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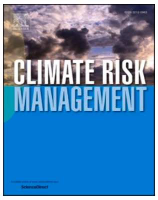

# Synergies of CGE and IAM modelling for climate change implications on WEFE nexus in the Mediterranean

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## ABSTRACT

The Mediterranean Sea Basin (MSB) is experiencing increasing pressure on its natural resources due to climate change (CC) and demographic growth, posing challenges to water and food sustainability. In line with the United Nations Sustainable Development Goals and the Water-Energy-Food-Ecosystems (WEFE) nexus, this study projects shifts in welfare and food security under various climatic conditions. Agriculture, a sector that is highly vulnerable to climate variability, depends predominantly on rainfed croplands, which constitute 70-100% of agricultural land in most MSB countries. The remaining areas are irrigated by climate-dependent water bodies such as rivers and aquifers.

A comprehensive analysis of the WEFE nexus is essential for a coherent examination of climate policy and future pathways for the economy and the natural environment. Using a dual-modeling approach, this research assesses the impacts of alternative water sources and irrigated agriculture within the MSB amidst uncertainties of CC-driven extreme events. A global computable general equilibrium (CGE) model, based on the GTAP framework, was used to examine inter-sectoral and inter-regional impacts. In tandem, the Integrated Assessment Model (IAM) based on the RICE-99 framework quantifies the uncertainties related to future extreme climatic events. This synergistic approach provides a comprehensive assessment of CC impacts, integrating adaptation strategies for alternative water sources and irrigated agriculture, as well as mitigation strategies to reduce greenhouse gas emissions from energy production.

The focus on cross-sectoral and multi-scale management of water, ecosystems, and food in the MSB was embedded into the economic models - CGE GTAP-AW and IAM RICE-MED, to analyze the impacts of CC adaptation and mitigation strategies on the WEFE nexus. The results indicate a reduced impact of CC on food production, and provide a comprehensive overview of potential adaptation and mitigation measures to reduce food security risks in the MSB. These findings are

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crucial for policymakers to promote sustainable water and agricultural practices in the face of a changing climate.

## 1. Introduction

The Mediterranean Sea Basin (MSB) is currently facing a unique combination of challenges, including climate change (CC) and demographic growth, which are putting significant strain on its natural resources. This escalating pressure threatens the sustainable provision of water and food, vital for the region's ecological and economic stability (Ali et al., 2022).The surge in greenhouse gas (GHG) emissions is primarily caused by fossil fuel consumption for energy generation due to the intertwining of human activities and natural processes (Mardani et al., 2019). This increase in emissions is closely associated with industrial development. However, its impacts, including altered precipitation patterns, heightened droughts, and extreme weather events, are expected to affect certain regions and sectors more severely. Projections for CC in the MSB suggest a potential reduction in rainfall of 4-27 percent and a temperature increase ranging from +2.2°C to +5.1°C by the end of the century (Galeotti, 2020; Kutiel, 2019). Given the current situation, there is significant potential for a decline in welfare in the MSB. Forecasts indicate that agricultural output will decrease by mid-century (Ali et al., 2022). This situation highlights the urgent need for sustainable management of the agricultural and water sectors, which are integral components of the MSB region's economic framework. However, there has been a historical tendency to overvalue economic and social benefits while neglecting negative externalities. This has led to the degradation of ecosystem services (ES), which in turn has put essential water and food provisioning at risk (Palatnik and Nunes, 2015; FAO, 2022). The United Nations Sustainable Development Goals (SDGs) aim to achieve food security, promote sustainable agriculture and improve water management. They also call for urgent action to mitigate the adverse impacts of climate change and protect marine and terrestrial ecosystems. The goals of Zero Hunger and Clean Water Supply are among the six most critical development objectives (United Nations, 2022).

The Mediterranean Strategy for Sustainable Development (MSSD) 2016-2025 is an inclusive policy framework that aims to implement and monitor the 2030 SDGs of the Mediterranean region at regional, sub-regional, national, and local levels. Its initiatives focus on managing the Water-Energy-Food-Ecosystems (WEFE) Nexus in the region (UNEP, 2020). Agriculture is highly vulnerable to climate variability, with 70-100% of global food production relying on rainfed croplands and pastures (FAO, 2022). The equilibrium in croplands is maintained through irrigation sourced from climate-dependent water bodies such as rivers and aquifers (D'Odorico et al., 2019). Climate change is disrupting food security by increasing temperatures, altering precipitation patterns, and increasing the frequency of certain extreme events. Warming, exacerbated by drought, has led to significant yield declines in various parts of the Mediterranean, particularly impacting food security in arid regions of Africa. Heat stress diminishes fruit set and accelerates the growth of annual vegetables, resulting in yield losses, compromised product quality, and a rise in food loss and waste (IPCC, 2019). The livestock sector, which is also affected by water scarcity, requires supplementary feed, shade, breed adaptation, and alternative market strategies to address these challenges (Halimani et al., 2021). The impact of climatic factors such as temperature, precipitation, and soil radiation on the agricultural sector is well-documented. There is extensive discourse on the interplay between CC, natural water scarcity, GHG emissions, and the resulting economic and agricultural impacts (Khan et al., 2020; Magnan et al., 2023; Baum et al., 2016; Prasad et al., 2023).

The use of alternative water sources (AWS) is a vital adaptive measure to improve freshwater availability and ensure food security sustainability. These sources, which encompass treated wastewater and desalinated water, are increasingly recognized for their economic significance in alleviating natural freshwater deficits and maintaining continuous food provision (Luckmann et al., 2020; Khadem et al., 2021; Al-Zubari et al., 2018; Baum et al., 2016). In 2016, AWS accounted for 33% of Israel's total water supply, primarily used by the agricultural sector (Palatnik, 2019). Diversifying water resources is crucial not only at the national level but also regionally, especially in the Mediterranean, where climate change is expected to exacerbate natural freshwater scarcity (FAO, 2022). AWS have significant economic value due to their role in mitigating natural freshwater shortages and supporting food provision (Raviv et al., 2022). Recent discussions suggest expanding the definition of 'blue water' to include desalinated and treated brackish water, in addition to groundwater and surface water. This reflects their growing importance in water resource management (Fridman et al., 2021). Therefore, the strategic advancement of AWS is essential, especially in water-stressed regions where they are expected to play an increasingly vital role in the coming decades (Palatnik et al., 2011; FAO, 2020). Researchers worldwide are showing continued interest in water reuse as a strategy to mitigate the impacts of climate change on water scarcity. Asia has seen a significant number of publications, with China, India, and Israel being the primary contributors to research. North America follows, with the USA leading in publications, followed by Canada and Mexico. Among European countries, Spain, Italy, Germany, and Greece have made significant contributions. In Africa, Egypt, Ghana, and Kenya are the main contributors to publications (Rao et al., 2023).

The economic assessment of AWS must take into account direct impacts, indirect and structural economic changes, and externalities. Direct costs mainly arise from the energy requirements of water desalination and purification processes (Luckmann et al., 2020; Khadem et al., 2021). Indirect effects result from shifts in water supply dynamics, which affect sectors such as agriculture (Bardazzi and Bosello, 2021). For example, when local water resources are insufficient for domestic food production, the need to import food requires the use of air and water transport methods. This results in significant emissions of greenhouse gases (GHGs) and local pollutants (Windsperger et al., 2020). Consequently, externalities refer to the costs associated with environmental degradation and the emissions of GHGs and local air pollutants from waste byproducts of water desalination and purification (treatment) processes (Pistocchi et al., 2020; Shanafield et al., 2020).

The WEFE nexus has been identified as a priority for sustainable development in line with the SDGs (European Commission, 2021).

To achieve the WEFE nexus objectives, policies aimed at sustainable water management and the adoption of innovative agricultural technologies are crucial (Raviv et al., 2022; Kahil et al., 2019). These policies will ensure the secure provision of food and water, as well as efficient utilization of natural resources to mitigate potential climate change impacts (Bozoglu et al., 2020; Tewabe et al., 2021). Technological advancements in irrigation, such as drip or precision irrigation, have been shown to enhance water efficiency. These enhancements reduce water consumption and support more sustainable food provisioning compared to traditional methods (Soulis and Elmaloglou, 2018; Benyezza et al., 2021).

Despite the potential advantages of AWS for households, industry, agriculture, and ecosystems, there is still a significant gap in thoroughly assessing its costs and benefits (Raviv et al., 2022). This article makes a novel contribution in the evaluation of the impacts of climate change by simultaneously using the GTAP-AW (alternative water) and RICE-MED models. The GTAP-AW model integrates alternative water sources into a global Computable General Equilibrium (CGE) framework for the first time, representing a pioneering advancement in water economics and policy analysis. At the same time, the RICE-MED model, which is part of the Integrated Assessment Model (IAM) family, enhances the analysis by incorporating a critical layer that reflects the uncertainties surrounding future catastrophic climate events. This innovative dual-model approach enables a robust and nuanced examination of the impacts of climate change, offering a crucial perspective on the interplay between food and water security in the MSB region. It emphasizes the importance of aligning economic projections with environmental uncertainties, setting a new standard for comprehensive climate-related economic analysis.

This study offers a unique perspective on the intersection of climate policy, water management, and agricultural sustainability by incorporating the policy aspect of the Social Cost of Carbon (SCC). Its findings are essential for policymakers and stakeholders in the Mediterranean region and beyond.

## 2. WEFE nexus in macroeconomic models

The analysis of the WEFE nexus within macroeconomic modeling is a widely discussed topic. Various methodologies are used to evaluate the impact of water management practices on food security and the economy. Economists usually distinguish between two types of models: CGE models (Walras, 2013) and IAMS. CGE models consider international trade patterns across all markets and sectors (Palatnik and Roson, 2012; Delzeit et al., 2020), while IAMs examine the relationship between climate and the economy, with some featuring a multi-regional perspective (Weyant, 2020; Yang, 2020).

The development of the Shared Socioeconomic Pathways (SSPs) has recently provided a framework to describe various alternative futures of societal development (IPCC, 2022). These pathways, together with the Representative Concentration Pathways (RCPs), provide a toolkit for the climate change research community, enabling integrated, multi-disciplinary analyses. The SSPs delineate five distinct trajectories of global development with varying levels of challenges, while the RCPs provide information on the potential impacts of mitigation and adaptation efforts, including their ability to mitigate the impacts of climate change (Fricko et al., 2017; Riahi et al., 2017). One method to evaluate mitigation efforts and their associated costs is by measuring the social cost of carbon capture and sequestration (SCCS). This metric represents the potential impacts of greenhouse gas emissions on future scenarios (IPCC, 2022; Herzog et al., 2021; Butnar et al., 2020).

Two distinct aggregate economic models are examined, each approaching agriculture and the impacts of climate change differently. The aim of this article is to illuminate various dimensions of climate change impacts on the WEFE nexus and economic growth.

### 2.1. CGE

CGE is a macroeconomic modeling approach that intricately examines the interconnectedness between regional and national trade dynamics across diverse market sectors. It forecasts potential socioeconomic scenarios that may impact human wellbeing. These models embrace nonlinear substitution possibilities and intricate supply-demand interactions across multiple sectors. They integrate macro-variables and mechanisms to achieve equilibrium across aggregates and all markets. Consequently, the demand for any good depends on the prices of all other goods and income, which in turn depend on wages, profits, and rents influenced by technology, factor supplies, and production—where production, in a cyclical manner, is contingent upon sales (i.e., demand). Prices are intertwined with wages and profits, and vice versa. The simultaneous determination of prices and incomes reflects both the direct and indirect impacts of policies related to CC. Consequently, the CGE model offers a nuanced understanding of real-world implications and has a significant advantage in evaluating welfare changes across the entire economy (Hertel and Liu, 2019).

The Global Trade Analysis Project (GTAP) is an example of a CGE model. It is a multi-region, multi-sector model that operates under the assumption of perfect competition. The model features a general production function with constant returns to scale (Hertel, 1997). The GTAP model also offers a diverse array of closure options, including considerations such as unemployment, tax revenue replacement, and trade balance. In addition, it provides a range of partial equilibrium closures, allowing for comparisons with studies based on partial equilibrium assumptions (Damania, 2020; Delzeit et al., 2020).

CGE models demonstrate how water-related disturbances, such as droughts, and deviations from a hypothetical equilibrium, can impact food provisioning and global economic growth (Hertel and Liu, 2019). Nonetheless, most studies using CGE models face difficulties in accurately representing the value of water, especially in nations with abundant water resources but without a clear assessment of their economic value (Baum et al., 2016; D'Odorico et al., 2020; Baldos et al., 2019). Typically, these studies only model potable water (Wittwer, 2019). Haqiqi et al. (2016) distinguish between rainfed and irrigated agriculture, but predominantly focus on a single water type for irrigation. While this modeling approach makes a significant contribution, it may not be suitable for economies reliant on AWS. This is because it fails to account for constraints associated with utilizing low-quality water sources and may misestimate an economy’s capacity to cope with increasing natural water scarcity (Damania, 2020; Bardazzi and Bosello, 2021).

CGE models that focus on the WEFE nexus typically analyze individual economies or river basins. For example, research has been conducted on the management of water and land quality in Egypt, assessing its implications on crop yield and associated costs (Osman et al., 2019). Similarly, studies have explored water management strategies in Israel (Baum et al., 2016; Luckmann et al., 2020; Yerushalmi, 2018), Morocco (Taheripour et al., 2020), as well as changes in water demand across the Nile river basin spanning Egypt, Sudan, and Ethiopia (Kahsay et al., 2019).

Bardazzi and Bosello (2021) observed that most studies using global CGE models focus on a ’first-order’ cost assessment related to productivity rather than explicitly considering the decline in water availability (Bardazzi and Bosello, 2021). Consequently, many of these studies fail to capture the subsequent ’second-round’ effects of structural economic adjustments that result from changes in natural resources, particularly water, across various economic sectors such as agriculture, energy, and industry. For further literature on CGE modeling of the WEFE nexus, readers may refer to Raviv et al. (2022).

Recently, a significant advancement in CGE modeling was introduced with the GTAP-AW model. For the first time, this model explicitly integrates alternative water sectors as intermediate inputs and goods into a global CGE framework (Palatnik et al., under review). GTAP-AW accounts for direct and the second-round effects of substitutability of water sectors that differ for quality and costs, on economic sectors. This unique model is a significant step forward in assessing climate adaptation strategies. It highlights the pivotal role of AWS in maintaining food security and economic stability in the MSB and the global economy.

### *2.2. IAM*

Over the past three decades, Integrated Assessment Models (IAMs) have been essential in guiding policy decisions and scholarly inquiry by encompassing both economic and natural processes contributing to GHG emissions. Weyant distinguishes between two types of IAMs – detailed process models and benefit–cost analysis IAMs (Weyant, 2020).

The detailed process models focus on CC mitigation options and impacts with a level of granularity, without necessarily assigning values or aggregating all potential impacts into a single measure of projected climate damages. Notable examples of this type include the MESSAGE-GLOBOIM (Fricko et al., 2017) and IMAGE (Stehfest et al., 2014) models. These models were recently used by IIASA to generate a range of SSP and RCP projected scenarios encompassing various factors such as GDP, population, capital, energy, and land use estimates (Riahi et al., 2017).

The second category of IAMs adopts a more aggregated approach, focusing on determining carbon emissions trajectories and carbon prices that optimize global welfare. An example of this type is the Dynamic Integrated Climate-Economy (DICE) model, which projects the optimal cost of carbon (Nordhaus, 2017).

The Regional Integrated model of Climate and the Economy (RICE) is an advancement of the DICE model. It focuses on regional economic damages caused by climate change within a dynamic framework that intertwines optimal economic growth with a climate module (Nordhaus and Yang, 1996). The overarching structure of the RICE model integrates optimal economic growth with a climate module, a feature well-known among IAMs that enables long-term simulations of the relationship between climate and the economy. Countries worldwide are grouped into different regions, allowing for the disaggregation of economic damages associated with climate change at a more detailed spatial level. In the context of analyzing the WEFE nexus, this aspect is significant due to the spatial disparities in the economic impact of climate change.

The outcomes of the model include the carbon tax, i.e. the Social Cost of Carbon (SCC), which represents the economic expense associated with an additional ton of carbon dioxide emissions (Nordhaus, 2017). It is important to note that this value is also influenced by the level of regionalization (Schumacher, 2018).

The initialization of the RICE-MED represents a significant improvement over the original RICE model. It takes into account the economic equilibrium within each country or region, as well as the disaggregation of the energy sector into various fossil-fuel-based energy plants. Additionally, the RICE-MED-U model introduces uncertainty regarding potential future catastrophic events triggered by temperature fluctuations (Castelli et al., 2023).

## 3. Modeling framework

The study uses both GTAP-AW and RICE-MED to evaluate the impacts of CC during the years 2050-2055. This dual-model approach, delineated below, offers a comprehensive assessment of the effects of CC on food and water security in the MSB. It underscores the innovative integration of projections from IAM, which account for climate-related uncertainties, with the explicit representation of AWS, irrigated agriculture, and broader economic activities within the CGE model (Palatnik et al., under review; Castelli et al., 2023).

### *3.1. The GTAP-AW framework*

GTAP-AW builds upon the foundational GTAP platform (Hertel, 1997) and its associated database GTAP10A (Aguiar et al., 2019). It introduces desalinated and treated water, as well as irrigated agriculture, as distinct economic sectors. The AWS sectors are conceptualized in conjunction with the freshwater industry, encompassing activities ranging from extraction and collection to treatment and distribution of water to end-users. To accurately represent the dynamics of irrigated agriculture, which relies on various water sources, the water sector is divided into three discrete subsectors. The agricultural sector is also disaggregated into rain-fed and irrigated subsectors through a split procedure (Horridge, 2008). The GTAP database distinguishes these three water-related and two agricultural sectors as separate activities and commodities. This is based on their consumption of intermediate inputs and their dependency on capital, natural resources, labor, and land availability (Palatnik et al., under review).

The GTAP-AW innovation regarding irrigated agriculture includes several important aspects: (1) Implementation of a new regionalization approach, where all Mediterranean nations are individually considered at the country level, facilitating a more detailed assessment of CC economic impacts (Horridge, 2019); (2) Introduction of new alternative water sectors and differentiation between irrigated and rainfed agriculture sectors, calibrated to the year 2014 and available in all MSB countries (Horridge M. , 2008; FAO, 2014; Plat et al., 2019); (3) Projection of the 2050 Shared Socioeconomic Pathway 2 (SSP2) baseline in GTAP-AW, simulating the effects of CC on the economy as defined by the Intergovernmental Panel on Climate Change (IPCC) (Riahi et al., 2017; Kuiper et al., 2020; Fricko et al., 2017); (4) Projection of the SSP2-Representative Concentration Pathway 4.5 (RCP4.5) scenario in GTAP-AW, simulating the effects of mitigation efforts to reduce emissions using the RCPs (RCP 2.6, 4.5, 6.0) corresponding to different levels of mitigation efforts (IPCC, 2022; Fricko et al., 2017; Riahi et al., 2017).

The study uses the standard static version 7 of RunGTAP (Corong et al., 2017). This model allows certain sectors to generate multiple products and multiple sectors to produce the same or closely substitutable products. This capability is especially important in the context of agricultural food production, which can arise from various sources, such as irrigated and rainfed practices (Chepeliev et al., 2021).

Figure 1 illustrates the projections of both the original GTAP and modified GTAP-AW models for total agricultural output in 2050 across different climate scenarios. For the purpose of comparison with the results from the RICE-MED model presented below, the output value of the agriculture sector includes contributions from rainfed and irrigated crops, as well as livestock.

GTAP-AW introduces enhanced adaptability to CC through AWS and irrigated crops, while scenarios RCP4.5 and RCP6.0 reflect CC mitigation efforts. Comparing the projections to those made by GTAP for the SSP2 baseline, GTAP-AW forecasts an increase in output under RCP4.5. This is particularly noticeable in the North African countries, despite the additional costs associated with adaptation and mitigation efforts (Palatnik et al., under review). Under RCP6.0, the additional mitigation measures lead to a slight decrease in output in the developed countries of Southern Europe, and to a minor increase in output in the developing countries of North Africa.

These results serve as the initial stage before integration with the RICE-MED measures of uncertainty arising from CC extreme events.

### 3.2. The RICE-MED model

The primary innovations of the RICE-MED climate and economy model (Castelli et al., 2023) include several key aspects: (1) An updated calibration of the RICE-99 model (Nordhaus and Boyer, 2000) to the base year 2015, employing their original initialization methodology; (2) Introduction of a new regionalization approach, wherein all Mediterranean nations are individually considered at the country level, enabling a more detailed assessment of CC economic impacts compared to the original version; (3) Incorporation of a novel damage function based on Golosov et al. (Golosov et al., 2014); (4) Extension of the RICE-MED model with uncertainty (RICE-MED-U), following methodologies proposed by Castelnuovo et al. (2003), facilitating the incorporation of societal awareness regarding potential future catastrophic events triggered by temperature increases and variations over time; (5) Application of the model to assess economic damages linked to the effects of climate change on the agricultural sector of Mediterranean countries, utilizing data provided by Roson and Sartori (2016).

The RICE-MED BAU scenario serves as a reference point, depicting a baseline condition that is not affected by uncertainty associated to the consequences of climate change. Conversely, in the RICE-MED-U version, uncertainty arises from society's inability to determine the precise global temperature threshold at which a catastrophic event might occur. Consequently, this lack of certainty forces individuals to estimate the probability of a climate-related disaster, their chances of survival and the associated consequences in terms of loss of utility. The magnitude of such damages is defined by parameter b: the higher the parameter, the greater the negative consequences (damage) for society in the event of such a disaster.

The RICE-MED model forecasts expected changes up to the year 2305 at 10-year intervals, considering three scenarios: (1) Business As Usual (BAU), where the negative environmental impact linked to climate change remains unaddressed; (2) Social Optimal (OPT) scenario, which incorporates this negative externality into the welfare maximization problem for each region; (3) Temperature Limit (TL), aimed at constraining the temperature rise to below 2°C compared to preindustrial levels by the end of the century.

Both the OPT and TL scenarios closely mirror the conditions of SSP2 RCP4.5 (Riahi et al., 2017). The global CC outcomes considered include atmospheric $CO_2$ concentrations, temperature increases, carbon tax, and economic damages. All these outcomes vary at the regional level and are integrated into the analysis.

The findings from RICE-MED (Figure 2) indicate that there are additional uncertainties and CC risks and damages caused by extreme events beyond the SSP2-RCP4.5 scenario for the years 2050-2055. These factors must be taken into account due to their potential impacts on agricultural output. In the RICE-MED model, the agriculture sector is treated as a unified entity, encompassing both rainfed and irrigated croplands as well as livestock activities (Castelli et al., 2023).

The term "b" denotes the decline in intergenerational utility[1] resulting from the uncertain catastrophic event. Figure 2 illustrates the change in output attributed to uncertainty-induced damage, expressed as a percentage of the country's GDP contributed by the agricultural sector.

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[1] The term *Utility* mentioned here and later in this study means **benefit** and relates to the social welfare function in RICE-MED. See more details in Castelli et al. (2023).

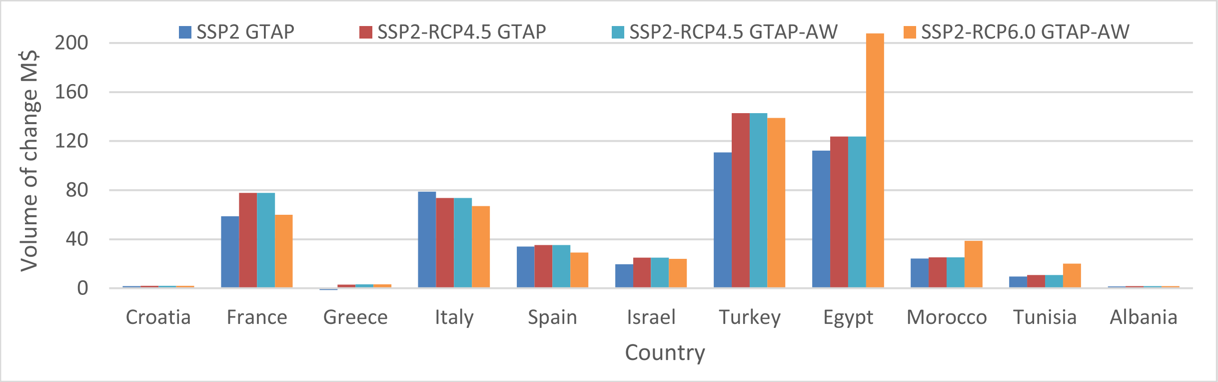

**Fig. 1.** The impact of AWS, irrigation and mitigation on agriculture output in GTAP-AW at 2050

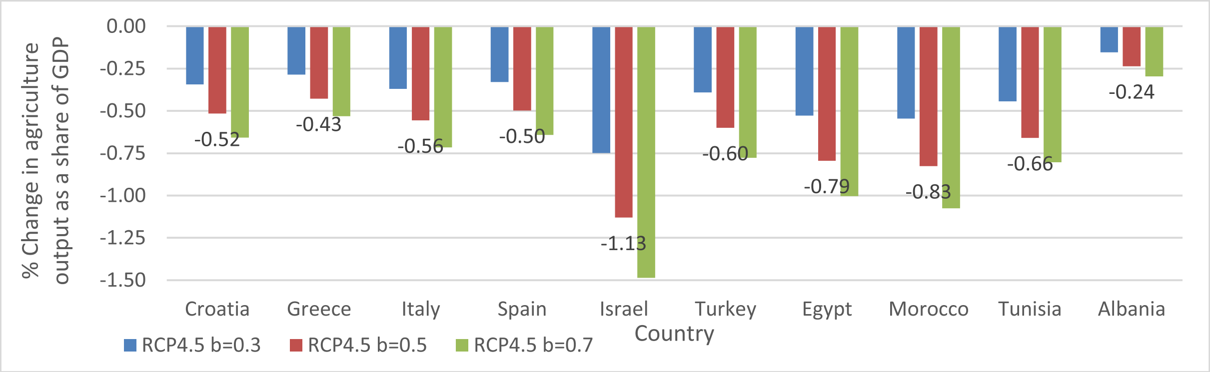

**Fig. 2.** The decrease in the share of agriculture as part of 2055 GDP in RICE-MED *(OPT $0<b<1$ level of uncertainty, compared to BAU $b=0$)*

## 4. Synergy methodology

The remarkable synergy achieved by the GTAP-AW and RICE-MED models is exemplified by their exceptional complementarity. In particular, the outputs of GTAP-AW, which presently do not account for the indirect costs arising from uncertainties related to CC damages, could enhance their accuracy through the integration of RICE-MED's more refined assessments of CC damage and the integration of risk probabilities into its forecasts.

This study underscores the methodologies required to achieve this synergistic integration, with a focus on capturing the additional uncertainties associated with CC damages in the MSB within the global CGE model. This model comprehensively represents economies and incorporates international trade in the analysis. Additionally, the research investigates the implications of adaptation and mitigation strategies on individual countries within the MSB.

The methodological approach to align modeling efforts between IAM and CGE frameworks follows the approach outlined by Delzeit et al. (2020). First, the RICE-MED model simulates GHG emissions under a specified scenario. Subsequently, these emissions are translated into climate impacts and uncertainties surrounding the level of damage caused by catastrophic events affecting agricultural productivity in individual countries (RICE-MED-U).

The estimated shifts in agricultural productivity from RICE-MED are then introduced into the GTAP-AW model as external shocks. This allows for an examination of the resulting impact on the economy, both with and without the implementation of AWS and irrigated crop practices. Thus, this enables an investigation into how CC damage and SCC policies can shape the contribution of AWS and irrigated agriculture practices to agricultural productivity.

The outputs from the GTAP-AW model (Figure 1) and the RICE-MED model (Figure 2) serve as inputs for the modeling scenarios presented in Figure 3 of this study. To incorporate the uncertainty regarding potential damage from CC-driven extreme events, as captured by the RICE-MED-U OPT damage scenarios, into the GTAP-AW model, these scenarios are translated into agricultural shocks reflecting their potential impact on agricultural production in various countries within the MSB.

Furthermore, to align with the definition of the agriculture sector in RICE-MED-U, the scope of GTAP-AW is expanded beyond solely covering croplands to include both croplands and livestock (Figure 3). The extreme event is characterized by the effect of GHG emissions on each country, where GHG levels in the atmosphere are linked to the usage of fossil fuels within each country. Due to France's substantial reliance on nuclear energy in its energy mix, the RICE-MED model, primarily oriented towards fossil fuel analysis, suggests a negligible impact of CC uncertainty on energy supply, SCC, and agriculture in France. Hence, the GTAP-AW climate change

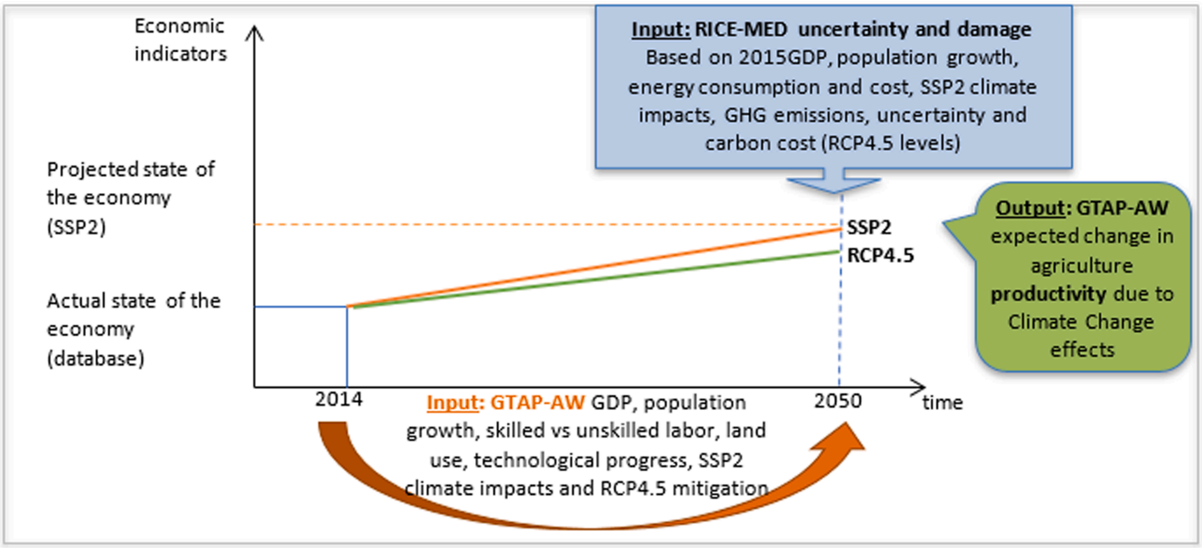

**Fig. 3.** Modeling the RICE-MED CC damage impact on the agriculture sector in GTAP-AW

damage results in this study do not include France.

Incorporating the RICE-MED estimates of climate change impact, which account for uncertainties, into the GTAP-AW model to evaluate both direct and indirect economic ramifications, involves executing the subsequent methodological steps.

Initially, a validation process was undertaken to prevent duplication, verifying that the climate change damage estimated by RICE-MED-U does not duplicate the damage already factored into the GTAP-AW model (Table 1):

a. The outcomes of GTAP-AW depict the baseline conditions of SSP2-RCP4.5, considering the effects of climate change on capital, land, population, and greenhouse gas emission mitigation. The GTAP-AW projection for 2050 relies on the IIASA climate change impacts (Riahi et al., 2017).
b. The findings from RICE-MED-U introduce various climate change damage scenarios atop the SSP2-RCP4.5 baseline conditions for the year 2055. These scenarios vary in uncertainty at two different levels. The first stems from the challenge of determining the probability of a climate-induced disaster. The second refers to the magnitude of the event's consequences, expressed as utility loss. As a result, the disaster impacts agricultural output, represented by the percentage change in the agriculture sector as a component of the 2055 GDP (Figure 2) across each MSB country (Castelli et al., 2023).

Table 1 delineates the attributes of the input data employed in the models, encompassing both GTAP-AW and RICE-MED models, as well as the estimates related to SSP2 and RCP4.5 (Riahi et al., 2017). Notably, the estimations generated by both the GTAP-AW model and the IIASA initially do not encompass the uncertainty associated with climate change-induced extreme events. This gap allows for the incorporation of economic damage scenarios from RICE-MED-U, which do consider uncertainty, alongside the GTAP SSP2-RCP4.5 scenarios. This amalgamation aims to evaluate the potential risks linked to extreme climate events. Hence, our analysis proceeds under the assumption that there is no duplication of climate change damage estimates.

c. The utility loss due to the uncertainty of extreme events in RICE-MED was converted into a GTAP-AW estimate by using the relative change estimates of the RICE-MED OPT scenario compared to the BAU scenario. For example, when examining a potential utility loss at a level of $b=0.3$, the relative change is determined by subtracting the BAU estimate ($b=0$) from the $b=0.3$ estimate (i.e., the estimate at $b=0.3$ minus the estimate at $b=0$), and dividing the result by the $b=0$ estimate. This approach was consistently applied to the damage estimates at $b=0.5$ and $b=0.7$ levels. This methodology safeguards against any baseline effects inherent in the original RICE-MED inputs influencing the damage calculations within the GTAP-AW model, thereby providing a pure percentage change estimate.

**Table 1**
Input information characterization

| Models' Data | SSP2 baseline | RCP4.5 baseline | RCP4.5 uncertainty damage |
|---|---|---|---|
| GTAP | using IIASA estimates | using IIASA estimates | not applicable |
| IIASA | using IPCC estimates | using IPCC estimates | not applicable |
| RICE-MED | BAU scenario | Assuming $b=0$ for OPT/TL scenario | $b>0$ for RICE-MED-U OPT/TL scenario |

Subsequently, the estimated damage, initially defined in RICE-MED as the percentage share of agriculture in GDP, was adjusted to reflect the percentage share of agriculture according to GTAP-AW's estimated GDP. Specifically, we proportionally adjusted the percentage estimates from RICE-MED to match the GDP figures in GTAP-AW. This adjustment assumes that the 2055 estimates from RICE-MED accurately reflect potential changes in GTAP-AW's 2050 GDP figures.

Finally, the CC damage estimates from RICE-MED were transformed into economic shocks in the GTAP-AW model. Since the RICE-MED model allows for the identification of potential changes in agriculture output due to climate change, these changes were translated into the GTAP-AW shock, termed "aintall". This shock reflects a composite intermediate input augmenting technical changes in activity (agricultural sectors such as rainfed crops, irrigated crops, and livestock) in each MSB country region.

The GTAP-AW SSP2-RCP4.5 scenario underwent modifications based on three different levels of RICE-MED-U uncertainty damage estimates (associated with b=0.3, b=0.5, and b=0.7 levels of potential utility loss) to represent the expected changes in agriculture output and GDP.

The outcomes of the GTAP-AW simulations, which include adaptation, mitigation and uncertainty related to CC-driven extreme events, are outlined in the following section.

## 5. Results

The comprehensive examination utilizes a dual-model strategy to analyze the economic consequences of potential CC impacts, with a specific focus on the WEFE nexus and the agricultural sector. By incorporating estimates from the RICE-MED-U model, which quantifies the uncertainty linked to climate-induced extreme events and their consequences, the GTAP-AW model accommodates three distinct levels of damage shocks derived from the RICE-MED-U model.

Figure 4 depicts the expected percentage variations in agricultural output, encompassing forecasts for both rainfed and irrigated crops, as well as estimates for livestock. The findings unveil a diverse impact across MSB countries. Notably, nations like Italy, Spain, and Croatia are expected to endure significantly adverse CC effects, despite ongoing adaptation and mitigation endeavors. In particular, Italy and Spain may face a decline of up to 5% in agricultural output compared to the RCP4.5 scenario, which disregards uncertainty. Conversely, Croatia could see a reduction of up to 10% in agricultural output. In contrast, countries such as Morocco and Greece might stand to gain from adaptation and mitigation strategies, potentially witnessing a rise in agricultural output of up to 5%.

Figure 5 expands upon Figure 4, providing an in-depth analysis of agricultural output by breaking it down into its constituent sectors: rainfed crops, irrigated crops, and livestock. This detailed analysis enables a more nuanced understanding of the impacts of CC damage, as well as adaptation and mitigation strategies. Figure 5 illustrates the range of uncertainty regarding potential damage from extreme events, as depicted by the b=0.3 and b=0.7 OPT scenarios.

The findings suggest that the primary source of output loss across most countries is concentrated in the livestock (meat) subsector. In contrast, the rainfed and irrigated crop sectors seem to benefit from the implemented mitigation and adaptation measures.

Egypt emerges as a compelling example of a nation where adaptation strategies focused on irrigated crops could effectively offset declines in agricultural output, even in the face of reductions in rainfed crops and livestock production. Conversely, in countries such as Spain, Italy, Israel, and Turkey, the reductions in output stemming from the livestock sector outweigh the benefits gained from expanding the utilization of AWS and irrigation.

Upon comparing the results of the b=0.3 and b=0.7 OPT scenarios, it is evident that the overall trend of change remains consistent across all countries. The main discrepancy between the two scenarios lies in the magnitude of change, with the b=0.7 scenario posing a higher risk to the livestock sector. Interestingly, the irrigated crops sector sometimes benefits from this uncertainty, exhibiting increased output in the b=0.7 scenario compared to the b=0.3 scenario, as observed in Egypt and Italy. These differences are relatively minor and could be influenced by international trade factors.

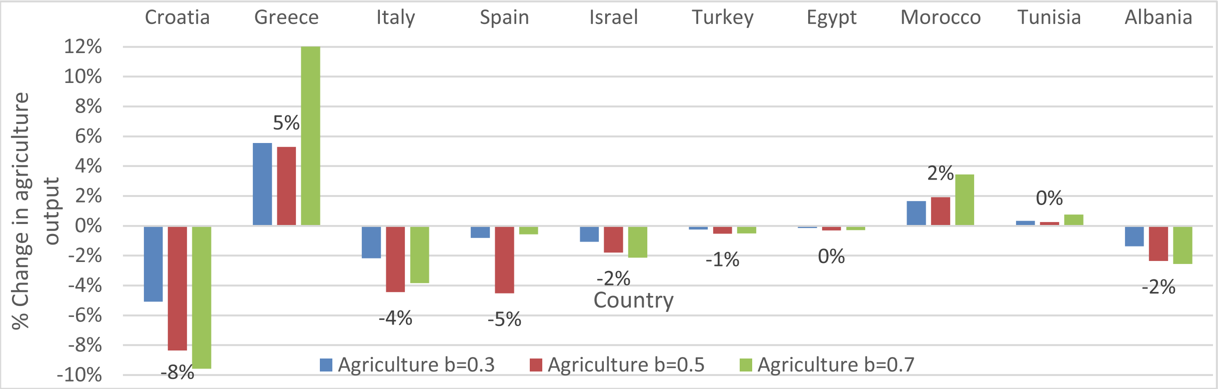

**Fig. 4.** Output % change in agriculture by CC uncertainty level in GTAP-AW *(compared to RCP4.5-BAU)*

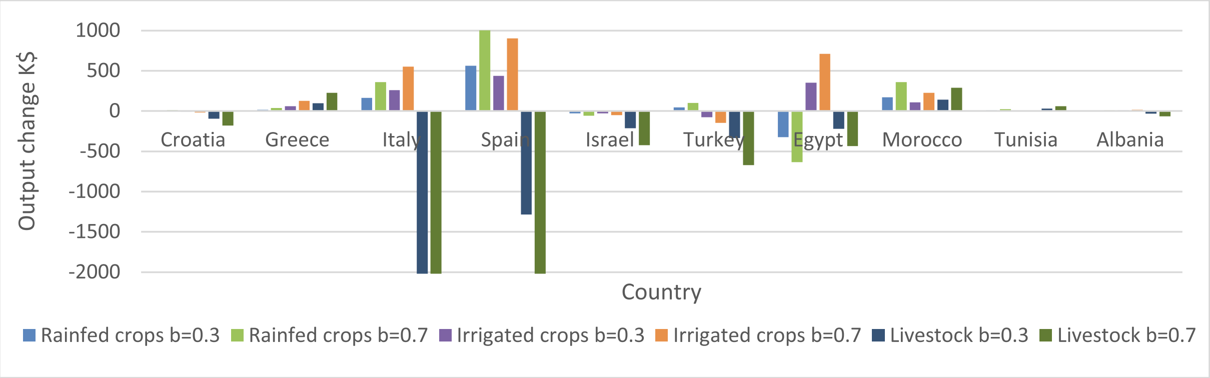

**Fig. 5.** Output change [K$] in agriculture sectors by uncertainty level in GTAP-AW (compared to RCP4.5-BAU)

The multisector CGE model GTAP-AW enables the tracking of interdependencies and transmission effects across sectors and countries resulting from CC impacts on agriculture. These cascading second-level effects (Figure 6) vary in trajectory and magnitude of output change across each country. A notable effect is observed in sectors such as processed food or textiles, which rely on crop yields as input, and experience a decrease in output, as noticeable in most countries, with Morocco being particularly affected. Another group of sectors comprises the water sectors, primarily providing inputs to the field crops sectors. The decline in agricultural output due to CC impacts leads to reduced demand for inputs from the desalinated water sector, a trend particularly evident in Spain and Morocco. Conversely, a minor increase is projected in the treated water sector, mainly in Italy and Spain.

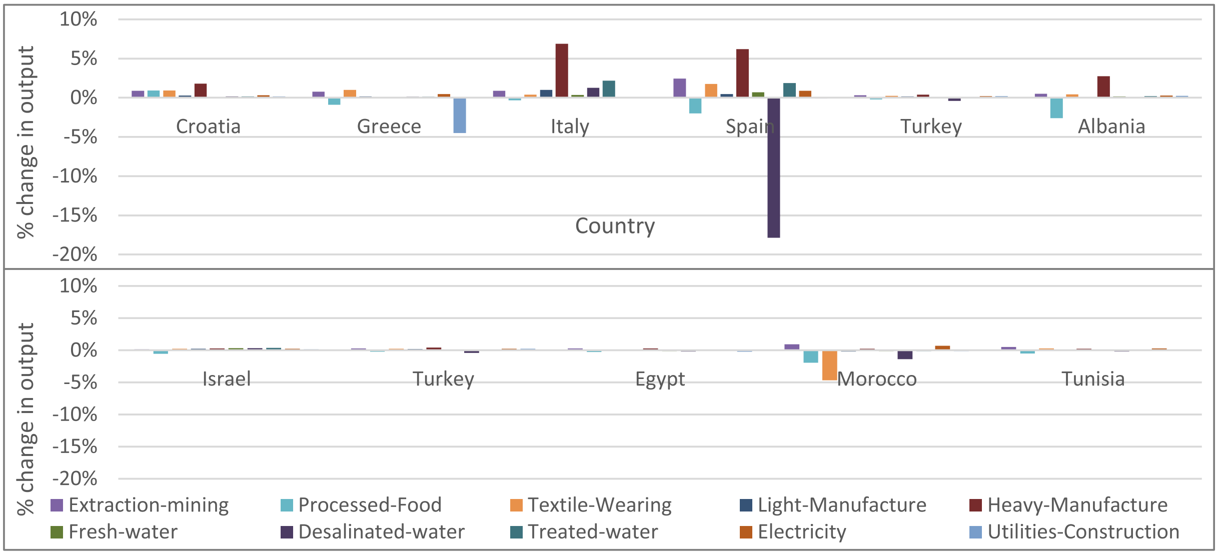

**Fig. 6.** Output % change of non-agriculture sectors due to uncertainty (b=0.5) (compared to RCP4.5-BAU)

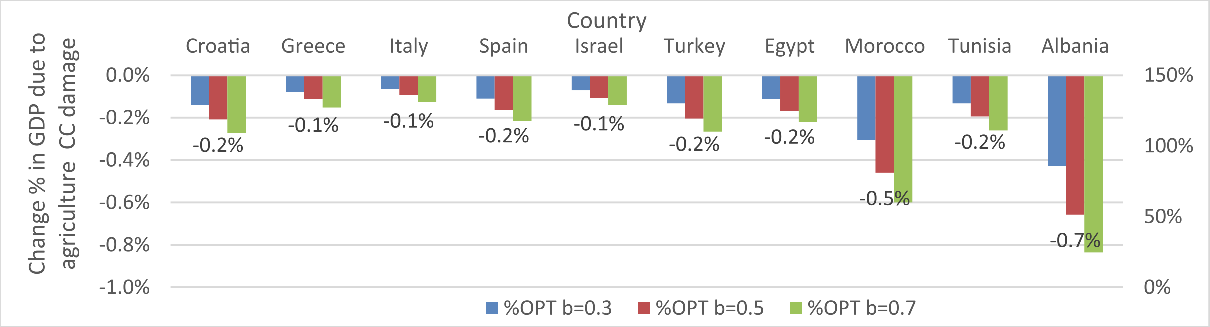

**Fig. 7.** The GDP % change due to agriculture loss (b=0.3,0.5,0.7), compared to RCP4.5

Overall, climate change-related losses in the agricultural sectors, coupled with their secondary impacts on other sectors, lead to a reduction in GDP across all MSB countries (Figure 7). This reduction is more pronounced (0.2%-0.7%) in the southern MSB countries of North Africa, where agriculture contributes between 7% to 13% of the GDP. This contrasts with the northern MSB countries of Southern Europe, where the decrease in GDP is less pronounced (0.1%-0.2%), with agriculture accounting for 1%-3% of the GDP (except for Turkey, where agriculture output constitutes 7% of their GDP).

## 6. Discussion and Conclusions

This study uses a dual-model approach, combining the GTAP-AW model utilizing CGE techniques with insights from the IAM model RICE-MED. The research highlights the advantages of integrating these two macroeconomic models, especially in their ability to incorporate AWS and irrigated agriculture as adaptive strategies against extreme climate change events amid uncertainty.

The CGE-based methodology enables a thorough exploration of the potential for AWS and irrigated agriculture to mitigate the impacts of climate change across various uncertainty and mitigation scenarios. Despite the adoption of irrigation and other water management practices, the study confirms that climate change uncertainty adversely impacts both food security and the global economy. Additionally, the study reveals that indirect consequences stemming from carbon emissions and mitigation efforts could lead to a reduction in agricultural output ranging from 1% to 8% across most countries in the MSB, in contrast to a Business-as-Usual scenario. This trend is particularly pronounced in developed nations, where the utilization of fossil fuels and mitigation initiatives has a significant impact on utility output.

A more thorough analysis of agricultural sectors indicates that nations with significant livestock management, such as Italy and Spain, are increasingly vulnerable to climate change-induced damage and potential decreases in output. The research underscores the advantages of AWS and irrigated agriculture in enhancing adaptive capabilities, particularly for field crops. However, it is noteworthy that the GTAP-AW model currently lacks adaptive measures specifically tailored to the livestock sector.

Earlier studies have already investigated the economic repercussions of climate change on livestock management, with a specific focus on pasture regions that are heavily reliant on rain (Halimani et al., 2021). Policy recommendations tailored for the Mediterranean region advocate for the utilization of treated urban wastewater as a sustainable and promising strategy to address water scarcity in pasture areas dedicated to livestock. This approach not only improves soil fertility but also conserves natural resources, fosters the development of local products, and enhances the living conditions of agriculture and farmers (El Moussaoui et al., 2019; Aguilera et al., 2020).

Future research should explore additional adaptive strategies within pasture regions to alleviate potential utility losses stemming from catastrophic climate events.

The limitations of this study are intertwined with its strengths. GTAP-AW effectively captures input-output relationships among sectors and countries, reflecting the effects of technological advancements and incorporating macroeconomic feedback loops. It is complemented by the integration of climate change-induced uncertainty regarding the impact of extreme events on agriculture, sourced from a global climate-economic uncertainty model like RICE-MED-U. Conversely, RICE-MED assumes an aggregated economy without international trade in goods, thus benefiting from the possibilities offered by GTAP-AW. Consequently, this study underlines the need for a synergistic approach, as exemplified here.

The groundbreaking findings presented in this article have important implications for policymaking. They underscore that while AWS and adaptive strategies can bring about positive changes, the potential benefits may be significantly reduced when uncertainty risks are taken into account. Consequently, further efforts to adapt to potential damage are needed to effectively manage uncertain periods and mitigate food security risks in both crop cultivation and livestock management. These findings are of great value in promoting sustainable agricultural and water management practices, especially in water-scarce regions such as the MSB, to more effectively secure food supplies under the challenges of climate change.

## CRediT authorship contribution statement

**Orna Raviv:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing – original draft, Writing – review & editing, Project administration. **Ruslana Rachel Palatnik:** Methodology, Validation, Supervision, Writing – review & editing, Funding acquisition. **Marta Castellini:** Resources, Validation, Writing – review & editing. **Camilla Gusperti:** Resources. **Sergio Vergalli:** Supervision, Funding acquisition. **Julia Sirota:** Writing – review & editing. **Mordechai Shechter:** Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data available on request, but only to referees

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