	TUN	0.154745943
ETH	0.277	TUR	0.227293275

Remarks: parameters are calibrated to assure that the population by 2100 approach IIASA-SSP2 projections.

Table 5: Parameters - RICE-MED-U.

Parameter	Value
$HR(t-1)$	0.0013
φ_0	0.005
φ_1	0.0025
η	2.5
b	$\{0.30, 0.50, 0.70\}$

Table 6: Initial conditions

Region j	$Q_j\,(0)$	$L_j\,(0)$	$E_j\,(0)$	$K_j\,(0)$	$A_j\,(0)$	$\beta_j(0)$	$Markup_j\,(0)$
USA	18.238	321	1.298	49.089	0.131	0.042	507.181
China	11	1379.86	2.744	31.018	0.038	0.055	127.430
Europe	11	234.053	0.47	27.858	0.097	0.017	283.587
OHI	8.159	204.47	0.592	21.288	0.085	0.012	20
EE	3	311.126	0.7	7.542	0.036	0.037	42.153
MI	4.264	339.04	0.591	11.291	0.043	0.027	84.010
LMI	4	541.586	0.667	11.309	0.034	0.042	165.317
LI	6	3463.487	1.166	17.252	0.013	0.04	117.720
Mediterranean Countries							
ALB	0.011	2.881	0.001	0.029	0.0187	0.023	147.255
DZA	0.166	39.728	0.038	0.488	0.042	0.124	502.643
HRV	0.05	4.203	0.005	0.139	0.059	0.074	595.426
CYP	0.02	1.16	0.002	0.035	0.041	0.02	50
EGY	0.329	92.44	0.058	0.903	0.024	0.061	252.982
ETH	0.065	100.84	0.003	0.169	0.005	0.008	60.711
FRA	2.438	66.55	0.085	6.352	0.08	0.011	196.558
GRC	0.196	10.821	0.017	0.546	0.078	0.075	817.167
ISR	0.3	8.38	0.017	0.97	0.076	0.016	165.548
ITA	1.836	61	0.088	4.441	0.084	0.047	807.304
LBN	0.05	6.534	0.007	0.133	0.03	0.01	-100
LYB	0.028	6.41	0.014	0.084	0.046486	0.144	165.548
MLT	0.011	0.445	0.00041	0.02499	0.051	0.004	-50
MNE	0.004	0.622	0.0006	0.0085	0.023	0.03	-5
MAR	0.101	34.66	0.016	0.1	0.02	0.01	-100
ESP	1.195	46.44	0.068	3.167	0.0711	0.028	384.091
SDN	0.052	38.903	0.005	0.20	0.0083	0.036	165.548
SYR	0.016	17.99	0.007	0.03	0.012	0.09	165.550
TUN	0.046	11.18	0.008	0.138	0.049	0.139	813.771
TUR	0.864	78.53	0.093	2.264	0.036	0.017	-48.49

Table 7: Total (θ_j) and agricultural $\left(\theta_j^A\right)$ damage parameters.

Regions	Parameter θ_j	Parameter θ_j^A
USA	1.55281E-06	-1.46594E-05
China	1.0432E-05	-2.25708E-05
Europe	-1.16633E-05	-1.7125E-05
OHI	8.75422E-05	3.02736E-05
EE	-1.01069E-05	-3.6192E-05
MI	3.82824E-05	9.59173E-05
LMI	4.37687E-05	-9.1971E-05
LI	7.68147E-05	9.69983E-05
ALB	2.48498E-05	2.9264E-05
DZA	3.79714E-05	9.99616E-05
HRV	1.76457E-06	6.116E-05
CYP	4.57677E-05	0.000253129
EGY	3.79714E-05	0.000101669
ETH	5.81472E-05	9.75653E-05
FRA	-2.90483E-06	-1.20782E-07
GRC	1.31805E-05	5.25615E-05
ISR	2.17705E-05	0.000138357
ITA	1.74708E-06	6.5807E-05
LBN	1.31805E-05	6.0444E-05
LYB	2.17705E-05	0.00013205
MLT	6.5693E-05	0.0001695
MNE	3.08377E-05	9.57475E-05
MAR	3.6762E-05	8.89674E-05
ESP	7.49581E-06	5.93155E-05
SDN	5.81472E-05	0.000112316
SYR	5.81472E-05	0.000105469
TUN	3.08377E-05	8.33139E-05
TUR	8.08234E-06	6.85408E-05

D.2 Results

Table 8: Increase in the global mean temperature, concentration and radiative forcing

Year Model	△Temperature (wrt 1900, °C)			Concentration (GtC)			Radiative forcing (W/m^2)		
Scenarios	*BAU*	*OPT*	*TL<2°C*	*BAU*	*OPT*	*TL<2°C*	*BAU*	*OPT*	*TL<2°C*
2015 RM	1.10	1.10	1.10	883.36	883.36	883.36	2.63	2.63	2.63
RM-U0.30	1.10	1.10	1.10	883.36	883.36	883.36	2.63	2.63	2.63
Δ0.30	-	-	-	-	-	-	-	-	-
RM-U0.50	1.10	1.10	1.10	883.36	883.36	883.36	2.63	2.63	2.63
Δ0.50	-	-	-	-	-	-	-	-	-
RM-U0.70	1.10	1.10	1.10	883.36	883.36	883.36	2.63	2.63	2.63
Δ0.70	-	-	-	-	-	-	-	-	-
2025 RM	1.19	1.19	1.19	957.52	957.52	957.52	3.05	3.05	3.05
RM-U0.30	1.19	1.19	1.19	957.52	957.52	957.52	3.05	3.05	3.05
Δ0.30	-	-	-	-	-	-	-	-	-
RM-U0.50	1.19	1.19	1.19	957.52	957.52	957.52	3.05	3.05	3.05
Δ0.50	-	-	-	-	-	-	-	-	-
RM-U0.70	1.19	1.19	1.19	957.52	957.52	957.52	3.05	3.05	3.05
Δ0.70	-	-	-	-	-	-	-	-	-
2035 RM	1.31	1.31	1.31	1024.28	1012.22	977.78	3.41	3.35	3.16
RM-U0.30	1.31	1.31	1.31	1005.50	997.02	974.82	3.31	3.27	3.15
Δ0.30	-	-	-	-1.83	-1.50	-0.30	-2.88	-2.39	-0.51
RM-U0.50	1.31	1.31	1.31	996.64	988.92	973.04	3.26	3.22	3.14
Δ0.50	-	-	-	-2.70	-2.30	-0.48	-4.25	-3.71	-0.82
RM-U0.70	1.31	1.31	1.31	988.89	982.92	971.41	3.22	3.19	3.13
Δ0.70	-	-	-	-3.46	-2.89	-0.65	-5.49	-4.66	-1.11
2055 RM	1.60	1.58	1.53	1145.98	1115.88	1016.30	4.00	3.86	3.36
RM-U0.30	1.57	1.56	1.53	1099.71	1076.74	1010.07	3.78	3.67	3.33
Δ0.30	-1.58	-1.33	-	-4.04	-3.51	-0.61	-5.47	-4.92	-0.98
RM-U0.50	1.56	1.55	1.52	1076.41	1054.60	1006.16	3.67	3.56	3.31
Δ0.50	-2.36	-2.07	-0.42	-6.07	-5.49	-1.00	-8.32	-7.77	-1.61
RM-U0.70	1.55	1.54	1.52	1055.09	1038.01	1002.46	3.56	3.48	3.29
Δ0.70	-3.16	-2.70	-0.58	-7.93	-6.98	-1.36	-10.97	-9.95	-2.17

Scenarios	*BAU*	*OPT*	*TL<2°C*	*BAU*	*OPT*	*TL<2°C*	*BAU*	*OPT*	*TL<2°C*
2105 RM	2.36	2.29	1.96	1407.96	1356.82	1086.99	5.09	4.89	3.71
RM-U0.30	2.25	2.18	1.95	1331.80	1280.92	1081.02	4.79	4.59	3.69
Δ0.30	-4.73	-4.54	-0.73	-5.41	-5.59	-0.55	-5.80	-6.26	-0.78
RM-U0.50	2.18	2.12	1.94	1284.86	1228.40	1076.83	4.60	4.36	3.66
Δ0.50	-7.41	-7.44	-1.21	-8.74	-9.46	-0.93	-9.55	-10.79	-1.35
RM-U0.70	2.12	2.06	1.93	1233.60	1187.69	1072.51	4.39	4.19	3.64
Δ0.70	-11.28	-10.75	-1.71	-12.38	-12.47	-1.33	-13.80	-14.45	-1.91

Remarks - RM rows reports the outcomes of the RICE-MED model, while RM-U those obtained from the RICE-MED-U extension. The number after RM-U refers to the level of the parameter b, determining the utility loss associated to the catastrophic event. The higher is b, the greater loss of utility. Δ refers to the percentage variation of the RM-U scenarios wrt to the RM one. Cells marked with "- " refer to changes close to zero.

Table 9: RICE-MED-U. Survivor Probability, $SP(t)$ and probability of a catastrophic event, $1 - SP(t)$

Year	Model	Survivor probability, $SP(t)$			Probability of a catastrophic event, $1 - SP(t)$		
	Scenarios	*BAU*	*OPT*	*TL<2°C*	*BAU*	*OPT*	*TL<2°C*
2015	RM-U0.30	0.999	0.999	0.999	0.001	0.001	0.001
	RM-U0.50	0.999	0.999	0.999	0.001	0.001	0.001
	RM-U0.70	0.999	0.999	0.999	0.001	0.001	0.001
2025	RM-U0.30	0.998	0.998	0.998	0.002	0.002	0.002
	RM-U0.50	0.998	0.998	0.998	0.002	0.002	0.002
	RM-U0.70	0.998	0.998	0.998	0.002	0.002	0.002
2035	RM-U0.30	0.997	0.997	0.997	0.003	0.003	0.003
	RM-U0.50	0.997	0.997	0.997	0.003	0.003	0.003
	RM-U0.70	0.997	0.997	0.997	0.003	0.003	0.003
2055	RM-U0.30	0.990	0.991	0.991	0.010	0.009	0.009
	RM-U0.50	0.991	0.991	0.991	0.009	0.009	0.009
	RM-U0.70	0.991	0.991	0.991	0.009	0.009	0.009
2105	RM-U0.30	0.938	0.942	0.955	0.062	0.058	0.045
	RM-U0.50	0.942	0.946	0.956	0.058	0.054	0.044
	RM-U0.70	0.946	0.949	0.956	0.054	0.051	0.044

Remarks - The number after RM-U refers to the level of the parameter b, determining the utility loss associated to the catastrophic event. The higher is b, the greater loss of utility.

Table 10: Carbon tax (USD/tC)

Year / Model	Carbon Tax		Year / Model	Carbon Tax	
Scenarios	*OPT*	*TL<2°C*	*Scenarios*	*OPT*	*TL<2°C*
2015 RM	38.94	39.76	2055 RM	209.45	1268.63
RM-U0.30	39.02	39.76	RM-U0.30	369.79	1348.86
Δ0.30	0.20	-	Δ0.30	76.56	6.32
RM-U0.50	39.30	39.76	RM-U0.50	521.68	1410.66
Δ0.50	0.91	-	Δ0.50	149.07	11.20
RM-U0.70	39.48	39.76	RM-U0.70	680.90	1479.04
Δ0.70	1.37	-	Δ0.70	225.09	16.59
2025 RM	133.87	617.36	2105 RM	406.42	4104.60
RM-U0.30	263.98	714.03	RM-U0.30	558.07	3961.38
Δ0.30	97.19	15.66	Δ0.30	37.31	-3.49
RM-U0.50	373.37	782.20	RM-U0.50	783.04	3890.40
Δ0.50	178.91	26.70	Δ0.50	92.67	-5.22
RM-U0.70	486.09	853.29	RM-U0.70	1031.71	3838.53
Δ0.70	263.11	38.22	Δ0.70	153.85	-6.46
2035 RM	157.29	788.72			
RM-U0.30	299.85	885.57			
Δ0.30	90.63	12.28			
RM-U0.50	423.50	955.02			
Δ0.50	169.24	21.08			
RM-U0.70	551.38	1028.28			
Δ0.70	250.54	30.37			

Remarks - RM rows reports the outcomes of the RICE-MED model, while RM-U those obtained from the RICE-MED-U extension. The number after RM-U refers to the level of the parameter b, determining the utility loss associated to the catastrophic event. The higher is b, the greater loss of utility. Δ *refers to the percentage variation of the RM-U scenarios wrt to the RM one. Cells marked with "- "refer to changes close to zero.*

Table 11: Average Carbon tax (USD/tC)

Model - Final year	*OPT*	$TL < 2^{\circ}C$
RM - Average 2105	231.32	1728.41
RM - Average 2305	806.23	53724.93
RM-U0.30 - Average 2105	371.31	1752.02
RM-U0.30 - Average 2305	618.72	50731.62
RM-U0.50 - Average 2105	521.45	1778.67
RM-U0.50 - Average 2305	797.47	48778.99
RM-U0.70 - Average 2105	681.66	1814.11
RM-U0.70 - Average 2305	1020.14	46853.24

Table 12: RICE-MED. Variation in output with respect to the baseline, BAU scenario (%).

Regions	Scenario	2015	2025	2035	2055	2105
USA	OPT	-0.05	0.15	-0.07	-0.20	-0.13
	TL <2°C	-0.05	-0.49	-1.49	-2.50	-4.86
OHI	OPT	-2.61	-4.60	-5.44	-6.74	-9.36
	TL <2°C	-2.61	-5.55	-6.64	-7.80	-9.60
EUROPE	OPT	0.35	0.94	0.82	0.89	1.38
	TL <2°C	0.35	0.94	0.12	-0.51	-1.41
EE	OPT	0.31	0.38	0.35	0.53	1.17
	TL <2°C	0.31	-2.19	-2.85	-3.38	-4.93
MI	OPT	-1.15	-2.05	-2.54	-3.16	-4.23
	TL <2°C	-1.15	-3.50	-4.56	-5.70	-7.82
LMI	OPT	-1.31	-2.39	-2.19	-3.60	-4.86
	TL <2°C	-1.31	-4.40	-5.48	-6.71	-9.54
CHINA	OPT	-0.31	-0.74	-0.94	-1.07	-1.16
	TL <2°C	-0.31	-3.78	-4.49	-5.14	-7.30
LI	OPT	-2.30	-4.22	-4.97	-6.11	-8.39
	TL <2°C	-2.30	-6.42	-7.56	-8.95	-12.12
Mediterranean countries						
ALB	OPT	-0.75	-1.17	-1.55	-1.99	-2.72
	TL <2°C	-0.75	-1.88	-2.78	-3.63	-5.26
DZA	OPT	-1.14	-2.36	-2.86	-3.48	-4.47
	TL <2°C	-1.14	-6.54	-7.95	-9.93	-16.25
HRV	OPT	-0.05	0.09	-0.11	-0.19	-0.14
	TL <2°C	-0.05	-0.13	-1.87	-2.46	-4.23
CYP	OPT	-1.37	-2.40	-2.94	-3.68	-5.01
	TL <2°C	-1.37	-3.46	-4.48	-5.53	-7.25
EGY	OPT	-1.14	-2.14	-2.62	-3.23	-4.28
	TL <2°C	-1.14	-4.67	-5.80	-7.21	-11.08
ETH	OPT	-1.74	-2.81	-3.44	-4.36	-6.21
	TL <2°C	-1.74	-2.63	-3.53	-4.33	-5.33

Table 12: RICE-MED. Variation in output with respect to the baseline, BAU scenario (%).

Regions	Scenario	2015	2025	2035	2055	2105
FRA	OPT	0.09	0.48	0.30	0.24	0.39
	TL <2°C	0.09	0.71	-0.09	-0.66	-1.27
GRC	OPT	-0.40	-0.53	-0.85	-1.16	-1.48
	TL <2°C	-0.40	-1.59	-2.76	-4.11	-7.71
ISR	OPT	-0.66	-0.92	-1.29	-1.70	-2.35
	TL <2°C	-0.66	-1.10	-2.00	-2.79	-3.92
ITA	OPT	-0.05	0.20	-0.03	-0.16	-0.14
	TL <2°C	-0.05	-0.07	-1.04	-1.97	-4.09
LBN	OPT	-0.39	-1.01	-1.24	-1.40	-1.47
	TL <2°C	-0.39	-2.07	-2.84	-3.38	-3.78
LBY	OPT	-0.66	-2.81	-3.17	-3.42	-3.03
	TL <2°C	-0.66	-13.94	-16.10	-19.65	-29.24
MLT	OPT	-1.97	-3.22	-3.91	-4.93	-6.99
	TL <2°C	-1.97	-2.92	-3.82	-4.61	-5.39
MAR	OPT	-1.11	-2.27	-2.68	-3.18	-4.04
	TL <2°C	-1.11	-3.33	-4.15	-4.18	-5.42
MNE	OPT	-0.93	-1.93	-2.27	-2.68	-3.42
	TL <2°C	-0.93	-4.41	-5.17	-5.88	-7.53
ESP	OPT	-0.23	-0.14	-0.41	-0.62	-0.79
	TL <2°C	-0.23	-0.45	-1.38	-2.26	-3.90
SDN	OPT	-1.74	-3.08	-3.70	-4.61	-6.37
	TL <2°C	-1.74	-4.58	-5.63	-6.83	-9.51
SYR	OPT	-1.74	-3.84	-4.45	-5.27	-6.74
	TL <2°C	-1.74	-9.56	-10.98	-13.04	-18.77
TUN	OPT	-0.93	-1.80	-2.26	-2.80	-3.64
	TL <2°C	-0.93	-4.87	-6.22	-8.00	-13.89
TUR	OPT	-0.24	-0.62	-0.84	-0.96	-0.91
	TL <2°C	-0.24	-2.13	-2.97	-3.66	-4.60

Table 13: RICE-MED-U0.30. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.30$.

Regions	Scenario	2015	2025	2035	2055	2105
USA	OPT	-0.05	0.11	-0.14	-0.28	-0.26
	TL <2°C	-0.05	-0.55	-1.45	-2.35	-4.53
OHI	OPT	-2.61	-4.60	-5.30	-6.35	-8.65
	TL <2°C	-2.61	-5.32	-6.29	-7.38	-9.24
EUROPE	OPT	0.35	0.93	0.76	0.77	1.17
	TL <2°C	0.35	0.88	0.14	-0.41	-1.20
EE	OPT	0.31	0.34	0.23	0.34	0.85
	TL <2°C	0.31	-1.76	-2.43	-2.98	-4.55
MI	OPT	-1.15	-2.08	-2.53	-3.07	-4.06
	TL <2°C	-1.15	-3.28	-4.23	-5.28	-7.41
LMI	OPT	-1.31	-2.47	-2.94	-3.51	-4.63
	TL <2°C	-1.31	-4.22	-5.20	-6.33	-9.09
CHINA	OPT	-0.31	-0.85	-1.06	-1.17	-1.25
	TL <2°C	-0.31	-3.47	-4.16	-4.79	-6.88
LI	OPT	-2.30	-4.30	-4.93	-5.86	-7.88
	TL <2°C	-2.30	-6.17	-7.20	-8.49	-11.63
Mediterranean countries						
ALB	OPT	-0.75	-1.20	-1.56	-1.94	-2.58
	TL <2°C	-0.75	-1.83	-2.64	-3.42	-4.96
DZA	OPT	-1.14	-2.55	-3.01	-3.52	-4.46
	TL <2°C	-1.14	-6.43	-7.70	-9.50	-15.49
HRV	OPT	-0.05	0.03	-0.19	-0.27	-0.21
	TL <2°C	-0.05	-1.19	-1.86	-2.36	-3.91
CYP	OPT	-1.37	-2.41	-2.90	-3.52	-4.72
	TL <2°C	-1.37	-3.25	-4.17	-5.13	-6.89
EGY	OPT	-1.14	-2.25	-2.68	-3.20	-4.17
	TL <2°C	-1.14	-4.53	-5.55	-6.83	-10.55
ETH	OPT	-1.74	-2.81	-3.34	-4.09	-5.67
	TL <2°C	-1.74	-2.65	-3.46	-4.18	-5.12

Table 13: RICE-MED-U0.30. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.30$.

Regions	Scenario	2015	2025	2035	2055	2105
FRA	OPT	0.09	0.48	0.26	0.17	0.31
	TL <2°C	0.09	0.64	-0.07	-0.58	-1.09
GRC	OPT	-0.40	-0.59	-0.92	-1.21	-1.51
	TL <2°C	-0.40	-1.68	-2.73	-3.94	-7.27
ISR	OPT	-0.66	-0.93	-1.29	-1.65	-2.21
	TL <2°C	-0.66	-1.12	-1.92	-2.63	-3.68
ITA	OPT	-0.05	0.17	-0.09	-0.23	-0.22
	TL <2°C	-0.05	-0.18	-1.05	-1.88	-3.79
LBN	OPT	-0.39	-0.73	-1.02	-1.26	-1.51
	TL <2°C	-0.39	-1.31	-2.07	-2.70	-3.45
LBY	OPT	-0.66	-3.15	-3.55	-3.88	-4.07
	TL <2°C	-0.66	-12.65	-14.61	-17.96	-27.87
MLT	OPT	-1.97	-3.18	-3.76	-4.60	-6.37
	TL <2°C	-1.97	-2.88	-3.69	-4.41	-5.18
MAR	OPT	-1.11	-1.99	-2.42	-2.92	-3.84
	TL <2°C	-1.11	-2.57	-3.38	-4.12	-5.08
MNE	OPT	-0.93	-1.93	-2.27	-2.63	-3.32
	TL <2°C	-0.93	-3.85	-4.62	-5.37	-7.13
ESP	OPT	-0.23	-0.17	-0.45	-0.66	-0.81
	TL <2°C	-0.23	-0.51	-1.35	-2.12	-3.62
SDN	OPT	-1.74	-3.14	-3.68	-4.42	-5.96
	TL <2°C	-1.74	-4.46	-5.41	-6.51	-9.10
SYR	OPT	-1.74	-4.05	-4.59	-5.29	-6.69
	TL <2°C	-1.74	-8.97	-10.27	-12.20	-17.94
TUN	OPT	-0.93	-1.94	-2.37	-2.83	-3.60
	TL <2°C	-0.93	-4.89	-6.11	-7.72	-13.20
TUR	OPT	-0.24	-0.52	-0.78	-0.96	-1.04
	TL <2°C	-0.24	-1.56	-2.36	-3.08	-4.23

Table 14: RICE-MED-U0.50. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.50$.

Regions	Scenario	2015	2025	2035	2055	2105
USA	OPT	-0.05	0.07	-0.22	-0.39	-0.46
	TL <2°C	-0.05	-0.56	-1.38	-2.22	-4.26
OHI	OPT	-2.61	-4.62	-5.25	-6.18	-8.24
	TL <2°C	-2.61	-5.18	-6.07	-7.08	-8.93
EUROPE	OPT	0.35	0.92	0.71	0.67	0.97
	TL <2°C	0.35	0.86	0.18	-0.33	-1.05
EE	OPT	0.31	0.28	0.11	0.15	0.49
	TL <2°C	0.31	-1.45	-2.10	-2.66	-4.22
MI	OPT	-1.15	-2.13	-2.56	-3.08	-4.06
	TL <2°C	-1.15	-3.11	-3.98	-4.96	-7.05
LMI	OPT	-1.31	-2.56	-3.01	-3.55	-4.64
	TL <2°C	-1.31	-4.06	-4.95	-6.02	-8.70
CHINA	OPT	-0.31	-0.96	-1.20	-1.33	-1.47
	TL <2°C	-0.31	-3.20	-3.86	-4.50	-6.52
LI	OPT	-2.30	-4.39	-4.97	-5.80	-7.69
	TL <2°C	-2.30	-5.96	-6.91	-8.13	-11.20
Mediterranean countries						
ALB	OPT	-0.75	-1.23	-1.59	-1.96	-2.57
	TL <2°C	-0.75	-1.77	-2.52	-3.25	-4.72
DZA	OPT	-1.14	-2.78	-3.23	-3.74	-4.75
	TL <2°C	-1.14	-6.26	-7.42	-9.11	-14.85
HRV	OPT	-0.05	-0.05	-0.28	-0.38	-0.34
	TL <2°C	-0.05	-1.19	-1.81	-2.27	-3.69
CYP	OPT	-1.37	-2.44	-2.90	-3.47	-4.61
	TL <2°C	-1.37	-3.11	-3.95	-4.85	-6.58
EGY	OPT	-1.14	-2.37	-2.80	-3.29	-4.29
	TL <2°C	-1.14	-4.36	-5.30	-6.51	-10.09
ETH	OPT	-1.74	-2.80	-3.30	-3.95	-5.32
	TL <2°C	-1.74	-2.66	-3.40	-4.07	-4.98

Table 14: RICE-MED-U0.50. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.50$.

Regions	Scenario	2015	2025	2035	2055	2105
FRA	OPT	0.09	0.48	0.24	0.12	0.21
	TL <2°C	0.09	0.61	-0.05	-0.51	-0.97
GRC	OPT	-0.40	-0.65	-1.01	-1.31	-1.68
	TL <2°C	-0.40	-1.69	-2.66	-3.79	-6.92
ISR	OPT	-0.66	-0.94	-1.30	-1.65	-2.17
	TL <2 °C	-0.66	-1.11	-1.85	-2.50	-3.50
ITA	OPT	-0.05	0.14	-0.14	-0.32	-0.37
	TL <2°C	-0.05	-0.22	-1.03	-1.79	-3.57
LBN	OPT	-0.39	-0.66	-0.98	-1.25	-1.58
	TL <2°C	-0.39	-1.04	-1.75	-2.35	-3.15
LBY	OPT	-0.66	-3.57	-4.04	-4.55	-5.53
	TL <2°C	-0.66	-11.62	-13.43	-16.59	-26.45
MLT	OPT	-1.97	-3.16	-3.69	-4.42	-5.95
	TL <2°C	-1.97	-2.88	-3.62	-4.29	-5.04
MAR	OPT	-1.11	-1.93	-2.35	-2.83	-3.73
	TL <2°C	-1.11	-2.30	-3.06	-3.76	-4.77
MNE	OPT	-0.93	-1.97	-2.32	-2.68	-3.38
	TL <2°C	-0.93	-3.50	-4.24	-4.99	-6.77
ESP	OPT	-0.23	-0.19	-0.49	-0.72	-0.91
	TL <2°C	-0.23	-0.52	-1.29	-2.01	-3.41
SDN	OPT	-1.74	-3.21	-3.72	-4.38	-5.82
	TL <2°C	-1.74	-4.34	-5.22	-6.24	-8.75
SYR	OPT	-1.74	-4.29	-4.82	-5.50	-7.03
	TL <2°C	-1.74	-8.48	-9.68	-11.52	-17.16
TUN	OPT	-0.93	-2.11	-2.55	-3.00	-3.82
	TL <2°C	-0.93	-4.83	-5.95	-7.45	-12.66
TUR	OPT	-0.24	-0.50	-0.79	-1.01	-1.22
	TL <2°C	-0.24	-1.27	-2.02	-2.70	-3.89

Table 15: RICE-MED-U0.70. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.70$.

Regions	Scenario	2015	2025	2035	2055	2105
USA	OPT	-0.05	0.05	-0.23	-0.41	-0.51
	TL <2°C	-0.05	-0.52	-1.26	-2.01	-3.86
OHI	OPT	-2.61	-4.59	-5.15	-5.96	-7.77
	TL <2°C	-2.61	-5.02	-5.82	-6.73	-8.48
EUROPE	OPT	0.35	0.92	0.69	0.63	0.88
	TL <2°C	0.35	0.85	0.24	-0.20	-0.83
EE	OPT	0.31	0.33	0.14	0.13	0.38
	TL <2°C	0.31	-1.09	-1.69	-2.22	-3.68
MI	OPT	-1.15	-2.10	-2.51	-2.97	-3.86
	TL <2°C	-1.15	-2.91	-3.68	-4.55	-6.48
LMI	OPT	-1.31	-2.56	-2.97	-3.46	-4.45
	TL <2°C	-1.31	-3.82	-4.62	-5.59	-8.08
CHINA	OPT	-0.31	-0.95	-1.19	-1.33	-1.49
	TL <2°C	-0.31	-2.83	-3.45	-4.06	-5.97
LI	OPT	-2.30	-4.38	-4.90	-5.64	-7.32
	TL <2°C	-2.30	-5.69	-6.54	-7.64	-10.51
Mediterranean countries						
ALB	OPT	-0.75	-1.22	-1.57	-1.90	-2.46
	TL <2°C	-0.75	-1.68	-2.36	-3.01	-4.36
DZA	OPT	-1.14	-2.84	-3.27	-3.74	-4.72
	TL <2°C	-1.14	-5.91	-6.95	-8.49	-13.82
HRV	OPT	-0.05	-0.08	-0.31	-0.41	-0.38
	TL <2°C	-0.05	-1.13	-1.68	-2.10	-3.39
CYP	OPT	-1.37	-2.41	-2.84	-3.35	-4.36
	TL <2°C	-1.37	-2.95	-3.70	-4.50	-6.09
EGY	OPT	-1.14	-2.39	-2.79	-3.24	-4.16
	TL <2°C	-1.14	-4.10	-4.94	-6.03	-9.34
ETH	OPT	-1.74	-2.79	-3.24	-3.82	-5.01
	TL <2°C	-1.74	-2.67	-3.34	-3.95	-4.79

Table 15: RICE-MED-U0.70. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.70$.

Regions	Scenario	2015	2025	2035	2055	2105
FRA	OPT	0.09	0.48	0.23	0.11	0.18
	TL <2°C	0.09	0.59	0.00	-0.41	-0.80
GRC	OPT	-0.40	-0.69	-1.04	-1.33	-1.70
	TL <2°C	-0.40	-1.64	-2.51	-3.52	-6.40
ISR	OPT	-0.66	-0.94	-1.28	-1.60	-2.07
	TL <2°C	-0.66	-1.08	-1.74	-2.32	-3.24
ITA	OPT	-0.05	0.12	-0.16	-0.34	-0.41
	TL <2°C	-0.05	-0.24	-0.96	-1.65	-3.26
LBN	OPT	-0.39	-0.58	-0.89	-1.14	-1.45
	TL <2°C	-0.39	-0.83	-1.47	-2.00	-2.72
LBY	OPT	-0.66	-3.50	-3.95	-4.46	-5.59
	TL <2°C	-0.66	-10.26	-11.86	-14.71	-23.96
MLT	OPT	-1.97	-3.14	-3.62	-4.25	-5.58
	TL <2°C	-1.97	-2.89	-3.56	-4.16	-4.88
MAR	OPT	-1.11	-1.85	-2.24	-2.67	-3.47
	TL <2°C	-1.11	-2.10	-2.77	-3.40	-4.34
MNE	OPT	-0.93	-1.90	-2.24	-2.59	-3.23
	TL <2°C	-0.93	-3.12	-3.80	-4.52	-6.20
ESP	OPT	-0.23	-0.20	-0.50	-0.72	-0.91
	TL <2 °C	-0.23	-0.50	-1.19	-1.83	-3.10
SDN	OPT	-1.74	-3.21	-3.67	-4.27	-5.55
	TL <2°C	-1.74	-4.17	-4.95	-5.89	-8.22
SYR	OPT	-1.74	-4.28	-4.77	-5.40	-6.85
	TL <2°C	-1.74	-7.80	-8.88	-10.56	-15.84
TUN	OPT	-0.93	-2.18	-2.59	-3.01	-3.79
	TL <2°C	-0.93	-4.63	-5.63	-7.00	-11.82
TUR	OPT	-0.24	-0.43	-0.72	-0.93	-1.15
	TL <2°C	-0.24	-1.01	-1.68	-2.28	-3.37

D.2.1 Results accounting for the agricultural damage

Table 16: RICE-MED. Agri. Variation in output with respect to the baseline (%), BAU scenario

Regions	*Scenario*	2015	2025	2035	2055	2105
ALB	OPT	-0.88	-1.45	-1.81	-2.34	-3.35
	TL $<$ 2°C	-0.88	-2.17	-3.03	-3.90	-5.66
DZA	OPT	-2.98	-5.56	-6.57	-8.26	-11.71
	TL $<$ 2°C	-2.98	-9.74	-11.30	-13.68	-20.79
HRV	OPT	-1.83	-3.22	-3.87	-4.92	-7.06
	TL $<$ 2°C	-1.83	-4.41	-5.27	-6.19	-8.67
CYP	OPT	-7.37	-12.79	-14.87	-18.46	-25.74
	TL $<$ 2°C	-7.37	-13.91	-15.34	-17.30	-20.64
EGY	OPT	-3.03	-5.43	-6.41	-8.07	-11.48
	TL $<$ 2°C	-3.03	-8.00	-9.25	-11.02	-15.58
ETH	OPT	-2.91	-4.98	-5.91	-7.47	-10.71
	TL $<$ 2°C	-2.91	-4.81	-5.74	-6.72	-8.09
FRA	OPT	0.00	0.17	0.07	0.02	0.05
	TL $<$ 2°C	0.00	0.43	-0.29	-0.84	-1.51
GRC	OPT	-1.58	-2.75	-3.34	-4.26	-6.12
	TL $<$ 2°C	-1.58	-3.79	-4.98	-6.55	-10.70
ISR	OPT	-4.10	-7.09	-8.35	-10.49	-14.92
	TL $<$ 2°C	-4.10	-7.29	-8.41	-9.76	-11.95
ITA	OPT	-1.97	-3.40	-4.09	-5.20	-7.48
	TL $<$ 2°C	-1.97	-3.64	-4.70	-5.95	-8.77
LBN	OPT	-1.82	-3.28	-3.88	-4.85	-6.82
	TL $<$ 2°C	-1.82	-4.64	-5.47	-6.24	-7.13
LBY	OPT	-3.92	-7.82	-9.14	-11.35	-15.81
	TL $<$ 2°C	-3.92	-19.19	-21.64	-25.81	-36.25
MLT	OPT	-5.00	-8.61	-10.08	-12.62	-17.86
	TL $<$ 2°C	-5.00	-8.35	-9.43	-10.68	-12.35
MAR	OPT	-2.67	-4.77	-5.61	-7.01	-9.89
	TL $<$ 2°C	-2.67	-6.12	-7.02	-7.93	-9.06

Table 16: RICE-MED. Agri. Variation in output with respect to the baseline (%), BAU scenario

Regions	*Scenario*	2015	2025	2035	2055	2105
MNE	OPT	-2.86	-5.12	-6.02	-7.53	-10.68
	TL $<$ 2°C	-2.86	-7.78	-8.68	-9.74	-12.07
ESP	OPT	-1.78	-3.03	-3.66	-4.66	-6.71
	TL $<$ 2°C	-1.78	-3.32	-4.32	-5.45	-7.65
SDN	OPT	-3.34	-5.88	-6.94	-8.73	-12.44
	TL $<$ 2°C	-3.34	-7.42	-8.56	-10.05	-13.29
SYR	OPT	-3.14	-5.88	-6.92	-8.64	-12.18
	TL $<$ 2°C	-3.14	-11.80	-13.35	-15.75	-22.13
TUN	OPT	-2.49	-4.63	-5.52	-6.96	-9.91
	TL $<$ 2°C	-2.49	-7.69	-9.14	-11.26	-17.90
TUR	OPT	-2.06	-3.65	-4.34	-5.46	-7.73
	TL $<$ 2°C	-2.06	-5.37	-6.31	-7.31	-8.86

Table 17: RICE-MED-U0.30. Agri. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.30$

Regions	*Scenario*	2015	2025	2035	2055	2105
ALB	OPT	-0.88	-1.45	-1.76	-2.19	-3.08
	TL $<$ 2°C	-0.88	-2.13	-2.89	-3.68	-5.35
DZA	OPT	-2.98	-5.64	-6.42	-7.75	-10.80
	TL $<$ 2°C	-2.98	-9.65	-11.02	-13.19	-19.97
HRV	OPT	-1.83	-3.24	-3.75	-4.57	-6.45
	TL $<$ 2°C	-1.83	-4.48	-5.22	-6.04	-8.29
CYP	OPT	-7.37	-12.83	-14.38	-17.21	-23.73
	TL $<$ 2°C	-7.37	-13.73	-14.98	-16.79	-20.18
EGY	OPT	-3.03	-5.47	-6.23	-7.54	-10.56
	TL $<$ 2°C	-3.03	-7.86	-8.97	-10.59	-15.00
ETH	OPT	-2.91	-4.98	-5.69	-6.93	-9.78
	TL $<$ 2°C	-2.91	-4.83	-5.65	-6.53	-7.86
FRA	OPT	0.00	0.19	0.07	0.01	0.03
	TL $<$ 2°C	0.00	0.37	-0.27	-0.75	-1.33
GRC	OPT	-1.58	-2.76	-3.24	-3.98	-5.61
	TL $<$ 2°C	-1.58	-3.86	-4.93	-6.34	-10.21

Table 17: RICE-MED-U0.30. Agri. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.30$

Regions	*Scenario*	2015	2025	2035	2055	2105
ISR	OPT	-4.10	-7.10	-8.05	-9.74	-13.66
	TL $<$ 2°C	-4.10	-7.30	-8.29	-9.50	-11.63
ITA	OPT	-1.97	-3.40	-3.94	-4.83	-6.84
	TL $<$ 2°C	-1.97	-3.74	-4.68	-5.80	-8.42
LBN	OPT	-1.82	-3.17	-3.66	-4.47	-6.26
	TL $<$ 2°C	-1.82	-3.90	-4.70	-5.54	-6.77
LBY	OPT	-3.92	-8.05	-9.07	-10.84	-14.81
	TL $<$ 2°C	-3.92	-18.03	-20.21	-24.12	-34.86
MLT	OPT	-5.00	-8.59	-9.70	-11.70	-16.36
	TL $<$ 2°C	-5.00	-8.30	-9.26	-10.41	-12.09
MAR	OPT	-2.67	-4.66	-5.33	-6.46	-9.06
	TL $<$ 2°C	-2.67	-5.39	-6.25	-7.21	-8.68
MNE	OPT	-2.86	-5.13	-5.83	-7.02	-9.81
	TL $<$ 2°C	-2.86	-7.24	-8.11	-9.19	-11.62
ESP	OPT	-1.78	-3.03	-3.53	-4.33	-6.14
	TL $<$ 2°C	-1.78	-3.38	-4.26	-5.27	-7.33
SDN	OPT	-3.34	-5.91	-6.72	-8.13	-11.41
	TL $<$ 2°C	-3.34	-7.31	-8.32	-9.68	-12.84
SYR	OPT	-3.14	-5.99	-6.78	-8.15	-11.27
	TL $<$ 2°C	-3.14	-11.24	-12.63	-14.87	-21.25
TUN	OPT	-2.49	-4.68	-5.37	-6.52	-9.11
	TL $<$ 2°C	-2.49	-7.71	-8.99	-10.92	-17.15
TUR	OPT	-2.06	-3.62	-4.17	-5.07	-7.10
	TL $<$ 2°C	-2.06	-4.82	-5.69	-6.69	-8.46

Table 18: RICE-MED-U0.50. Agri. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.50$

Regions	*Scenario*	2015	2025	2035	2055	2105
ALB	OPT	-0.88	-1.45	-1.73	-2.10	-2.91
	TL < 2°C	-0.88	-2.07	-2.76	-3.50	-5.10
DZA	OPT	-2.98	-5.68	-6.35	-7.50	-10.25
	TL < 2°C	-2.98	-9.48	-10.74	-12.77	-19.29
HRV	OPT	-1.83	-3.25	-3.69	-4.40	-6.09
	TL < 2°C	-1.83	-4.48	-5.16	-5.90	-8.03
CYP	OPT	-7.37	-12.84	-14.14	-16.57	-22.49
	TL < 2°C	-7.37	-13.61	-14.74	-16.43	-19.81
EGY	OPT	-3.03	-5.50	-6.15	-7.27	-10.00
	TL < 2°C	-3.03	-7.71	-8.72	-10.23	-14.51
ETH	OPT	-2.91	-4.97	-5.58	-6.65	-9.22
	TL < 2°C	-2.91	-4.84	-5.58	-6.41	-7.69
FRA	OPT	0.00	0.19	0.07	0.00	0.02
	TL < 2°C	0.00	0.34	-0.24	-0.68	-1.20
GRC	OPT	-1.58	-2.77	-3.19	-3.84	-5.31
	TL < 2 °C	-1.58	-3.87	-4.85	-6.16	-9.83
ISR	OPT	-4.10	-7.10	-7.91	-9.36	-12.90
	TL < 2 °C	-4.10	-7.30	-8.19	-9.32	-11.40
ITA	OPT	-1.97	-3.40	-3.88	-4.65	-6.46
	TL < 2°C	-1.97	-3.78	-4.64	-5.68	-8.16
LBN	OPT	-1.82	-3.13	-3.56	-4.27	-5.90
	TL < 2°C	-1.82	-3.64	-4.37	-5.17	-6.45
LBY	OPT	-3.92	-8.14	-9.02	-10.57	-14.21
	TL < 2°C	-3.92	-17.09	-19.09	-22.78	-33.48
MLT	OPT	-5.00	-8.58	-9.52	-11.23	-15.45
	TL < 2°C	-5.00	-8.30	-9.17	-10.24	-11.91
MAR	OPT	-2.67	-4.63	-5.20	-6.18	-8.55
	TL < 2°C	-2.67	-5.13	-5.92	-6.83	-8.36
MNE	OPT	-2.86	-5.13	-5.72	-6.76	-9.27
	TL < 2°C	-2.86	-6.91	-7.73	-8.79	-11.24
ESP	OPT	-1.78	-3.04	-3.47	-4.17	-5.79
	TL < 2°C	-1.78	-3.39	-4.19	-5.12	-7.09
SDN	OPT	-3.34	-5.92	-6.61	-7.83	-10.79
	TL < 2°C	-3.34	-7.19	-8.12	-9.39	-12.47

Table 18: RICE-MED-U0.50. Agri. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.50$

Regions	*Scenario*	2015	2025	2035	2055	2105
SYR	OPT	-3.14	-6.03	-6.71	-7.90	-10.73
	TL < 2°C	-3.14	-10.76	-12.05	-14.17	-20.44
TUN	OPT	-2.49	-4.72	-5.31	-6.30	-8.64
	TL < 2°C	-2.49	-7.65	-8.82	-10.62	-16.56
TUR	OPT	-2.06	-3.60	-4.07	-4.86	-6.70
	TL < 2°C	-2.06	-4.55	-5.35	-6.29	-8.10

Table 19: RICE-MED-U0.70. Agri. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.70$

Regions	*Scenario*	2015	2025	2035	2055	2105
ALB	OPT	-0.88	-1.45	-1.71	-2.04	-2.75
	TL < 2°C	-0.88	-1.98	-2.60	-3.26	-4.73
DZA	OPT	-2.98	-5.78	-6.36	-7.34	-9.76
	TL < 2°C	-2.98	-9.15	-10.27	-12.12	-18.25
HRV	OPT	-1.83	-3.28	-3.66	-4.26	-5.69
	TL < 2°C	-1.83	-4.41	-5.02	-5.70	-7.70
CYP	OPT	-7.37	-12.87	-13.93	-15.97	-21.06
	TL < 2°C	-7.37	-13.47	-14.47	-16.02	-19.28
EGY	OPT	-3.03	-5.55	-6.10	-7.06	-9.44
	TL < 2°C	-3.03	-7.45	-8.36	-9.74	-13.75
ETH	OPT	-2.91	-4.97	-5.49	-6.38	-8.58
	TL < 2°C	-2.91	-4.85	-5.51	-6.26	-7.49
FRA	OPT	0.00	0.20	0.07	-0.01	0.00
	TL < 2°C	0.00	0.32	-0.19	-0.58	-1.03
GRC	OPT	-1.58	-2.79	-3.17	-3.73	-5.02
	TL < 2°C	-1.58	-3.83	-4.69	-5.88	-9.28
ISR	OPT	-4.10	-7.11	-7.78	-9.00	-12.03
	TL < 2°C	-4.10	-7.27	-8.06	-9.09	-11.09
ITA	OPT	-1.97	-3.41	-3.83	-4.49	-6.04
	TL < 2°C	-1.97	-3.80	-4.56	-5.50	-7.81
LBN	OPT	-1.82	-3.11	-3.49	-4.10	-5.51
	TL < 2°C	-1.82	-3.44	-4.09	-4.80	-6.00
LBY	OPT	-3.92	-8.35	-9.12	-10.48	-13.86

Table 19: RICE-MED-U0.70. Agri. Variation in output with respect to the baseline, BAU scenario (%), with $b = 0.70$

Regions	*Scenario*	2015	2025	2035	2055	2105
	TL < 2°C	-3.92	-15.85	-17.62	-20.96	-31.12
MLT	OPT	-5.00	-8.57	-9.35	-10.78	-14.38
	TL < 2°C	-5.00	-8.32	-9.08	-10.07	-11.70
MAR	OPT	-2.67	-4.61	-5.10	-5.93	-7.97
	TL < 2°C	-2.67	-4.93	-5.63	-6.45	-7.91
MNE	OPT	-2.86	-5.14	-5.65	-6.53	-8.71
	TL < 2°C	-2.86	-6.56	-7.30	-8.29	-10.65
ESP	OPT	-1.78	-3.04	-3.42	-4.02	-5.42
	TL < 2°C	-1.78	-3.38	-4.08	-4.92	-6.76
SDN	OPT	-3.34	-5.95	-6.53	-7.56	-10.12
	TL < 2°C	-3.34	-7.03	-7.85	-9.01	-11.91
SYR	OPT	-3.14	-6.13	-6.72	-7.74	-10.27
	TL < 2°C	-3.14	-10.12	-11.26	-13.20	-19.12
TUN	OPT	-2.49	-4.79	-5.31	-6.15	-8.21
	TL < 2°C	-2.49	-7.45	-8.50	-10.14	-15.70
TUR	OPT	-2.06	-3.59	-4.01	-4.68	-6.28
	TL < 2°C	-2.06	-4.30	-5.00	-5.85	-7.55

E Appendix - Figures

Figure 1: Mediterranean region

E.1 Results accounting for agricultural damage

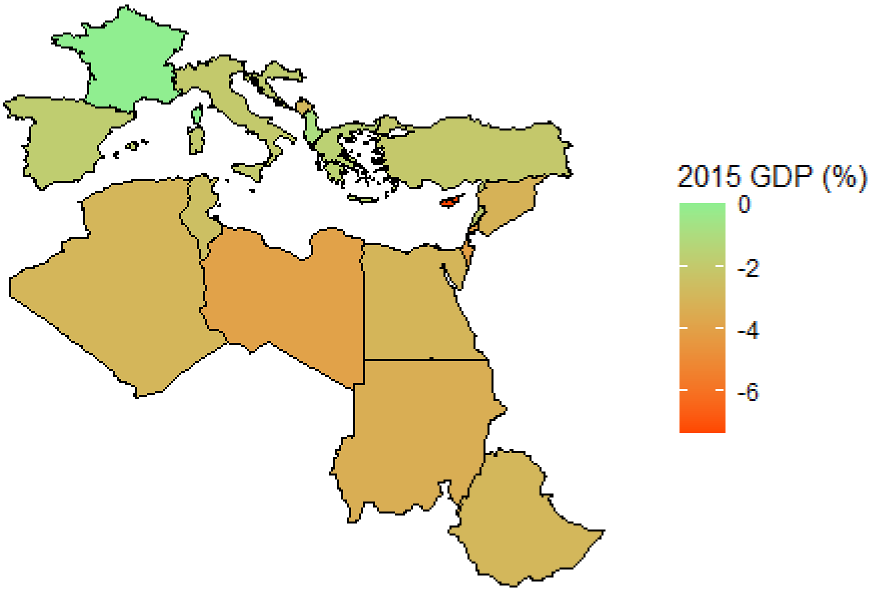

Figure 2: RICE-MED. Percentage of output loss under the OPT Scenario (2015), Mediterranean Countries

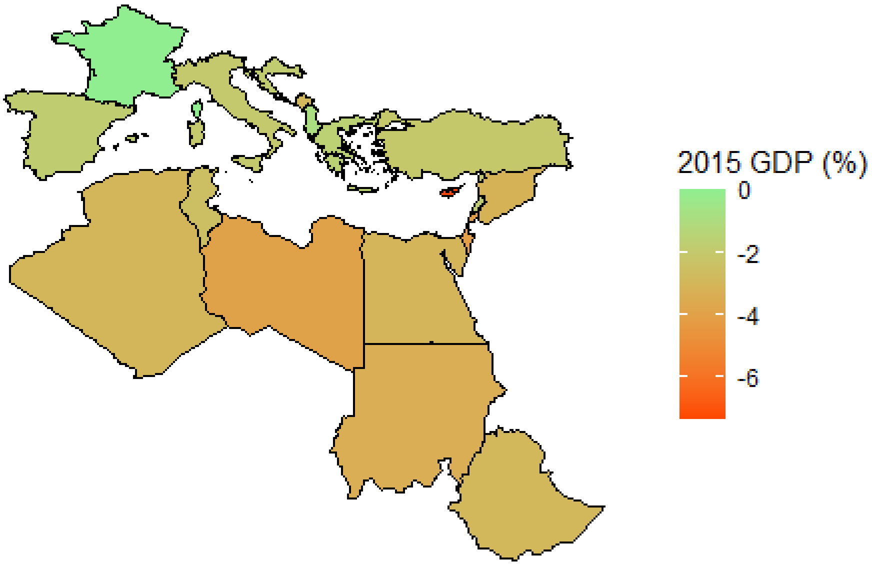

Figure 3: RICE-MED-U0.30. Percentage of output loss under the OPT Scenario (2015), Mediterranean Countries

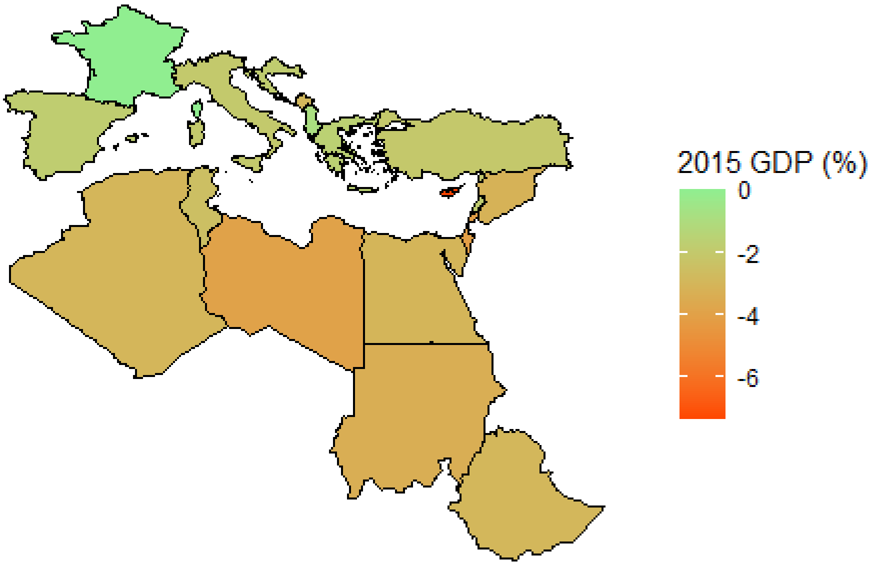

Figure 4: RICE-MED-U0.50. Percentage of output loss under the OPT Scenario (2015), Mediterranean Countries

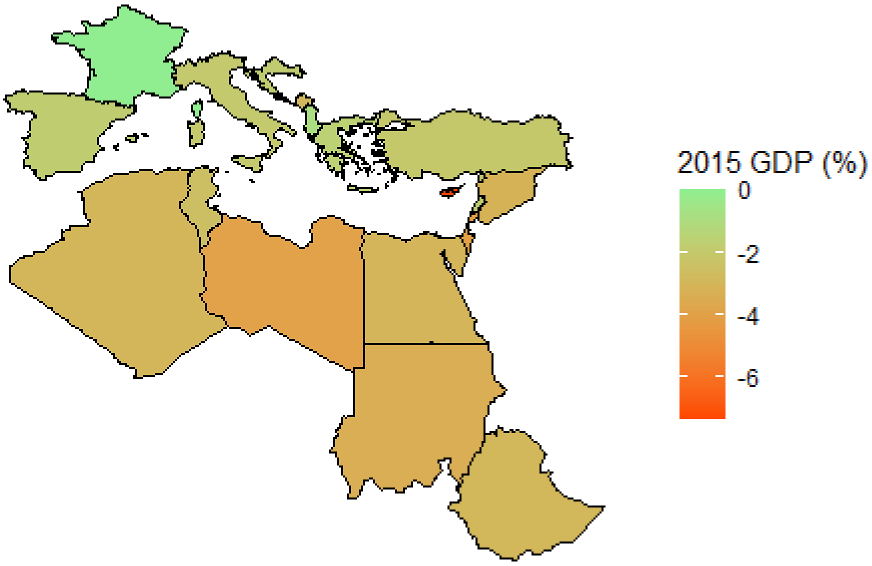

Figure 5: RICE-MED-U0.70. Percentage of output loss under the OPT Scenario (2015), Mediterranean Countries

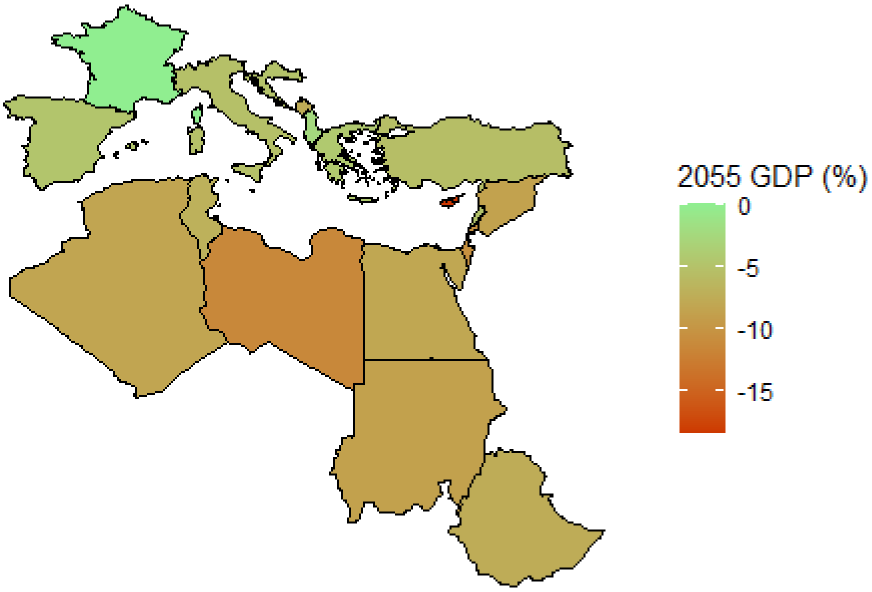

Figure 6: RICE-MED. Percentage of output loss under the OPT Scenario (2055), Mediterranean Countries

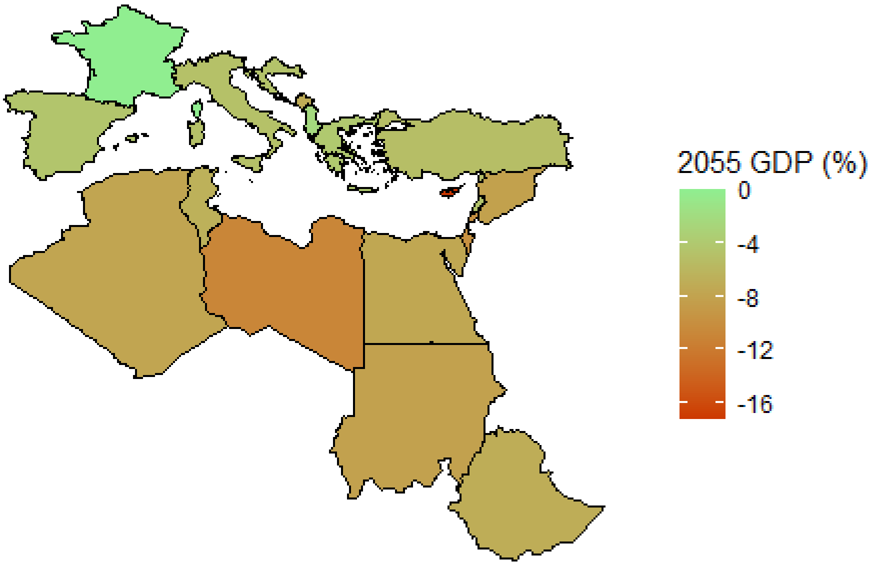

Figure 7: RICE-MED-U0.30. Percentage of output loss under the OPT Scenario (2055), Mediterranean Countries

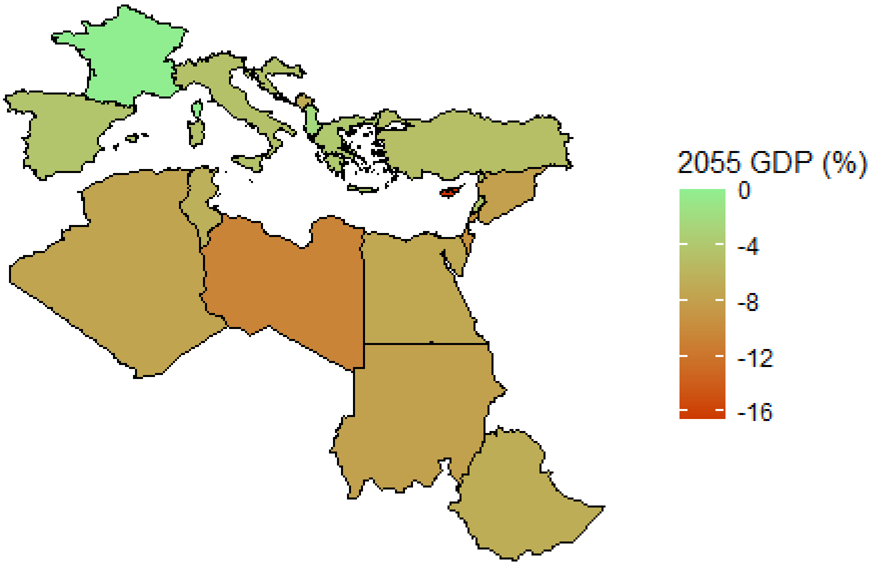

Figure 8: RICE-MED-U0.50. Percentage of output loss under the OPT Scenario (2055), Mediterranean Countries

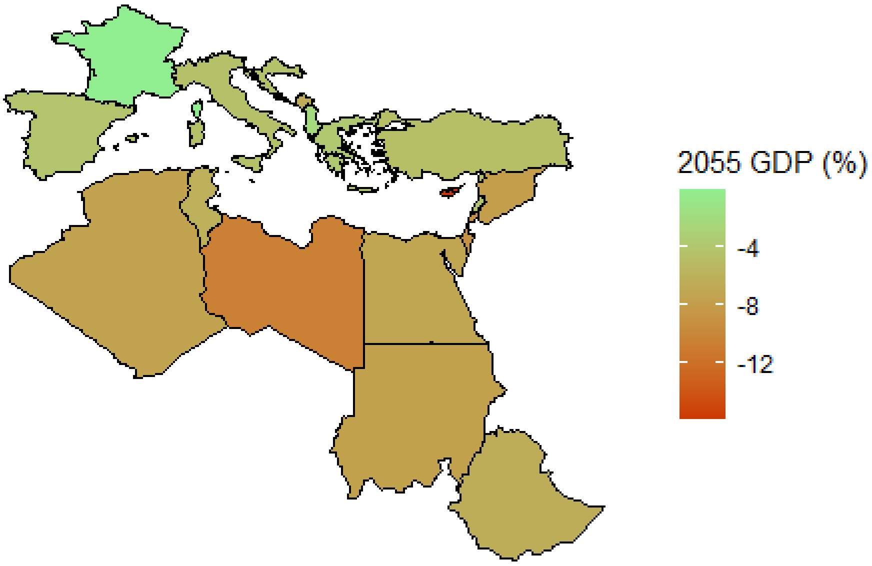

Figure 9: RICE-MED-U0.70. Percentage of output loss under the OPT Scenario (2055), Mediterranean Countries

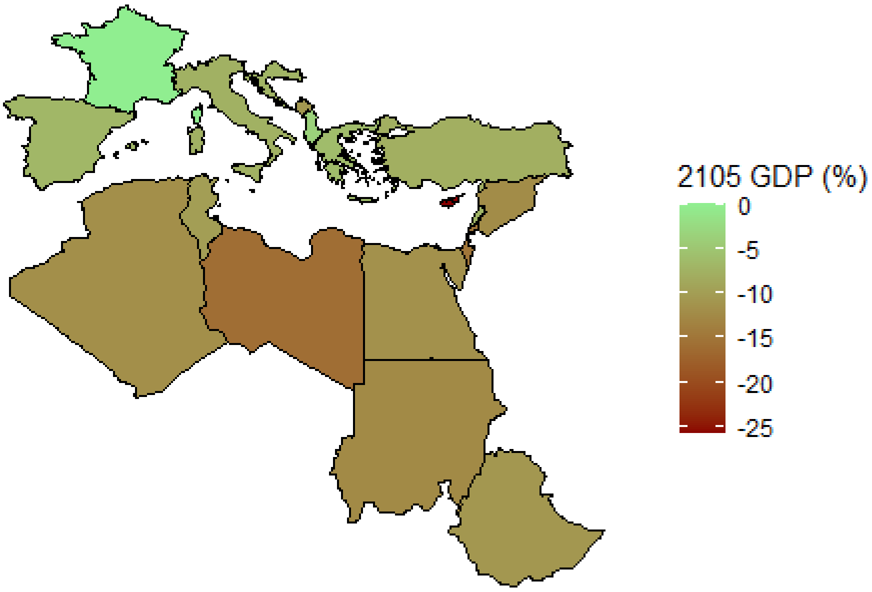

Figure 10: RICE-MED. Percentage of output loss under the OPT Scenario (2105), Mediterranean Countries

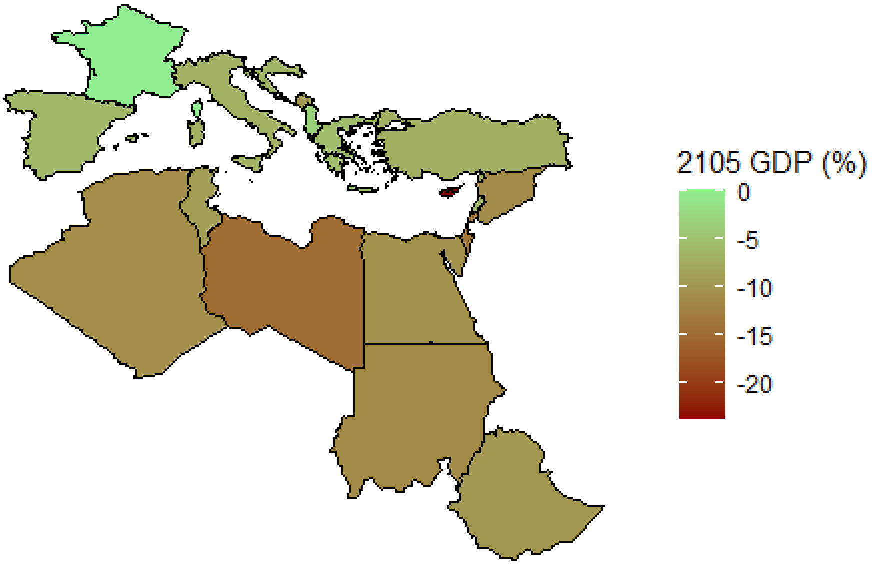

Figure 11: RICE-MED-U0.30. Percentage of output loss under the OPT Scenario (2105), Mediterranean Countries

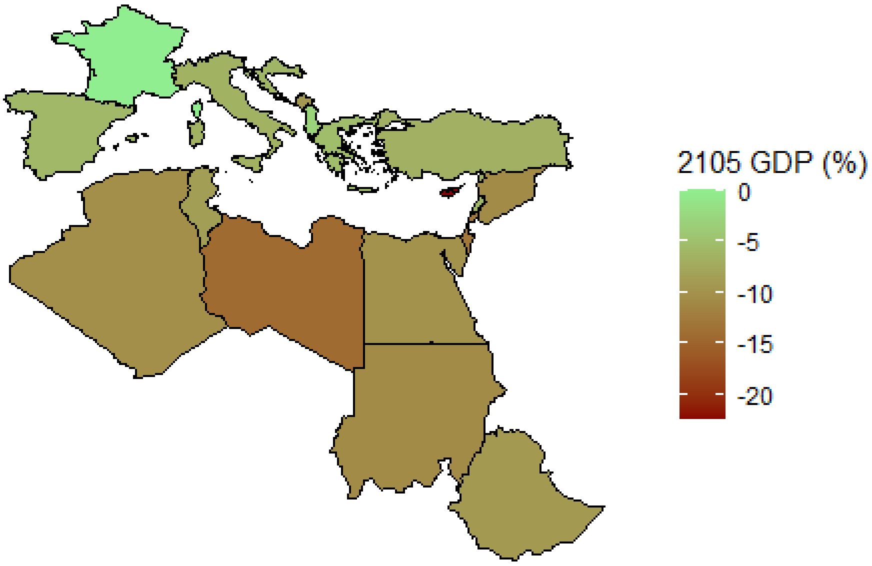

Figure 12: RICE-MED-U0.50. Percentage of output loss under the OPT Scenario (2105), Mediterranean Countries

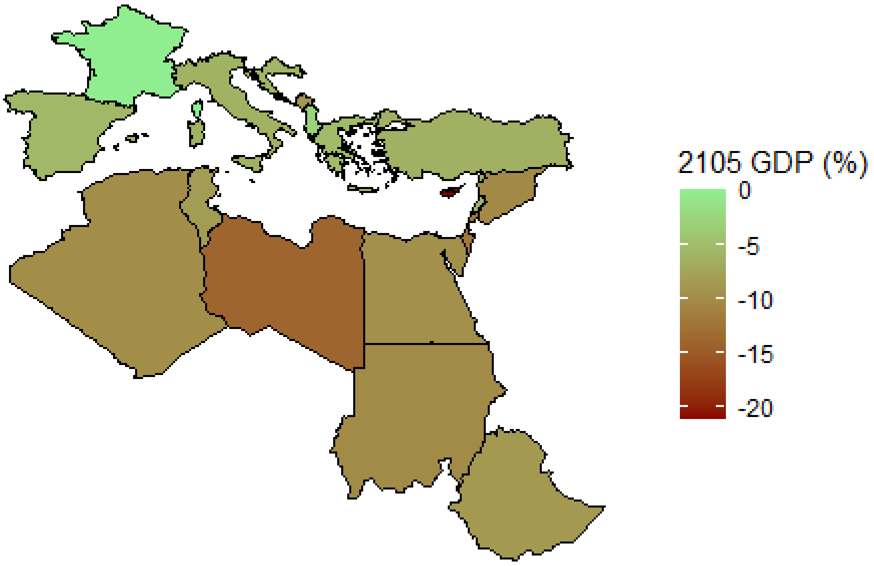

Figure 13: RICE-MED-U0.70. Percentage of output loss under the OPT Scenario (2105), Mediterranean Countries

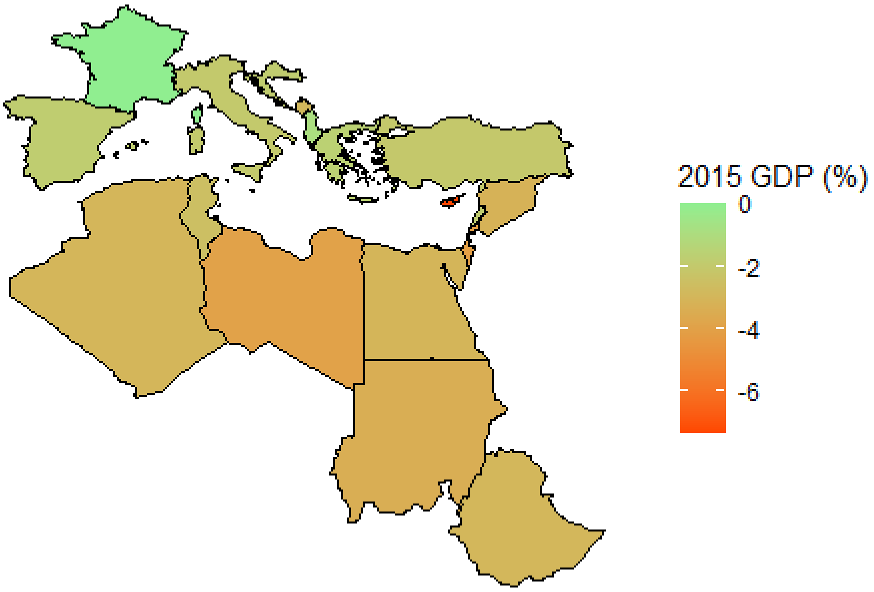

Figure 14: RICE-MED. Percentage of output loss under the TL Scenario (2015), Mediterranean Countries

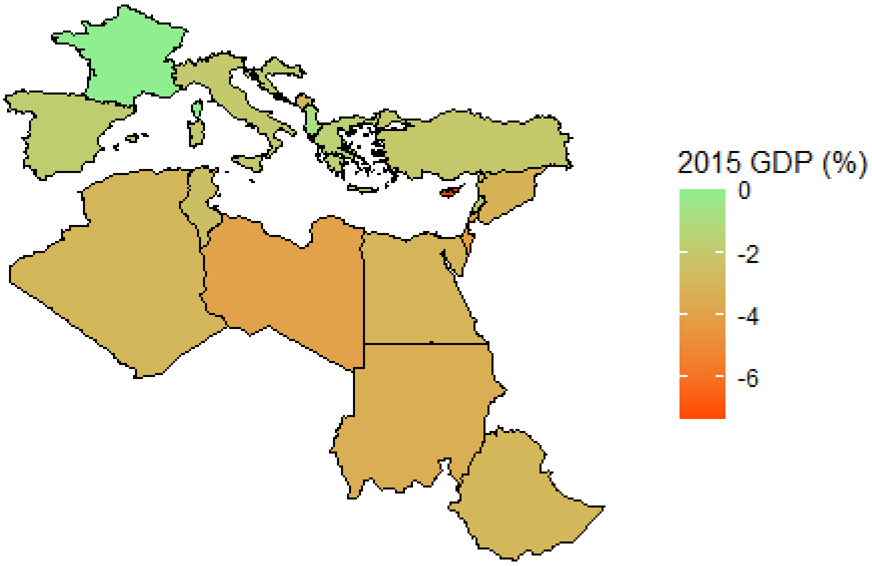

Figure 15: RICE-MED-U0.30. Percentage of output loss under the TL Scenario (2015), Mediterranean Countries

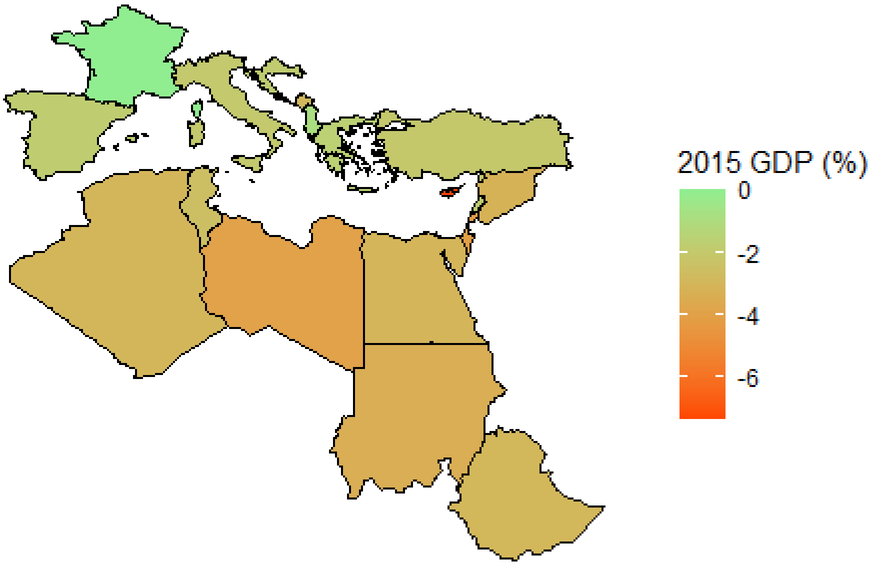

Figure 16: RICE-MED-U0.50. Percentage of output loss under the TL Scenario (2015), Mediterranean Countries

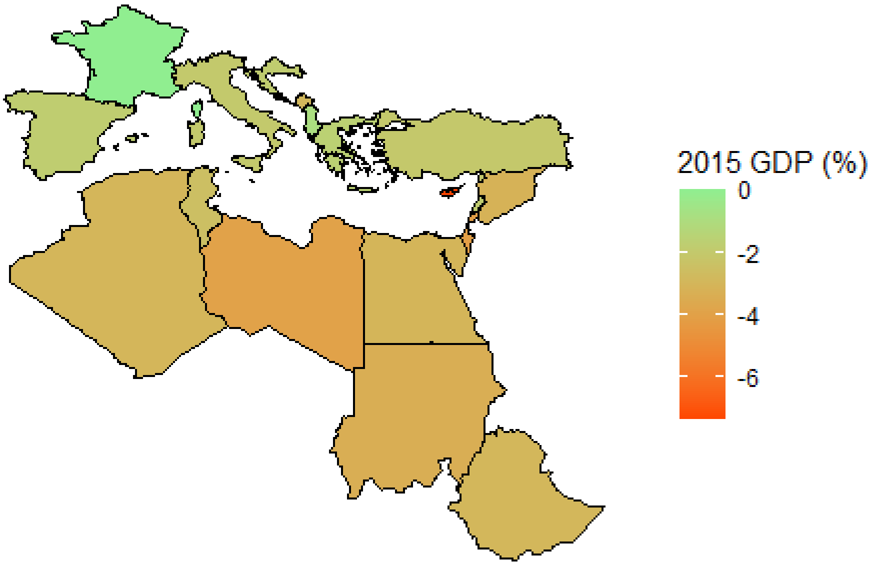

Figure 17: RICE-MED-U0.70. Percentage of output loss under the TL Scenario (2015), Mediterranean Countries

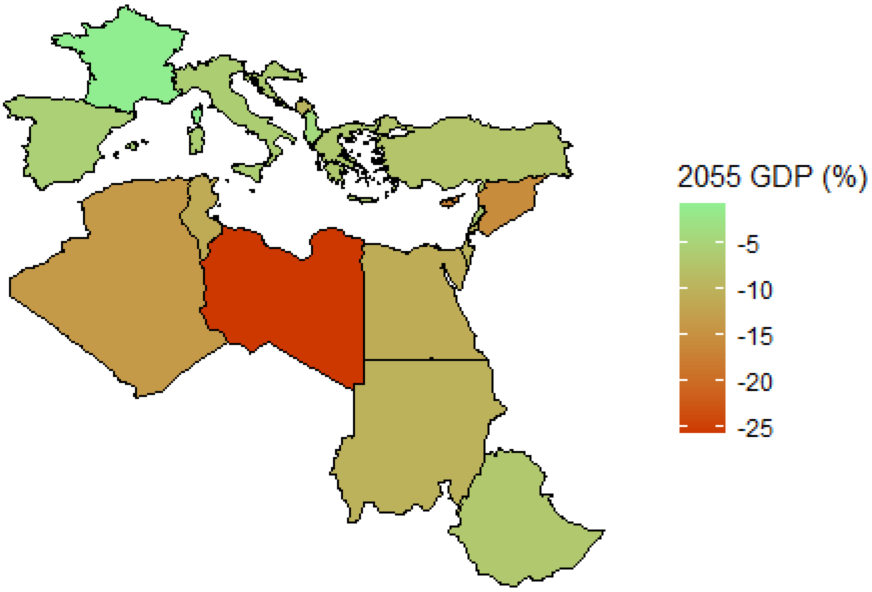

Figure 18: RICE-MED. Percentage of output loss under the TL Scenario (2055), Mediterranean Countries

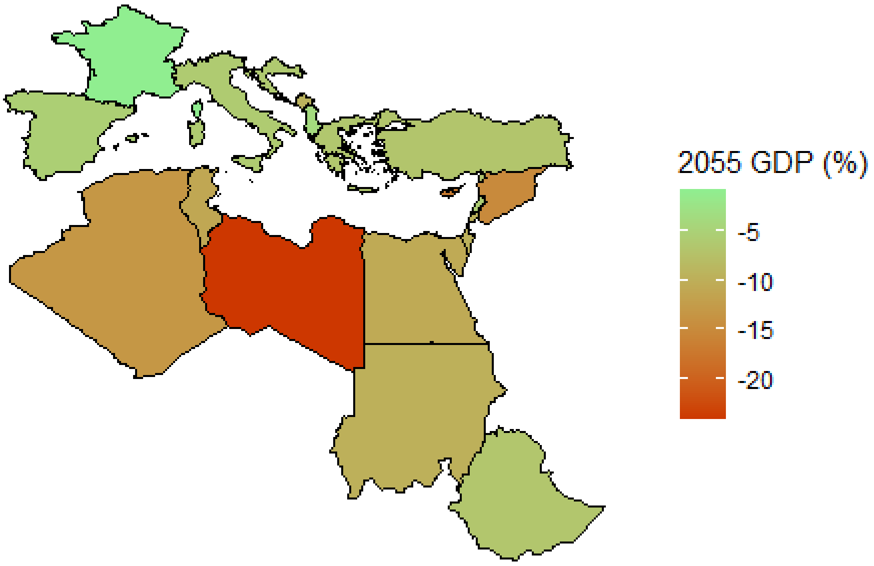

Figure 19: RICE-MED-U0.30. Percentage of output loss under the TL Scenario (2055), Mediterranean Countries

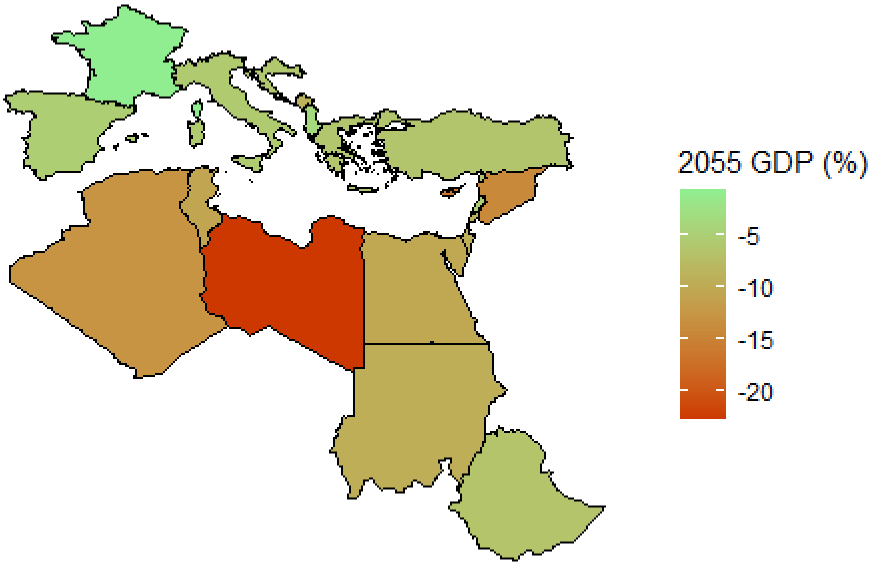

Figure 20: RICE-MED-U0.50. Percentage of output loss under the TL Scenario (2055), Mediterranean Countries

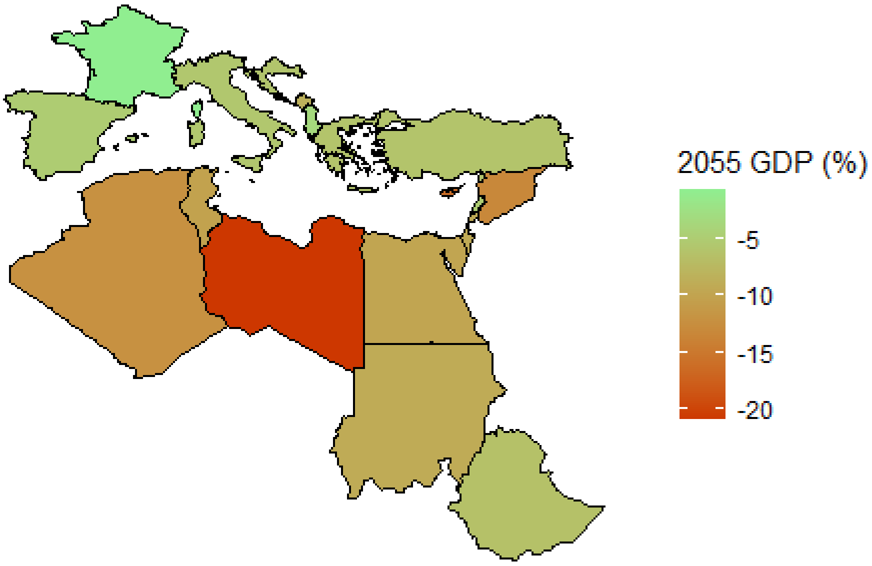

Figure 21: RICE-MED-U0.70. Percentage of output loss under the TL Scenario (2055), Mediterranean Countries

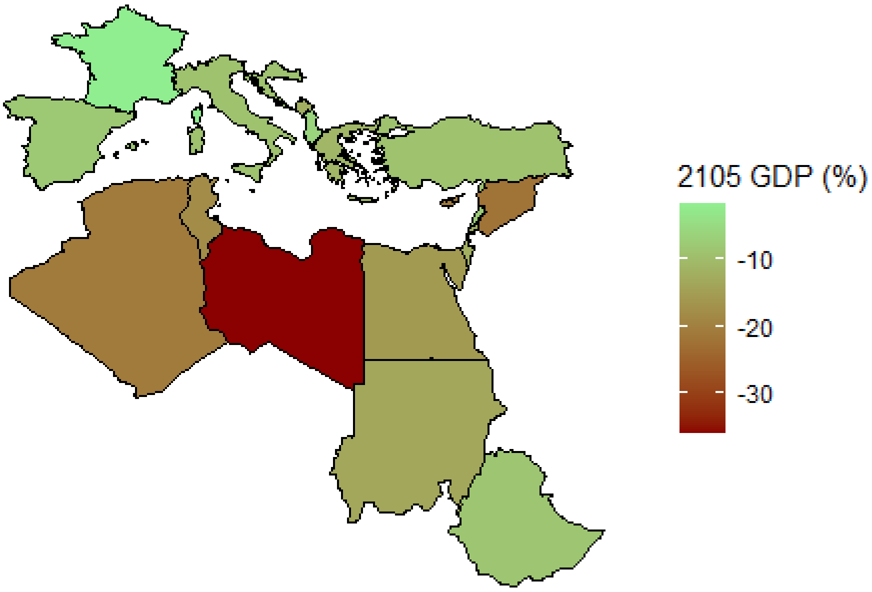

Figure 22: RICE-MED. Percentage of output loss under the TL Scenario (2105), Mediterranean Countries

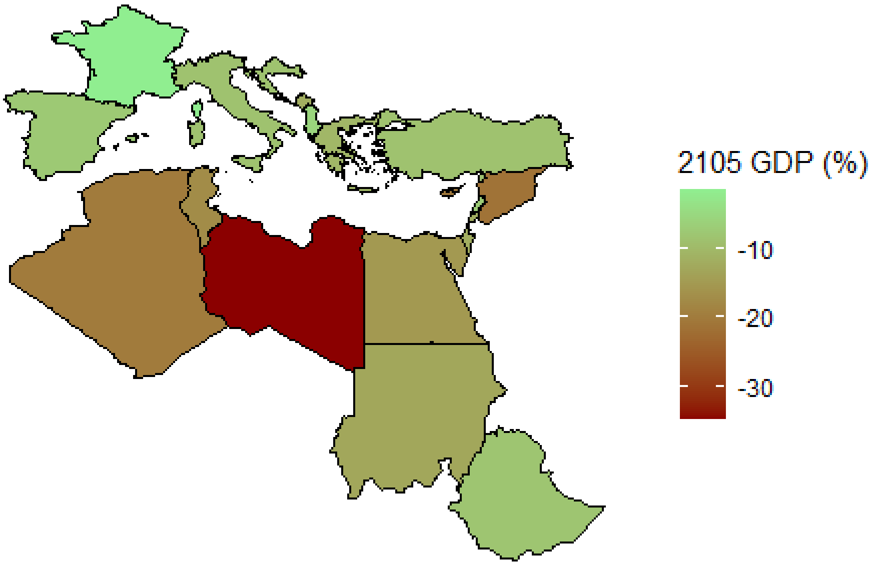

Figure 23: RICE-MED-U0.30. Percentage of output loss under the TL Scenario (2105), Mediterranean Countries

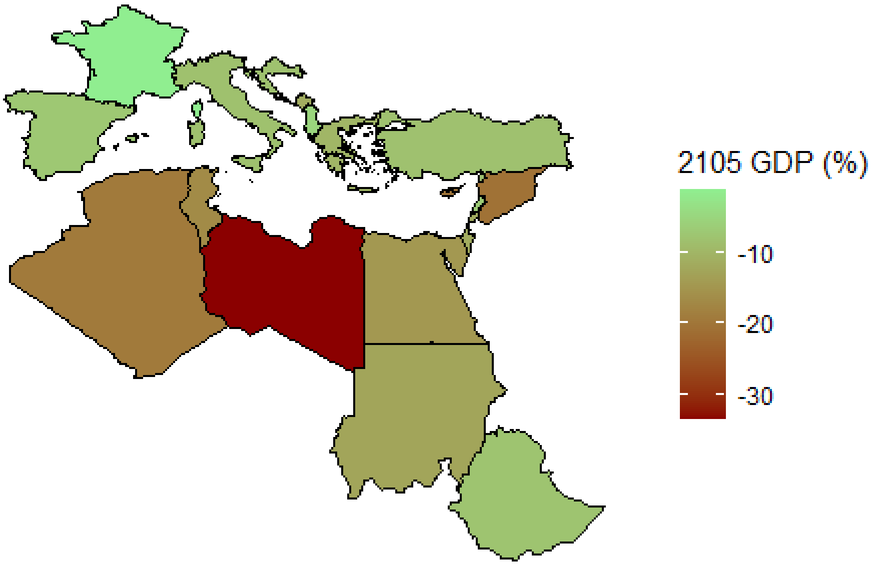

Figure 24: RICE-MED-U0.50. Percentage of output loss under the TL Scenario (2105), Mediterranean Countries

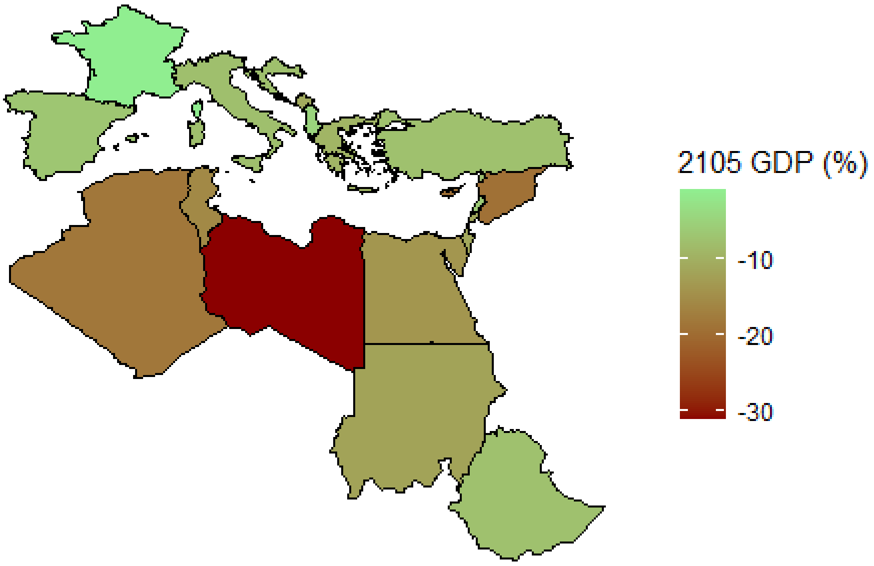

Figure 25: RICE-MED-U0.70. Percentage of output loss under the TL Scenario (2105), Mediterranean Countries

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