AWESOME

WATER-ECOSYSTEM-FOOD

Synergies of modelling efforts for water-food nexus assessment in the Mediterranean

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List of Acronyms

BAU:	Business as usual
CC:	Climate Change
CEA:	Controlled-environment agriculture
CGE:	Computable General Equilibrium
DDP:	Deliverable Development Plan
DM:	Deliverable Manager
EC:	European Commission
ES:	Ecosystem Services
GHG:	Green House Gases
GTAP:	Global Trade Analysis Project
GTAP-AW	GTAP with alternative water
IAM	Integrated assessment models
MSB:	Mediterranean Sea basin
Mx:	Month number
OPT:	Pareto Optimal – RICE scenario
PE:	Partial Equilibrium
RCP:	Representative Concentration Pathways
RICE	Regional dynamic Integrated Climate and Economy
RICE-MED-U:	RICE model for the Mediterranean Sea basin area, with uncertainty
SCC:	Social Cost of Carbon
SSP:	Shared Socioeconomic Pathways
SDG:	Sustainable Development Goals
TL:	Temperature Limit – RICE scenario
WEFE:	Water-Energy-Food-Ecosystem
WP:	Work Package
UN:	United Nations

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EXECUTIVE SUMMARY

Climate change (CC) and demographic expansion are intensifying the strain on natural resources in the Mediterranean Sea Basin (MSB), raising concerns about the sustainable supply of water and food. Aligned with the United Nations Sustainable Development Goals (UN SDGs) and the Water-Energy-Food-Ecosystems (WEFE) nexus, this study aims to project shifts in welfare and food security under varying climatic conditions. Agriculture, a climate-sensitive sector, predominantly relies on rainfed croplands, which constitute 70-100% of agricultural land in most countries. The remaining areas are irrigated by climate-dependent water bodies like rivers and aquifers.

This research employs a novel dual-modeling approach to assess the WEFE nexus in the MSB under the uncertainties of climate change. Utilizing the General Equilibrium (CGE) model, the study delves into intersectoral and inter-regional impacts, while the Integrated Assessment Model (IAM) based on the RICE-99 framework addresses the uncertainties related to future extreme climatic events. This synergistic approach offers a unique evaluation of CC impacts, incorporating adaptation measures such as alternative water sourcing and precision agriculture.

The study is part of the AWESOME project under PRIMA Nexus 2019 RIA, focusing on cross-sectoral and multi-scale management of water, ecosystems, and food in the MSB. The report encapsulates the efforts of Work Package 3 (WP3) in employing different economic models, namely CGE GTAP-AW and IAM RICE-MED, to analyze the effects of climate change adaptation and mitigation strategies on the WEFE nexus. The findings reveal diverse impacts on food production, offering a comprehensive perspective on potential adaptation and mitigation measures to alleviate food security risks in the MSB. These insights are instrumental for policy-making aimed at fostering sustainable water and agricultural development in a changing climate.

1. INTRODUCTION

Climate change (CC) and population growth are increasing the strain on natural resources in the Mediterranean region, to a point where they may compromise the sustainable provisioning of water and food. An overestimation of the economic and social benefits of human actions and underestimation of their negative externalities may lead to the degradation of ecosystem services (ES), risking water and food provisioning [1, 2]. The UN Sustainable Development Goals (SDGs) promote the achievement of food security, sustainable agriculture, and water management along with urgent action to combat negative impacts of climate change and protect marine and terrestrial ecosystems. In addition, the *Zero Hunger* and *Clean Water Supply* goals are within the six most important development goals [3].

Most of the world's food production from agriculture is based on the cultivation of non-irrigated croplands along with livestock using rainfed pasture. The share of rainfed croplands in most countries varies between 70-100 % [4]. The remaining cultivated areas are irrigated using water bodies such as rivers and groundwater aquifers, which rely heavily on climatic conditions [5]. Hence, agriculture is among the most climate-sensitive sectors of an economy. It is sensitive to temperature, precipitation, soil radiation, and other attributes that are directly associated with the risk of CC [6]. The link between CC and natural water scarcity, GHG emission and economic damage affecting agriculture, food and the economy is widely discussed [7, 8].

The synergy report builds on two distinct macroeconomic modeling approaches - CGE and IAM - to investigate the extent to which CC damage and the policy of Social Cost of Carbon (SCC) can impact the contribution of alternative water sources and irrigated agriculture practices to agricultural productivity under uncertainty.

1.1. Climate Change adaptation - alternative water sources

Alternative water sources have been developed to increase freshwater availability and support food provisioning. For instance, a recent study argues that desalinated and treated brackish water should be included in the blue-water category that originally included only groundwater and surface water [9]. For example, 53% of the water demand in Israel in 2019 was for agricultural use, with 20% being fresh water and the remaining 33% being alternative water sources such as treated wastewater and desalinated water [10]. Alternative water sources have a substantial economic value due to their role in diminishing natural freshwater shortages and sustaining food provisioning.

In the decades to come, alternative water sources are expected to be highly important in water-stressed countries such as the Mediterranean region, where a further decline in natural freshwater availability is projected due to CC [11, 12]. Several studies address the diversification of alternative water sources (e.g., desalinated, brackish, and reused water) to meet the demand [7, 5]. However, the costs and benefits of each alternative water source should consider both their direct impacts and their indirect links with the economic activities, as well as any externalities. The primary direct costs are mainly associated with the energy consumption costs of the energy-intensive desalination and purification plants. The indirect effects of structural economic change arise due to shifts in the water supply. The external costs pertain to the impact of process' waste which degrades the quality of ecosystems, land, and water resources, and emits greenhouse gas (GHG) and local air pollutants [13, 14]. For example, in addition to electricity production and use, the import and export of products that require avian and water transport significantly contribute to GHG emissions and other pollutants [15].

While alternative water sources can yield numerous benefits to households, industry, agriculture, and ecosystems through the sustainable use of natural water resources, the comprehensive costs and benefits of alternative water supply have often been ignored [10].

1.1. Climate Change mitigation – carbon cost

Climate change arises from the interplay between natural dynamics and human activities, with its causes and consequences varying in both time and spatial dimensions. The increase in greenhouse gasses (GHG) emissions, and particularly those stemming from the use of fossil fuels for energy generation, has been driven over time with different and shifting degrees of intensity and timing. While the relation between industrial development and GHG emissions is recognized [16], what is becoming increasingly evident is that CC will predominantly impact specific regions and economic sectors across the world.

An overview of the expected climate in the MSB is provided by Galeotti [17], reporting an expected decrease in rainfalls from 4% to 27% during the 21st century, an increase in frequency and intensity of drought periods, and extreme weather events with air temperature change ranging between +2.2°C and +5.1°C approaching the end of this century, with respect to the end of the previous one. In such a framework, the potential welfare loss of Southern 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 [18]. At sectoral level, agriculture and tourism have significant economic relevance for the Mediterranean area [19].

With the aim of better managing interlinked resources and in line with the UN SDGs, the UN has declared the water-ecosystems-food-energy (**WEFE**) nexus a priority area for sustainable development [20]. Sustainable water management policies and innovative agricultural technologies can be drivers toward secure provisioning of food and water, following the objectives of the WEFE nexus [21]. Efficient irrigation technologies enhance food provisioning and manage potential CC damage by the efficient use of natural resources. For example, the use of drip or precise irrigation reduces the water use, due to the higher irrigation efficiency, compared to crop field flooding and irrigation canals [22, 23].

The D3.5 report - Synergies of modeling efforts for water-food nexus assessment in the Mediterranean - aims to provide a comprehensive perspective for researchers and policymakers. The work is an outcome of other WP3 reports – specifically, the AWESOME deliverables D3.1 - Literature review of macroeconomic models for WEF nexus assessment [24]; D3.2 - WEF Macro-Economic model: RICE-MED [25]; D3.3 – CGE modeling for detailed water-food representation: setting the CGE baseline with the alternative water source, with the formation of GTAP-AW [26]; D3.4 - Assessment of the value of alternative water sources, showing results of GTAP-AW [27].It also relies on the work of D2.3 - specifying the expected 2050 water and agricultural yield in North Africa, D2.1 – specifying the demographic projections towards 2050, and the knowledge gathered in WP5 regarding the hydroponic and aquaponic agricultural practices [28, 29, 21].

2. WEFE analysis in macro-economic modelling

The WEFE analysis in macroeconomic modeling is widely discussed. Multiple approaches are assessing how water management alters food security and the economy. Economists generally distinguish between Computable General Equilibrium (**CGE**) models [30], which consider international trade patterns of all markets and sectors [31, 32], and the Integrated Assessment Models (**IAM**), which assess the relation between the climate and the economy, with some of them characterized by a multi-regional perspective [33, 34].

2.1. Computable General Equilibrium

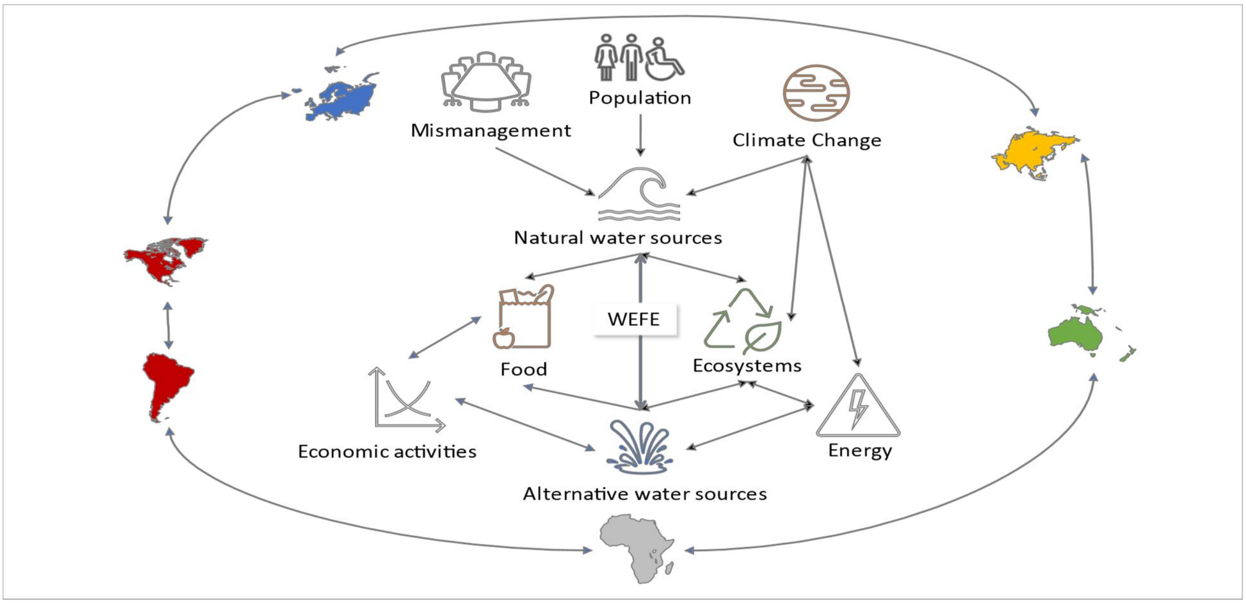

Figure 1: The role of alternative water sources in WEFE analysis in a global economic context.

CGE is a macroeconomic modeling approach that considers the interdependencies between regional and national aspects of trade among multi-sectoral markets to project the potential socioeconomic scenarios of human wellbeing. CGE models capture nonlinear substitution possibilities and multisectoral supply-demand interactions incorporating macro-variables and mechanisms for achieving balance (equilibrium) among aggregates and in all markets (Figure 1). Thus, the demand for any good depends on the prices of all other goods and income. Income, in turn, depends on wages, profits, and rents, which rely on technology, factor supplies, and production, the last of which, in turn, depends on sales (i.e., demand). Prices depend on wages and profits and vice versa [21].

One example of a CGE model is the Global Trade Analysis Project (**GTAP**), a multi-region, multi-sector model, with the assumptions of perfect competition and a general production function characterized by constant returns to scale [35]. The GTAP model also allows a wide range of closure options considering for example unemployment, tax revenue replacement, and trade balance, and a selection of partial equilibrium closures that facilitate comparison of results to studies based on partial equilibrium assumptions [8, 32].

CGE models can provide insights into how water-related distortions (e.g., droughts) and departures from a counterfactual equilibrium can influence food provisioning and global economic growth [36].

However, most CGE-based studies have difficulties adequately representing the value of water technologies, especially in water-abundant countries that lack an explicit economic value of water [7, 37]. In most studies, potable water is the only type of water modelled [38]. Haqiqi et al. [39] highlighted the difference between rainfed and irrigated agriculture while focusing on a single type of water for irrigation. This modelling approach does not suit a water economy that relies on alternative water sources as it does not reflect the constraints associated with the utilization of low-quality water sources and overestimates the ability of an economy to cope with an increasing natural water shortage. [40]

To analyze the WEFE interdependencies, the CGE models usually perform the analysis for a single economy or river basin, e.g. Israel [7, 41, 42], Morocco [43], changes in water demand in Egypt, Sudan and Ethiopia that use the water of the Nile river's basin [44], or the water and land quality management alternatives and their implications on crops yield and related costs in Egypt [45]. Bardazzi and Bosello [46] found that most studies employing global CGE models essentially examine a 'first-order' cost evaluation of productivity instead of an explicit loss of water availability. Thus, most of these studies do not capture the resulting 'second-round' effects of structural economic change that arise due to shifts in natural resources, and particularly water, on various economic sectors, such as agriculture.

Further details regarding CGE modeling of the WEFE nexus may be found in the AWESOME book chapters [21], and reports D3.3 [26] and D3.4 [27].

To assess the role that alternative water sources and irrigated agriculture may play in climate adaptation efforts in the Mediterranean and around the world, WP3 added an explicit representation of the water sectors in the global CGE model, **GTAP-AW** (GTAP with alternative water).

2.2. Climate Change damage modelling

The assessment of the regional economic damages due to CC is the main focus of the dynamic Regional Integrated model of Climate and the Economy (**RICE**) developed by Nordhaus and Yang in 1996 [40]. The general framework of the RICE model consists of optimal economic growth integrated with a climate module. This set up is a well-known feature of the IAMs and allows the simulations of the long-term relationship between climate and the economy. The countries of the world are grouped into several regions, allowing the economic damages associated with climate change to be disaggregated at a finer spatial scale. For the WEFE nexus analysis, this feature is relevant because of the spatial differences in the economic impacts of CC. The results of the model include the carbon tax as the social cost of carbon (SCC), i.e. the economic cost of an additional tone of carbon dioxide emissions [47], although it should be noted that this value is also affected by the degree of regionalization [48]. The **RICE-MED** model initialization is based on the economic equilibrium in each country/region, which considers also the disaggregation of the energy sector concerning different energy sources (all fossil sourced).

Further details concerning the theoretical background are available in AWESOME reports D3.1 and D3.2 [25, 24].

2.3. AWESOME results so far

Both AWESOME models - GTAP-AW and RICE-MED - predict the world condition in the years 2050 - 2055. The GTAP-AW world-trade model introduces into the global CGE database the enhanced agriculture practices and alternative water sources, on top of the freshwater industry, including the desalination and treated water industries. The RICE-MED provides emissions and SCC scenarios, estimations of CC economic damage and related effects on main macroeconomic variables at the regional and country level of the MSB, while also accounting for the probability of a climate derived catastrophic event.

The novelty of the GTAP-AW with irrigated agriculture and alternative water industries projects the potential change in the economy of the MSB countries between the years 2014-2050 [49], forming (1) new regionalization, where all the Mediterranean nations are considered at country level, allowing the assessment of CC economic impacts at a finer spatial level; (2) new alternative water sectors and irrigated vs rainfed agriculture sectors calibrated to year 2014 [12] and available in all MSB countries [50, 51, 52, 53]; (3) Projection of the 2050 SSP2 baseline in GTAP-AW, that simulates the climate change effect on the economy, as defined by the IPCC - Shared Socioeconomic Pathways (SSPs), and estimated by the IIASA models [54] [55, 56]; (4) Projection of the SSP2-RCP4.5 baseline in GTAP-AW, that simulates the effect of the mitigation efforts to reduce emission using the Representative Concentration Pathway (RCP 2.6, 4.5, 6.0), that were estimated by the IIASA models per the different level of mitigation efforts [55] [57]; and (5) Projection of the effect of water-industry efficiency in the agricultural sector, using controlled environment agriculture (CEA) and hydroponics practices as a case study[1], modifying the GTAP-AW data towards 2050 under changing climate conditions [58, 59, 60, 61, 62, 63].

The platform used in this study is GTAP for CGE modeling [64]. The GTAP components used are the database GTAP10A [65] and the standard static model RunGTAP version 7 [66], that offers the option for some sectors to produce multiple products, and for multiple sectors to produce the same or a closely substitutable product, as in the case of agricultural food production from multiple generation sources such as irrigated and rainfed practices [67].

The GTAP-AW model predicts the effect on the economy following climate change conditions (SSP2), mitigation effort to reduce GHG (RCP4.5) and the adaptation efforts of the water and food provisioning sectors, using efficiency in technology and practices.

<u>The main novelties of the RICE-MED climate and economy model</u> are (1) updated calibration of the RICE-99 model [68], to the initial year 2015, based on their original initialization approach, which is formalized analytically to facilitate future replication and improvements; (2) new regionalization, where all the Mediterranean nations are considered at country level, allowing the assessment of CC economic impacts at a finer spatial level with respect to the original version; (3) new damage function according to Golosov et al. [69]; (4) the implementation of an extension of the RICE-MED model with uncertainty (RICE-MED-U), following the approaches of Castelnuovo, Moretto and Vergalli [70], allowing the inclusion of the societal awareness towards a possible future catastrophic event, triggered by the temperature increase and variation over time; and (5) application of the model with economic damages linked to climate change effect on the agricultural sector of the Mediterranean countries, using data provided by Roson and Sartori [71].

The RICE-MED model predicts the expected change until the year 2305 with a time step of 10 years, under three scenarios; (1) the Business As Usual (BAU), where the negative environmental externality associated with climate change is not internalized; (2) the Social Optimal (OPT) scenario,

[1] Although included in the GTAP-AW model and in previous reports, this feature of hydroponic practices was omitted from the current report and analysis, in order to focus on the field-crops irrigation and cultivation, without the interference of other practices, and in alignment with the RICE-MED scope and assumptions.

accounts for that negative externality in the resolution of the welfare maximization problem of each region; and (3) the Temperature Limit (TL), designed to bind the temperature increase below 2°C for the preindustrial level by the end of the century. Both OPT and TL scenarios reflect, as close as possible, the SSP2 RCP4.5 conditions, as estimated in IIASA data [55]. Among the global CC outcomes, the CO_2 concentrations in the atmosphere, temperature increase, and the carbon tax are the main macroeconomic variables and damages that variated at regional level and were incorporated into the analysis.

The AWESOME GTAP-AW and RICE-MED frameworks are characterized by a significant degree of complementary to each other. In particular, the GTAP-AW results, which currently lack the external costs of uncertainty due to CC damages and energy emissions, can benefit from the results of RICE-MED to fine-tune the CC damage estimates and to add the risk probability of the projected scenarios to the current results.

This report focuses on the methods to follow and implement the synergy targets and the results received, reflecting the additional uncertainty relating to CC damage in the MSB in the years 2050-2055, as affected by adaptation and mitigation efforts, and following the impact in each and every country in the MSB.

3. METHODOLOGY

The methodological approach to synchronize modelling efforts of IAM and CGE frameworks is as follows: the RICE-MED model simulates the GHG emissions under a given scenario. These are translated to climate impacts and uncertainty in the level of catastrophic-event damage affecting agricultural productivity in each country. **The RICE-MED estimated change in agricultural productivity is introduced as external shocks to GTAP-AW**. The resulting impact on the economy, with and without alternative water sources, allows us to investigate the extent to which CC damage and SCC policy can impact the contribution of alternative water sources and irrigated agriculture practices to agricultural productivity.

The latest results of the AWESOME produced GTAP-AW and RICE-MED models [27, 25] respectively are the input to the modeling scenarios of this report and are presented respectively in Figure 2 and Figure 3.

Figure 2 shows the projection of three GTAP-AW 2014-2050 scenarios - one without the addition of alternative water sources and irrigated crops cultivation practices (i.e. the no-split scenarios), and two with the addition, i.e. SSP2 baseline (rainfed + irrigated) and SSP2-RCP4.5 (rainfed + irrigated). The results describe a summary of the croplands (only, no Livestock included at this stage) subsectors of agriculture in GTAP-AW, and show that the addition of alternative water sources and irrigation practices in RCP4.5 decrease the effect of CC damages in 2050 and increase the total output of the agricultural sectors, when relating to year 2014. With further mitigation efforts,, the RCP6.0 results vary among the countries, with a slight decrease of output in the European countries and an increase in the African countries.

And yet, Figure 3 shows that on top of the SSP2-RCP4.5 baseline scenario of the years 2050-2055, there are additional uncertainties and CC risks and damage due to catastrophic events, that need to be considered because of the potential impacts on agricultural output, as described by several RICE-MED scenarios. The RICE-MED results describe the agriculture sector as one entity, including the rainfed and irrigated crop lands and the livestock activities.

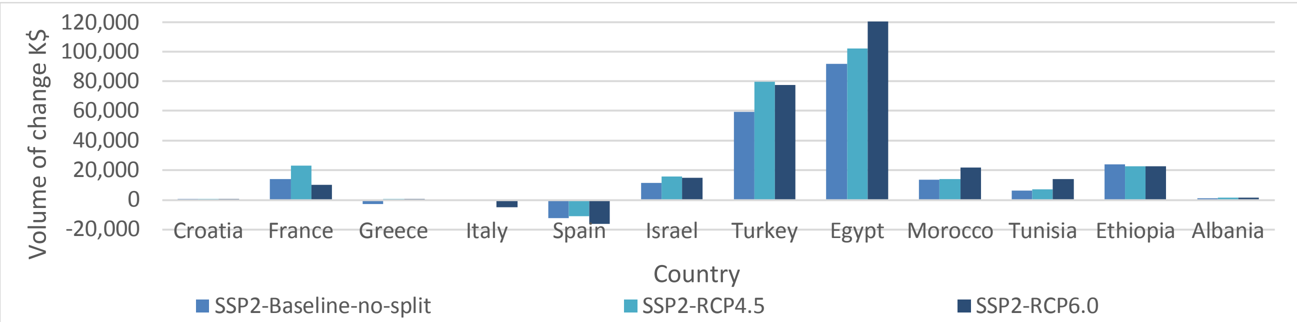

Figure 2: The impact of alternative water and irrigated crops on field crops output in 2050 in GTAP-AW

The RICE-MED BAU scenario (Figure 3) represents a baseline condition with no impact of uncertainty (assuming b=0) and with the RICE-MED-U the damage increases as uncertainty increases (0<b<1). The higher the term b, the greater is the decline in intergenerational utility[2] due to the catastrophic event. The event is defined by the effect of GHG emissions on the average world. The GHG levels in the atmosphere relate to the use of fossil fuel in each country. France has a large share of nuclear energy

[2] The term *Utility* mentioned here and later in this report means **benefit** and relate to the social welfare function in RICE-MED. See more details in AWESOME D3.1 report and in Castelli et al., 2022 [25] and 2023 [120] [Link].

in their energy supply and hence the RICE-MED model that focus on fossil energy shows a neglectable effect of CC uncertainty on the energy supply, SCC and the agriculture in France. Therefore, France will not be included in the GTAP-AW CC damage analysis and figures in the results of this report.

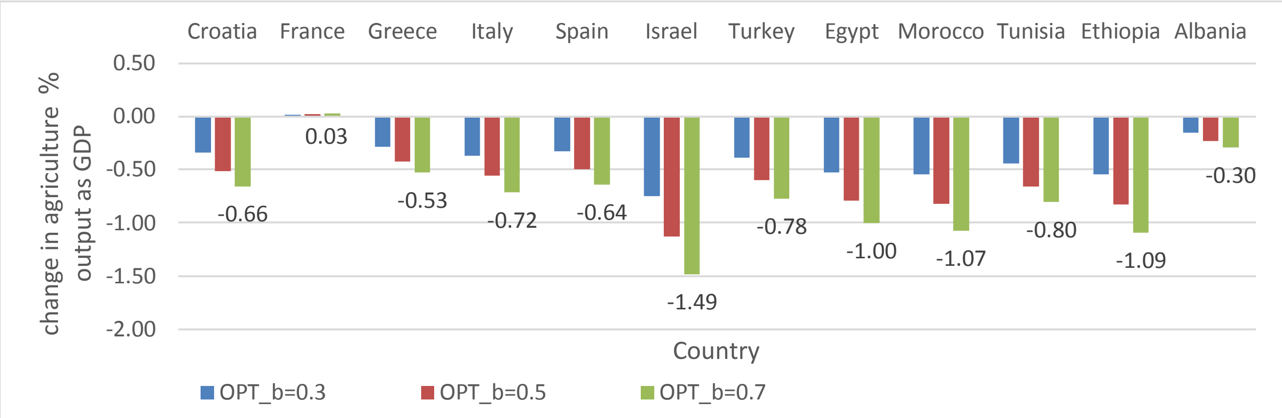

Figure 3: The decrease in the share of agriculture as part of 2055 GDP, compared to RICE OPT BAU (0<b<1 level of uncertainty)

To take the RICE-MED potential damage into account, the RICE-MED-U OPT damage scenarios will be translated into agricultural shocks in the GTAP-AW model, to reflect their potential effect on agricultural production in the different MSB countries. In addition, to correspond with the agriculture sector in RICE, the scope of GTAP-AW will be expanded from croplands only into croplands and livestock (Figure 4).

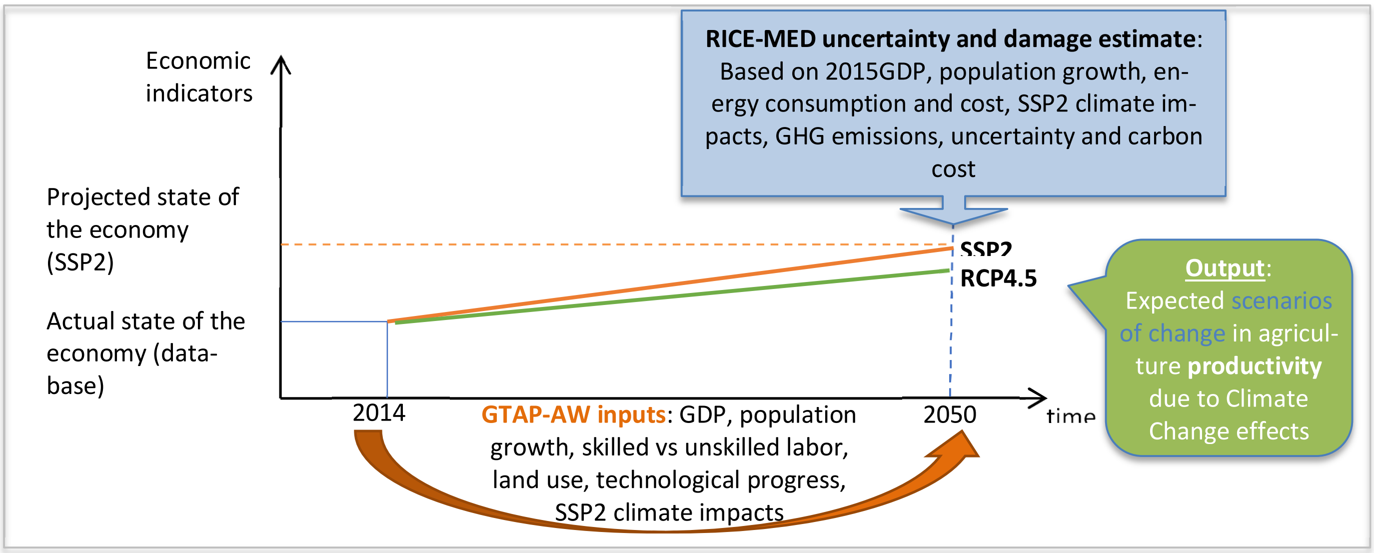

Figure 4: Incorporating the RICE-MED CC damage impact on agriculture as an input to GTAP-AW modeling

The steps to incorporate the RICE-MED-U CC damage OPT scenarios into the GTAP-AW alternative-water modeling include:

1. Verify that RICE-MED-U outcome do not result in double-counting of CC damage in the GTAP-AW model (Table 1):
    a. GTAP-AW results reflect SSP2-RCP4.5 baseline conditions through the CC effects on capital, land and population, and on GHG emission mitigation. GTAP-AW 2050 projection is based on IIASA CC impacts [55].
    b. RICE-MED-U results add, on top of SSP2-RCP4.5 baseline conditions in the year 2055, several CC damage scenarios that differ by the level of uncertainty. 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. Thus, disaster affects the agriculture output and is described by the percentage change of the agriculture sector as part of 2055 GDP (Figure2), in each MSB country.

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**

Table 1 describes the input data characteristics, as used in the models and input data involved in the analysis of this document, namely GTAP-AW and RICE-MED models and the IIASA based SSP2 and RCP4.5 estimates. The uncertainty-based CC damage estimation was not part of GTAP-AW or the IIASA estimates, that were used as an input to the GTAP-AW scenarios. Therefore, the assumption in this document is that no double counting exists, and the RICE-MED-U economic damage scenarios can be used on top of the GTAP SSP2-RCP4.5 baseline to check the potential risks of extreme events.

2. Translating utility loss due to uncertainty of extreme events from RICE-MED to GTAP-AW: At the second level of no-double-counting verification, we have only used the relative change estimates of the OPT scenario as compared to the BAU scenario.
    a. The meaning of 'relative change' is that the damage level defined by the OPT scenario in the RICE-MED-U model of b=0.3 (first level of potential utility loss) was calculated as the value of change relative to the RICE-MED-BAU b=0 estimates (i.e. [b=0.3_estimate] -minus- [b=0_estimate]). The same was done also with the estimates of b=0.5 and b=0.7. This way we eliminate any potential effect of a baseline linkage between RICE-MED original inputs and the damage calculation in GTAP-AW and use a pure percentage change estimate.
    b. The estimated share of agriculture in GDP reflected the RICE-MED GDP estimates and therefore had been translated to reflect the relative change by the GTAP estimates of GDP. Specifically, we proportionally scaled the percentage estimates from the RICE-MED based on GTAP's GDP figures. By doing so, we are assuming that RICE-MED's projections for 2055 provide an accurate representation of the potential changes in GTAP's GDP figures for 2050.
3. For the agriculture sector, RICE-MED and GTAP-AW represent the input-output of all agricultural activities. In GTAP-AW the agricultural sector includes two main subgroups – field crops and livestock. Until the recent report GTAP-AW agriculture scenarios were focused on the rainfed and irrigated field crops sub-sectors. To align to the RICE-MED scope, that includes the livestock sector's activities, this document will include also the livestock estimates as part of the GTAP-AW agriculture sector, to reflect a wholistic change in the agriculture sector in alignment with the RICE-MED scope.
4. The CC damage estimates provided by RICE-MED were translated into economic shocks in the GTAP-AW model. As the RICE-MED model allows the identification of potential change in agriculture output due to CC, such change was translated into the GTAP shock that reflects a

complimentary intermediate input augmenting a technical change of *activity a* (the agriculture sectors, including rainfed crops, irrigated crops and livestock) in *region r* (in all MSB countries)[3].

5. The GTAP SSP2 RCP4.5 baseline was shocked by the three different levels of RICE-MED-U based damage estimates (that relate to the b=0.3, b=0.5 and b=0.7 levels of potential utility loss) to reflect the expected change in agriculture output and GDP.

The results of the RICE-MED based CC damage and mitigation shocks on the GTAP-AW scenarios, including adaptation practices of irrigated crops and alternative water sources, are presented in the next section.

4. RESULTS

The integrated analysis employs a dual-model approach to scrutinize the economic ramifications of potential climate change (CC) impacts, with a particular emphasis on the agricultural sector. Utilizing estimations from the RICE-MED-U model, which quantifies the level of uncertainty associated with climate-induced disasters, the GTAP-AW model was adjusted to incorporate these shocks on top of the SSP2-RCP4.5 scenario. Consequently, the GTAP-AW model accounts for three distinct levels of damage shocks derived from the RICE-MED-U model. These shocks consider varying magnitudes of utility loss due to catastrophic events induced by CC according to the level of uncertainty. Additionally, the model incorporates a Climate Change Mitigation Optimal (OPT) scenario, which employs a set of policy instruments aimed at reducing greenhouse gas (GHG) emissions through the Social Cost of Carbon (SCC), as well as adaptation strategies in irrigated agriculture. The results encapsulate a multifaceted impact assessment for each Mediterranean Sea Basin (MSB) country.

Figure 5 delineates the anticipated percentage changes in agricultural output, which includes both rainfed and irrigated crops as well as livestock estimates, for each MSB country. The percentage labels correspond to three levels of uncertainty (*b*) within the OPT scenario.

The findings reveal a heterogeneous impact across MSB countries. Notably, countries like Italy, Spain, and Croatia are projected to experience significant negative impacts from climate change, despite ongoing adaptation and mitigation efforts. Specifically, Italy and Spain could face up to a 5% decline

[3] This shock in GTAP is called “aintall”

in agricultural output relative to the RCP4.5 Business-as-Usual (BAU) baseline. Croatia, on the other hand, may witness a reduction of up to 10% in agricultural output (Figure 5). Conversely, countries such as Morocco and Greece could potentially benefit from adaptation and mitigation strategies, with agricultural output possibly increasing by up to 5%.

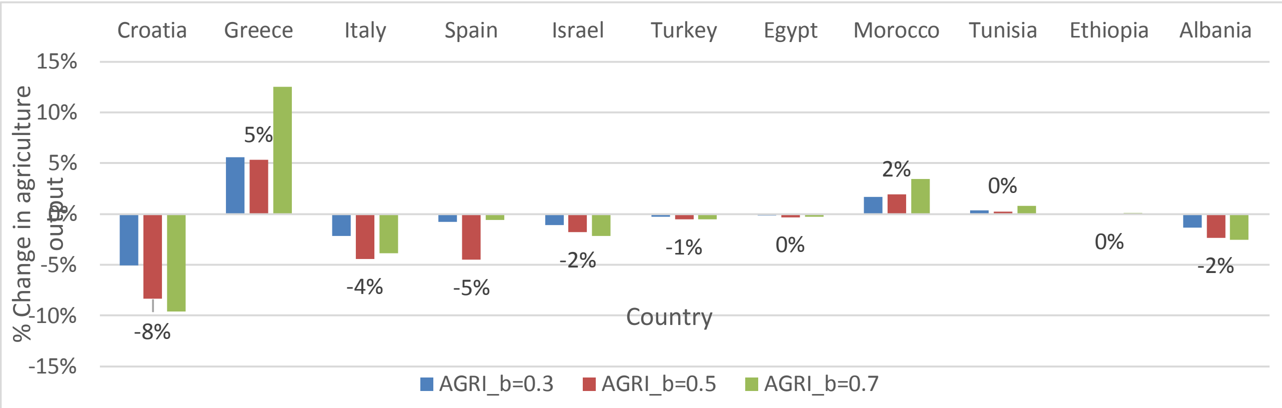

Figure 5: Agriculture output change [%] by CC damage in GTAP-AW, compared to 2050 RCP4.5 baseline

Figure 6 serves as an extension of Figure 5, further dissecting the agricultural output into its constituent sectors: rainfed crops, irrigated crops, and livestock. This granular analysis allows for a more nuanced understanding of the impacts of (CC) damage, as well as adaptation and mitigation strategies. Specifically, Figure 6 presents the range of uncertainty of potential damage of extreme events, illustrated by the b=0.3 and b=0.7 OPT scenarios.

The findings indicate that the primary source of output loss across most countries is concentrated in the livestock (meat) subsector. This contrasts with the rainfed and irrigated crop sectors, which appear to benefit from the implemented mitigation and adaptation measures.

Egypt serves as a compelling example of a country where adaptation strategies involving irrigated crops could effectively offset losses in agricultural output, despite declines in rainfed crops and livestock production. Conversely, in countries like Spain, Italy, Israel, and Turkey, the losses in output attributed to the livestock sector outweigh the gains achieved through alternative water sources and irrigated crops.

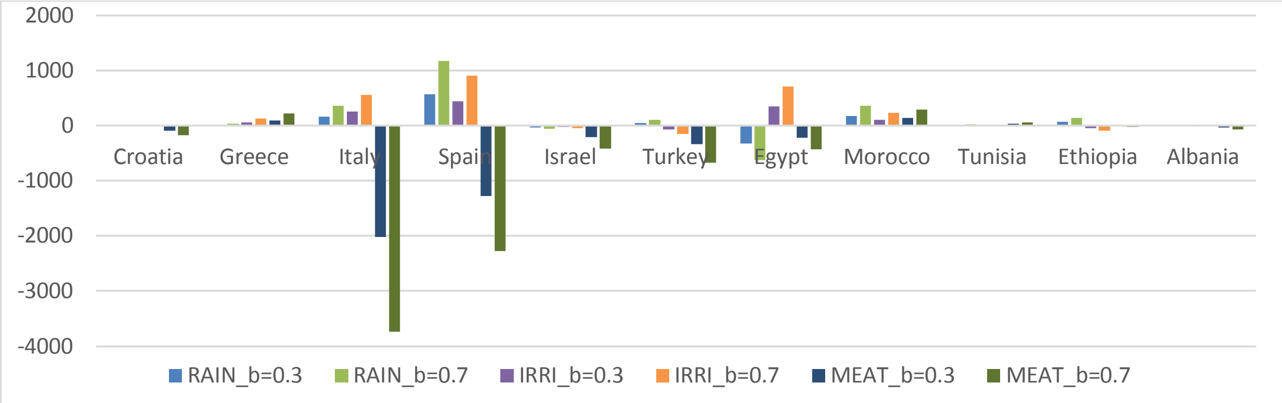

Figure 6: Change in rainfed and irrigated crops and livestock [M$] due to CC damage in GTAP-AW

When comparing the outcomes of the b=0.3 and b=0.7 OPT scenarios, it is evident that the directional trend of change remains consistent across all countries. The primary difference between the two scenarios lies in the magnitude of change, with the b=0.7 scenario posing a greater risk to the livestock sector. Interestingly, the irrigated crops sector occasionally benefits from this uncertainty, showing an increase in output in the b=0.7 scenario compared to the b=0.3 scenario, as observed in Egypt and Italy. However, these variations are relatively minor and could be influenced by multiple factors.

5. CONCLUSIONS and DISCUSSION

This report is an outcome of Work Package 3 (WP3) within the AWESOME project, employing a dual-model approach that integrates the GTAP-AW model based on CGE methods with inputs from the RICE-MED IA). The study underscores the advantages of combining these two macroeconomic models, which specifically account for alternative water sources and irrigated agriculture as adaptive measures against extreme CC events under uncertainty.

The CGE-based methodology enables an in-depth analysis of how alternative water sources and irrigated agriculture can aid in both mitigating and adapting to climate change under various uncertainty scenarios. Despite the implementation of irrigation and alternative water practices, the study reaffirms that climate change uncertainty negatively impacts food security and the global economy. It also reveals that indirect effects from energy consumption could reduce agricultural output by 1%-8% in most Mediterranean Sea Basin (MSB) countries compared to a Business-as-Usual (BAU) scenario. This is particularly evident in developed countries where fossil fuel usage and mitigation efforts have a pronounced effect on utility output.

A closer examination of agricultural sectors (as shown in Figure 6) indicates that countries with a significant livestock sector, such as Italy and Spain, are highly susceptible to climate change-induced damage and potential output reduction. The study emphasizes the benefits of alternative water sources and irrigated agriculture in enhancing adaptive capacities, particularly for field crops. However, the livestock sector currently lacks such adaptive measures in the GTAP-AW model.

Previous research has already discussed the economic impact of climate change on livestock sectors, particularly those reliant on rainfed pastures. Recommendations for the Mediterranean region include the adoption of agroforestry grazing and irrigated agroforestry as livestock feed. Future research should explore additional adaptive strategies in pasture areas to mitigate potential utility losses due to catastrophic climate events.

The limitations of this study relate to its strength. GTAP-AW can model the whole world's trade markets in a macro level model, that must be complemented with the climate driven disaster in-formation provided by a global climate-economic uncertainty model, such as the RICE-MED-U. The RICE-MED, in turn, assumes no international trade of goods and can benefit from these features provided by the GTAP-AW. Therefore, a synergistic approach, as demonstrated in this report, is essential.

The study's findings have significant implications for policy-making, affirming that while alternative water sources and adaptive measures can induce positive changes, these benefits may be substantially offset when uncertainty risks are considered. These insights are particularly valuable for enhancing sustainable agriculture and water practices, especially in water-stressed regions like the MSB, to better secure food supply in the face of climate change

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7. APPENDICES

In these appendices we share the details of the methodological steps of GTAP-AW, referred to in the Methodology section.

7.1. Data split of water and agriculture sectors

The split was performed using the standard procedure of SplitCom application [50], in which original dataset tables were reformed [51, 52] to use sub sectors and represent multiple water values (Table2) and multiple agriculture values (Table3).

Table 2: Regional disaggregation and share of water sources in the base year 2014.

	Region/Country	Natural water	Desalinated water	Treated water
1	Oceania	95%	4%	1%
2	East Asia	99%	0%	1%
3	South Asia	85%	0%	15%
4	North America	99%	0%	1%
5	Latin America	100%	1%	0%
6	Croatia	61%	0%	39%
7	France	85%	0%	15%
8	Greece	100%	0%	0%
9	Italy	100%	0%	0%
10	Spain	97%	1%	2%
11	Rest of EU28	100%	0%	0%
12	Israel	64%	15%	21%
13	Turkey	100%	0%	0%
14	Egypt	83%	0%	17%
15	Morocco	94%	0%	6%
16	Tunisia	97%	1%	2%
17	Rest of MENA	84%	0%	16%
18	Ethiopia	100%	0%	0%
19	Rest of SSA	91%	0%	9%
20	Albania	100%	0%	0%
21	Rest of the World	95%	4%	1%

Table 3: Share of irrigated land, irrigated crops, and yield ratio by region

Country or region	Irrigated cultivated area	Irrigation to rainfed yield ratio	% Irrigated crops-yield	% Non-irrigated crops-yield
1 Oceania	7%	2.2	15%	85%
2 East Asia	51%	1.5	62%	38%
3 South Asia	42%	2.2	61%	39%

Country or region	Irrigated cultivated area	Irrigation to rainfed yield ratio	% Irrigated crops-yield	% Non-irrigated crops-yield
4 North America	10%	1.8	17%	83%
5 Latin America	8%	1.7	13%	87%
6 Croatia	3%	1.8	6%	94%
7 France	15%	1.8	23%	77%
8 Greece	47%	1.8	61%	39%
9 Italy	45%	1.8	59%	41%
10 Spain	23%	1.8	34%	66%
11 Rest of EU28	10%	1.8	17%	83%
12 Israel	47%	1.9	63%	37%
13 Turkey	23%	1.6	33%	67%
14 Egypt	100%	1.5	100%	0%
15 Morocco	16%	1.8	25%	75%
16 Tunisia	10%	2.1	19%	81%
17 Rest of MENA	35%	2.2	54%	46%
18 Ethiopia	5%	1.4	6%	94%
19 Rest of SSA	3%	2.0	7%	93%
20 Albania	57%	1.8	70%	30%
21 Rest of the World	9%	1.8	15%	85%

7.2. CC: SSP2 baseline

The baseline used mainly IIASA model results per the SSP assumptions put by IPCC, and AWESOME D2.1 – detailing demographic changes in 2050 [55, 56, 29].

Table 4: CC SSP2-baseline change rates per country

Country/Region	Real GDP	Population	Unskilled Labor	Skilled Labor	Physical capital	Land Cover (Cropland)
1 Oceania	85%	13%	-37%	-3%	62%	11%
2 East-Asia	383%	19%	-51%	42%	166%	2%
3 South-Asia	383%	19%	-51%	42%	166%	2%
4 North America	85%	13%	-44%	-5%	62%	11%
5 Latin America	194%	26%	-54%	30%	153%	12%
6 Croatia	76%	-7%	-50%	29%	169%	11%
7 France	158%	19%	-61%	3%	79%	11%
8 Greece	144%	-1%	-53%	22%	115%	11%
9 Italy	155%	1%	-54%	19%	26%	11%
10 Spain	144%	13%	-59%	8%	26%	11%
11 Rest of EU28	85%	13%	-59%	8%	62%	11%
12 Israel	180%	47%	-60%	18%	279%	11%
13 Turkey	156%	28%	-55%	33%	312%	48%

14 Egypt	291%	47%	-55%	46%	517%	48%
15 Morocco	164%	14%	-43%	84%	188%	48%
16 Tunisia	206%	19%	-45%	77%	340%	48%
17 Rest of MENA	365%	81%	-63%	22%	401%	48%
18 Ethiopia	363%	79%	-63%	23%	292%	48%
19 Rest of SSA	365%	81%	-63%	22%	401%	48%
20 Albania	76%	0%	-53%	21%	303%	11%
21 Rest of World	209%	30%	-64%	-4%	126%	12%

7.3. CC: RCPs

The RCP scenarios update the SSP2 baseline with GDP, capital and agricultural land estimates, using IIASA modeling results per the RCP assumptions put by IPCC [55, 56]. The population and labor volumes were assumed to be similar to the SSP2 baseline data.

Table 5: RCP change rates per country

RCP	RCP 4.5		
Country/Region	Real GDP	Capital	Land
1 Oceania	85%	103%	14%
2 East-Asia	380%	172%	7%
3 South-Asia	380%	172%	7%
4 North America	85%	103%	14%
5 Latin America	194%	184%	12%
6 Croatia	76%	237%	14%
7 France	158%	124%	14%
8 Greece	144%	169%	14%
9 Italy	155%	57%	14%
10 Spain	144%	57%	14%
11 Rest of EU28	85%	103%	14%
12 Israel	180%	374%	14%
13 Turkey	155%	415%	53%
14 Egypt	289%	595%	50%
15 Morocco	163%	224%	50%
16 Tunisia	205%	396%	50%
17 Rest of MENA	360%	464%	50%
18 Ethiopia	361%	342%	50%
19 Rest of SSA	360%	464%	50%
20 Albania	76%	404%	14%
21 Rest of World	207%	165%	16%