

# Water scarcity and food security in the mediterranean region: The role of alternative water sources and controlled-environment agriculture

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## ABSTRACT

Climate change and population growth exacerbate water scarcity in the Mediterranean region, threatening food security. A variety of modeling approaches that embed water into a Computable General Equilibrium (CGE) framework is available. However, only a few studies incorporate non-conventional, alternative water sources (e.g., desalination, treated, brackish) into economic analyses. Alternative water sources vary in energy and capital intensity and, therefore, in costs and externalities. We present the first study to introduce alternative water sources to a global CGE model. We also investigate the role of novel technologies of controlled-environment agriculture (CEA) that save water and land at the cost of higher energy intensity than traditional agriculture practices. The results show that the availability of alternative water sources increases the domestic production of grain crops in the North Mediterranean region. The countries that gain the most from CEA technologies are those with a higher share of irrigation and skilled labor. The results reflect the significant value of alternative water sources and CEA technologies to the agricultural sector. The outcomes also indicate that alternative water practices and CEA may bring about a positive trajectory in food security and the global economy, with a negligible effect on energy use.

## 1. Introduction

This study evaluates the role of non-conventional, alternative water sources, such as desalination and reused wastewater, alongside novel agricultural technologies within the water-energy-food nexus in Mediterranean countries, particularly in the context of climate change (CC) adaptation. By uniquely integrating alternative water sources into a global computable general equilibrium (CGE) model, our research introduces a novel framework for assessing Controlled Environment Agriculture (CEA) effectiveness in addressing the challenges of climate adaptation.

The Mediterranean region, characterized by its unique combination of multiple severe climate hazards and heightened vulnerability, emerges as a hotspot for complex climate-related risks. Projected CC is expected to diminish the natural water supply. In

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contrast, population growth (Annex 1) [1] is projected to augment water demand, leading to increased natural water scarcity in the South and East Mediterranean regions alongside droughts in the north [2]. Other risks include coastal flooding, erosion, saltwater intrusion, wildfires, and loss of ecosystems, all of which threaten food security, human health, and well-being [3]. Recognizing these threats and the fundamental human right to clean water, the United Nations' Sustainable Development Goal (SDG) 6 aims to promote the sustainable management of water and sanitation [4]. Meeting this objective will boost energy demand in the water sector for expanding energy-intensive processes like desalination, wastewater treatment, and reuse. This could lead to increased greenhouse gas (GHG) emissions, which are affected by regional differences in regulations and technology. Furthermore, plans to expand power generation, including renewables and nuclear power, often rely on sufficient water availability, a premise that may be challenged by shifting climate conditions.

Water is a critical medium through which CC impacts are transmitted, altering key sectors of the global economy like energy, industry, agriculture, and urban development [5]. Improved water management crucial in climate adaptation and mitigation, highlighting the need to give water equal importance in climate policies alongside energy and land considerations [5].

Various adaptation strategies are expected to balance water demand and water availability. Technological advancements are likely to lower the water intensity per unit of output. Practices like minimum tillage are already improving moisture retention and soil conservation [6]. Biotechnology and precise agriculture technologies are enhancing drought resistance and boosting crop yields. The increasing water scarcity is expected to spur innovations that further conserve water, such as drip irrigation [7]. There will also be shifts in the composition of output to better align with the changing levels of water availability (Fig. 1). The pattern of international trade will evolve to buffer water shortfalls [8]. Additionally, alternative water, already dominant water sources in the Middle East and North Africa [9,10] are expected to become more prominent in water-stressed areas like the Mediterranean region [2].

The development of alternative water sources, such as desalinated, brackish, and reused water, has emerged as a solution to enhance water supply and support food production (Fig. 1). These sources hold significant economic value as they alleviate the strain on natural freshwater resources and ensure sustainable food provision [11]. Recent research advocates for a broader blue water concept to include desalinated and treated brackish water, underlining their significance [12].

Controlled-environment agriculture (CEA) is a recent technological approach that examines the methods to enhance food supply by efficiently using natural resources. Aquaponics is one example of CEA that minimizes the use of both - land and water resources in food production by creating a new semi-closed ecosystem. In this ecosystem, the non-soil hydroponic crops benefit from the fertilizing capabilities of the organic waste produced by the aquaculture plant, usually growing fish [13]. The economic viability of CEA in the Mediterranean Sea basin (MSB) is higher compared to other colder locations, as on top of the reduced costs of water and land, the warm temperatures reduce the costs of energy consumption [14].

Economy-wide analyses of the effect of water management on food security rarely consider alternative water sources, CEA practices, or the social costs and benefits of water and food provisioning [15–17]. Yet, the characteristics of local environments, water policy frameworks, and international supply chains play a critical role in shaping trade dynamics and thus directly impact food security, energy consumption, and social welfare [18,19]. Auffhammer (2018) emphasizes the need for economic models to account for spatial general equilibrium and sectoral spillover effects, highlighting a significant gap in understanding the water sector's climate sensitivity and its foundational importance.

Our study is the first effort to integrate alternative water sources into a neo-classical global CGE model. The results demonstrate that alternative water sources, precise agriculture, and international trade are essential for adaptation to even moderate climate change in the Mediterranean region. These findings are significant because they guide policymakers and stakeholders in the

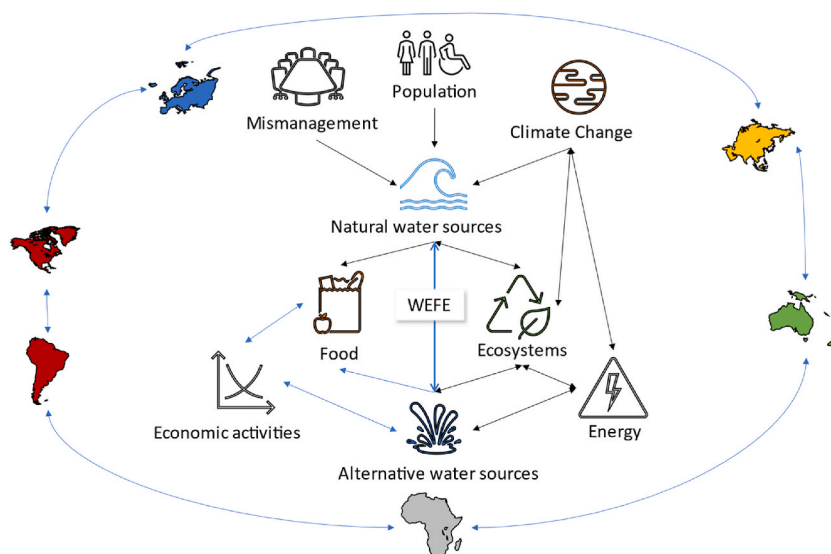


Fig. 1. The role of alternative water sources in WEFE analysis within a global economic context.

Mediterranean region as they develop strategies to adapt to climate change.

## 2. WEFE analysis in CGE

Water scarcity in the Mediterranean region poses significant challenges to food security, a concern exacerbated by CC and increasing water demand. The literature review emphasizes the need to enhance the framework of CGE models with innovative solutions, focusing on alternative water sources and controlled-environment agriculture to comprehensively evaluate climate adaptation strategies. These models, adept at capturing the complex interrelations within the Water-Energy-Food-Ecosystems (WEFE) Nexus, offer comprehensive insights into macroeconomic, demographic, and climatic shifts impacting water management and agricultural practices. Bardazzi and Bozello [20] present a comprehensive literature survey of CGE models for water-energy-food nexus analysis. The review below adds to their study from the perspective of alternative water sources in CGE.

Originating from the work of Leon Walras in the 19th century [21], CGE models have evolved to account for a complex network of market interdependencies, integrating entire economic transactions from local sectors to global trade. This foundation allows for an in-depth analysis of the WEFE Nexus, the complex network of market interdependencies. CGEs capture the nonlinear substitution possibilities in production and consumption, and supply and demand interactions across multiple sectors. They incorporate macroeconomic interlinks and mechanisms to reach general equilibrium, recognizing that the demand for any good is subject to the prices of all goods and overall income, which, in turn, is defined by wages, profits, rents, technology, and production dynamics [22].

The Global Trade Analysis Project (GTAP) model exemplifies a global CGE model's capacity to explore various economic environments and their implications on food provision [23]. CGE models can provide considerable insight into how water-related external shocks (e.g., droughts) and departures from equilibrium can influence food security and global economic growth [8]. However, traditional CGE studies often overlook the value of water, particularly in regions with abundant water resources that lack economic accounts of water [24]. Haqiqi et al. attempted to address the scarcity of monetary data for water by distinguishing between rainfed and irrigated agriculture while concentrating on a single water type for irrigation [25]. We enhance this modeling approach to suit a water economy that relies on alternative water sources and reflects the constraints associated with the utilization of low-quality water sources to estimate the ability of an economy to cope with an increasing natural water shortage.

To enhance the accuracy of CGE evaluation, global CGE models are frequently coupled with partial equilibrium (PE) or physical non-economic models, enriching the analysis with detailed water and agricultural attributes [22]. Most studies use scenario analysis to assess the micro-level, ecosystem-specific attributes that affect the macro-level CGE outcomes [18]. For example, to estimate the global economic impacts of soil erosion, a PE model RUSLE was coupled with the CGE model, MAGNET, to feed the CGE with ecosystem-specific parameters [26]. However, this methodology comes with inherent limitations. One primary challenge is the frequent non-convergence of models, which restricts the interactions to soft links, limiting the robustness of integrated analyses [27]. Additionally, the data requirements for feeding both comprehensive models are substantial, presenting a significant hurdle in the practical application of this approach [28].

Acknowledging the crucial role of localized water management, recent studies have employed country-specific approaches to delve into the WEFE Nexus using CGE models. Kahsay et al. [19] provided insights into how alterations in water demand impact various sectors within Nile River basin countries, employing the STAGE2 model to evaluate the effects of water and land quality management on Egypt's crop yield and related costs. Similarly, Zhang et al. [29] examined the policy implications of modifying water management strategies, highlighting the essential role of water in supporting ecosystem services, including crop provisioning. However, both analyses largely overlooked the long-term effects of water pumping on water quality and quantity and the nuanced interplay between food supply costs and benefits against economic and ecological values.

The CGE model, applied to the Israeli economy including water trade channels and two water types, aimed to appraise the value of agricultural amenities as by-products of agricultural production, [30]. Yet, this model falls short of distinguishing beyond potable and non-potable water sectors, lacking an explicit portrayal of desalination and treated water sectors.

The significant stride in this domain is presented by CGE models for Israel that feature the explicit incorporation of natural water, desalination, and treated water [24,31,32]. This detailed representation of water types offers a nuanced approach to understanding the value of water and its role in addressing water scarcity challenges. The subsequent evaluation of the value of desalinated water in Israel, revealing it to be nearly double its marginal supply cost, underscores the substantial economic benefits of adopting desalination technology, particularly for regions grappling with severe water shortages [11].

In the literature survey by Bardazzi and Bosello [20], the research of Taheripour, Tyner, Haqiqi, & Sajedinia [33] stands out for its comprehensive treatment of the Water-Energy-Food-Ecosystems (WEFE) Nexus for Morocco. This work highlights the significant challenges in modeling complex interdependencies and securing high-quality data, emphasizing the intricate nature of such analyses.

These country-specific studies offer invaluable insights, yet the broader implications of escalating water scarcity have a global character. The localized effects of increasing water scarcity can significantly diverge from the impacts observed on a global scale, altering the relative advantage and international trade patterns. The dynamics of local, regional, and global trade, heavily influenced by local physical attributes of natural resources, national water policies, CC, and international relationships, play a pivotal role in shaping economic development. However, global CGE models typically address water only implicitly [20], often missing the secondary effects of structural economic changes driven by shifts in water resources and overlooking the significance of alternative water sources.

To fully evaluate the role of non-conventional, alternative water sources and innovative agricultural practices in adapting to climate change, a global CGE framework that explicitly represents alternative water sectors is essential. A recent review of modeling approaches for alternative water sources, with a focus on wastewater treatment, in Integrated Assessment Models (IAMs) and Computable General Equilibrium (CGE) models concluded that these models should better capture the distinct characteristics of non-

conventional water sources to enhance accuracy (Dunn et al., 2024). Addressing this need, our study introduces the GTAP-AW model, the first global CGE model to explicitly incorporate alternative water sectors as intermediate inputs and goods within a global CGE-framework to support more comprehensive climate adaptation analyses.

### 3. Methodology

The study explicitly introduces desalination and treated water into the global CGE model and database. The modeling framework projects the potential change in the economy of the MSB countries between the years 2014–2050, assuming (1) alternative water sources and irrigated agriculture can be available in all regions; (2) the climate change effect on the economy is corresponding to the Shared Socioeconomic Pathways (SSPs) by IPCC [34], (3) the effect of the mitigation and adaptation efforts is according to Representative Concentration Pathways (RCPs) [35] and (4) the effect of technological change in the irrigated agricultural sector that adopts CEA according to the characteristics of hydroponics (Fig. 2).

The starting point for the simulation is calibrating the GTAP model to the state of the economy in 2050 in equilibrium (the benchmark) according to the SSP2-Baseline scenario (Fig. 2). At this initial stage, we fed into the model a projected accumulated change in population, skilled and unskilled labor, land use, physical capital, and technological progress, and calibrated the model to follow GDP growth in the SSP2-Baseline scenario [34]. Climate change-induced variation in the precipitations and evapotranspiration violates the equilibrium conditions prevailing in the benchmark, while alternative water sources and CEA can moderate the impact.

The GTAP model [23] is the starting point used for the global CGE model, utilizing the GTAP10A database [36].

#### 3.1. The pre-set of alternative water sectors

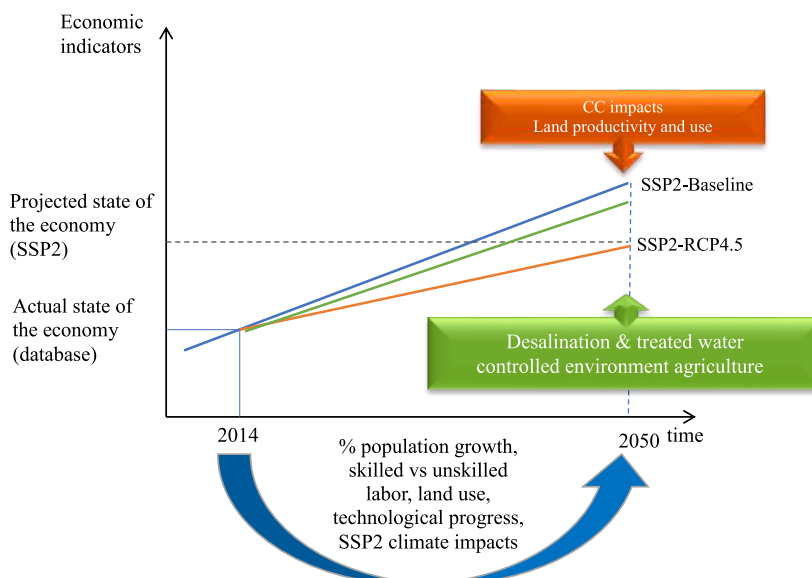
The water supply chain is a complex system involving upstream water extraction, midstream conveyance, downstream water distribution, sideways water uses for non-consumptive purposes and bottom wastewater treatment [6].

On average, more than 80 % of this wastewater is discharged without treatment, which can pollute waterways and pose a risk to human health [37]. Wastewater represents an untapped resource for irrigation and industrial water uses, while seawater desalination offers an opportunity to expand the potable water supply. However, only 11 % of the estimated total of domestic and industrial wastewater produced is currently being reused [38].

The adoption of wastewater treatment technologies has been uneven across countries (Annex 2, Table A1). The earlier adopters of these technologies were countries with water shortages and the capacity to finance research and investment, such as Australia [16,17], Spain [39], and Israel [11].

Following the UN classification [40], the standard GTAP dataset categorizes the water industry to encompass activities related to the collection, treatment, and distribution of water for domestic and industrial needs. The water sector reflects the collection of water from diverse sources and its distribution through various methods, including wastewater treatment and desalination.

To introduce alternative water sources in the CGE, several assumptions were made. Desalinated water is produced from the



**Fig. 2.** Schematic description of the methodology.

Note: The trajectories are linear purely for illustrative purposes. Text boxes share colors with trajectories to indicate correspondence between labels and their respective paths. The economic indicators are e.g. sectoral production and regional/country GDP. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

abundant resource – seawater. Therefore, the scarcity value attributed to depletable natural resources is not applicable. Likewise, treated water is produced by the reuse and purification of wastewater and brackish water that enters the system. Accordingly, rather than being defined as a natural resource, desalinated and treated water activities are considered as economic industries, joining the freshwater industry to pump, collect, treat, and distribute water to consumers.

Like any other sector, the water sector in GTAP reflects monetary transactions between the sector and other industries and economic agents [23]. The challenge was to split these values between the three new water sectors -water desalination, treatment, and distribution-employing a split procedure [41]. The water distribution sector after the split refers to the collection and distribution of precipitation, surface, and groundwater.

The share of each new sector in the original sector is required to perform the split. The supply data was mainly based on [42] and the demand data was mainly based on [43,44]. Where demand data was unavailable, the estimate was aligned with the supply data. The costs of inputs for desalinated water production were available mainly for the MSB countries [43,45]. The average data for the regional estimates in the global database were based on the largest countries in these regions. Capital and labor data follow available sources for the characteristics of each country/region [31,44–46]. Supplementary Material reports a detailed description of the methodology and the data used to represent alternative water sectors in GTAP-AW.

### 3.2. The pre-set of agriculture sectors

To simulate an irrigated agriculture that benefits from several types of alternative water sources, the grain crops sector in GTAP was divided into rainfed and irrigated grain crops sectors employing the split procedure [41]. The main parameters to update the split matrices with the agricultural data were the share of the cultivated area equipped for irrigation, and the ratio of irrigated-to-rainfed yield (Annex 2, Table A3), representing the added value of irrigation to yield of crops [42]. The country-specific split tables are constructed assuming that the market prices of irrigated and rainfed crops are similar and that the share of investment in irrigated crops follows the rainfed-to-irrigated crop yield ratio.

For the study, the resulting three water and two agriculture sectors are represented as activities and commodities in the GTAP database. On the supply side, the five subsectors are altered by the intermediate inputs used in each industry and the factor endowment of capital, natural resources, labor, and land. Annex 3, Annex 4 and the Supplementary Material present the key data and tools for splitting water and agricultural sectors.

### 3.3. Baseline for 2050 and CC effect

The Shared Socioeconomic Pathways (SSPs) are used to project possible futures of the world in terms of levels of economic development, technological advancement, and population growth.

To analyze the value of alternative water technologies and CEA in the future when CC is expected to become significant, we created a baseline equilibrium that reflects the state of the economy in the year 2050 according to the SSP2-Baseline [34]. The SSP2-Baseline describes a middle-of-the-road world where trends broadly follow their historical patterns of global socio-economic development, with moderate attainments and challenges in achieving economic growth and maintaining the capacity of global institutions and medium challenges to mitigation and adaptation. The SSP2-Baseline scenario represents the world without new policies to address CC, and the global mean temperature is projected to increase by 3.8–4.2°C above pre-industrial levels by the end of the century. To calibrate the model to the SSP2-Baseline, the increase in key economic indicators (Real GDP, Population, Labour, Physical capital, and Arable land) based on previous studies [35,47] was imposed. Land availability as a production factor heavily depends on CC effects and, therefore, represents the state of land use, land cover, and ecosystem services. Annex 3 presents the primary data served for the 2050 SSP2-baseline projection.

### 3.4. RCP mitigation efforts

Consistent with most global CGE models, GTAP-AW framework excludes natural water as an endowment given the complexity of representing a commonly unpriced primary factor of production in a global CGE model [16,17]. Consequently, we adopt the standard approach of introducing the impacts of CC indirectly through their effects on capital and land [20]. Representative Concentration Pathways (RCPs) project varying levels of GHG emissions and resulting levels of CC in the SSPs. In RCPs, CC effects are represented indirectly through their influence on capital and land, as changes in water availability drive shifts in land use and capital investment and vice versa [35]. The SSP2-RCP4.5 scenario assumes a moderate climate policy [35]. As a result, the 2050 projections under SSP2-RCP4.5 differ from those of SSP2-Baseline in terms of agricultural land use, capital investment, and ultimately, GDP [48]. The model was calibrated to each scenario. Annex 4 specifies the key data served for the 2050 RCPs projection.

### 3.5. CEA adoption

CEA practices like hydroponics allow for the efficient use of scarce land and water sources in arid regions. However, these technologies are more intensive in skilled labor and energy than traditional agriculture practices [14], leading to potential environmental burdens. Yet, their industrial-scale production and technical improvements allow for significantly higher output capacities and production efficiencies [49]. Hydroponic technologies are increasingly applied to growing leafy greens, and their technological adoption to vegetables is foreseen in the near future. Nevertheless, a significant breakthrough is required to employ the technology for field

crops such as tree fruits [50–55].

To evaluate the potential contribution of innovative agricultural practices in adapting to CC we simulate a scenario with the following key assumptions for the year 2050.

1. Approximately 30 % of irrigated agriculture is assumed to implement CEA technologies, specifically adopting the productivity and input efficiency metrics of hydroponic practices. This assumption is grounded in the feasibility of various crops for hydroponic cultivation (Annex 5). The selection of crops for this analysis aligns with the projected 2050 dietary patterns in Egypt, which outlines the expected water use and agricultural yields in North Africa [49,56].
2. CEA is modeled following hydroponic cultivation characteristics, which can potentially yield 2 to 10 times more than traditional irrigated crops while enhancing water efficiency by up to 60 times compared to conventional agricultural methods [52,53].
3. We follow FAO [49] assumption that an increase of 25 % in skilled labor is required to sustain the growth of enhanced agricultural practices such as hydroponics.

#### 4. Results

We explore the economic value of alternative water sources and CEA technologies as a means of adaptation to CC. To do so, we compare the results of.

- Orig - the original model (GTAP 6, and Database v10).
- GTAP-AW- the modified dataset and model with explicit representation of three water sectors (distribution, desalination, and treatment) and two-grain crop sectors: rainfed and irrigated.
- GTAP-AW\_CEA – the GTAP-AW with the implementation of CEA technologies that follow characteristics of hydroponics for 30 % of irrigated crops, including an external shock to the productivity of irrigated land and skilled labor.

A comparison of results between the SSP2-Baseline scenario and the counterfactual SSP2-RCP4.5 scenario describes the effects of mitigation and adaptation to CC on economies in 2050. Even though the model is global, the representation of the main findings focuses on the MSB countries at the core of the analysis.

##### 4.1. Water-energy-food nexus

We begin by examining the impact of alternative water sources and CEA on the WEF nexus under CC by exploring the results of the volume of output of agricultural activities in 2050 under SSP2-RCP4.5. Fig. 3 illustrates a percentage change of the total grain crop production in the modification (GTAP-AW) and the modification with CEA (GTAP-AW\_CEA) vs. the results of the original GTAP (Orig). The results show that the availability of alternative water sources increases the domestic production of grain crops in North Mediterranean countries. Adopting high-skilled, labor-intensive CEA technologies strengthens the comparative advantage of Israel, Italy, and Greece, while having minimal impact on crop production in other countries in the region. These findings highlight the significant value of alternative water sources and precision agriculture technologies for the agricultural sector, particularly in countries expected to experience higher growth in capital and skilled labor—both crucial for the successful implementation of capital- and skilled-labor-intensive technologies, such as nonconventional water resources and CEA.

The impact of CEA is most evident when comparing the production of irrigated grain crops with the adoption of CEA as 30 % of the sector versus the results of the same industry in the GTAP-AW - with alternative water sources but without CEA (Fig. 4). The countries that gain the most from precise agriculture technologies are those with an initial higher share of irrigation and skilled labor. The

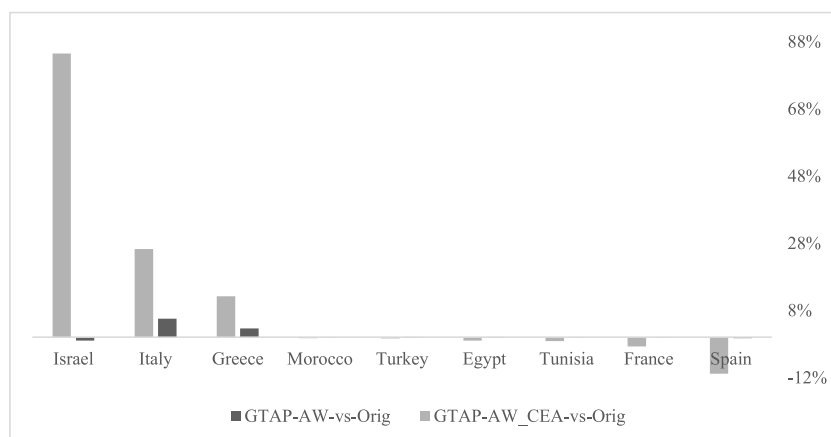


Fig. 3. Projected percent change in grain crops production in GTAP-AW vs. original model in 2050 SSP2-RCP4.5.

change in irrigated agriculture is correlated with the GDP (correlation level greater than 0.6).

The significant advantage of global CGE models is the ability to explore the impacts on international trade. Fig. 5 represents the change in the private household consumption of imported agricultural products, providing complementary information to the domestic agricultural production results presented in Fig. 3. Fig. 5 investigates the change in imports of grain crops due to alternative water sources and precise agriculture compared to the original model. The results reflect the different reactions of the MSB countries to the CC impacts in 2050. In most countries, agriculture imports decline compared to the original model, signaling that alternative water sectors increase food security. The impact of CEA on imported grain crops is essentially the opposite of its effect on domestic production. Israel is expected to reduce its imports more significantly due to CEA technologies. Italy and Greece are projected to increase both domestic production and import of grain crops, which can be explained by the high demand that is met jointly by domestic supply and import.

These results highlight the importance of mitigation efforts and the use of alternative water sources and irrigation practices to reduce agricultural import costs and related GHG emissions.

Next, we explore the impact of alternative water sources and CEA on the water sector. For this purpose, we compare the water production in the original model with the total of the three split water sectors in the modifications. While the total water production under GTAP-AW changes negligibly compared to the original model, adding CEA reduces water production significantly (Fig. 6). The results reflect that highly water-efficient, precise agriculture technologies can substantially reduce water shortages in water-stressed economies of the Mediterranean while facing CC. The leaders in this respect are Israel, Spain, Greece, and Italy.

Fig. 7 presents the results of the sensitivity analysis for various rates of CEA adoption by the year 2050 in the range of 24-30-36 percent of irrigated agriculture under the SSP2-RCP4.5 scenario in the GTAP-AW\_CEA model against GTAP-AW. The results indicate that CEA contributes to the domestic production of irrigated crops in the countries with higher initial irrigation and skilled labor shares, specifically Greece, Italy, and Israel. An increase in CEA adoption reduces water use across all water types in MSB countries. Notably, introducing an energy-intensive CEA has a negligible, mostly negative impact on electricity production across the region. The possible explanation is that water-efficient, precise agriculture practices significantly reduce water use. Therefore, the increase in the demand for electricity for irrigated agriculture is counterbalanced by the decline in electricity for energy-intensive water desalination, and treatment.

#### 4.2. Alternative waters and CEA as means of adaptation

The adoption of Controlled-Environment Agriculture (CEA) presents an intriguing scenario for demonstrating the model's capabilities, as the implementation of this technology significantly alters the demand for water services. We start with exploring the scenario that compares the adoption of CEA with and without the inclusion of alternative water resources.

Fig. 8 illustrates the impact of adopting CEA on water usage across MSB countries by the year 2050 using two distinct economic models: GTAP\_AW and Orig. The figure depicts the percent change in water use from 2014 and presents the difference in percent change in water-related sectors (one in the original model and three in GTAP\_AW) with CEA compared to the respective model without precise agriculture technologies. The results consistently show a reduction in water use across all Mediterranean countries compared to when CEA is in place. This highlights the potential of CEA to mitigate water stress by increasing water efficiency in agricultural production.

The magnitude of change varies by country, reflecting differences in initial agricultural water dependency, climate impact projections, and the adaptability of local farming systems to CEA in terms of skilled labor. Our findings underscore the significant contribution of CEA in altering water demand dynamics, particularly when paired with alternative water resource strategies. This analysis highlights the critical role of integrated approaches in optimizing resource use and enhancing the resilience of agricultural systems. The results clarify the potential of CEA and non-conventional water sources to ease natural water pressures, making it a central technology for sustainable agricultural practices amid CC challenges.

To investigate the role of alternative water sources and precise agriculture as means of adaptation to CC, we also provide the results of the comparison between the SSP2-Baseline and SSP2-RPC4.5 in GTAP-AW with and without CEA in irrigated agriculture between 2014 and 2050. Fig. 9 focuses on the separated volumes of rainfed and irrigated crops with the possibility of CEA technologies. The result clarifies that in most of the MSB countries, the growth in agricultural production between 2014 and 2050 is mainly driven by

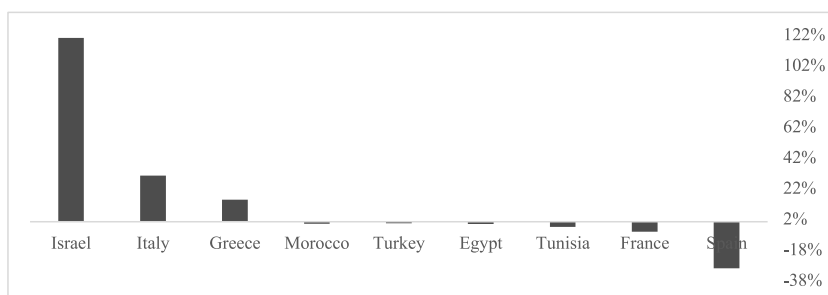


Fig. 4. Projected percent change in irrigated grain crops in GTAP-AW CEA vs. without in 2050 SSP2-RCP4.5.

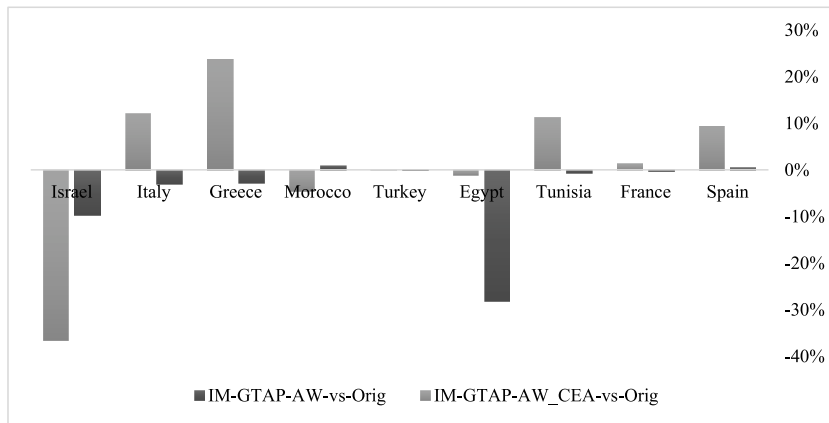


Fig. 5. Projected percent change in import of grain crops in GTAP-AW vs. original model in 2050 SSP2-RCP4.5.

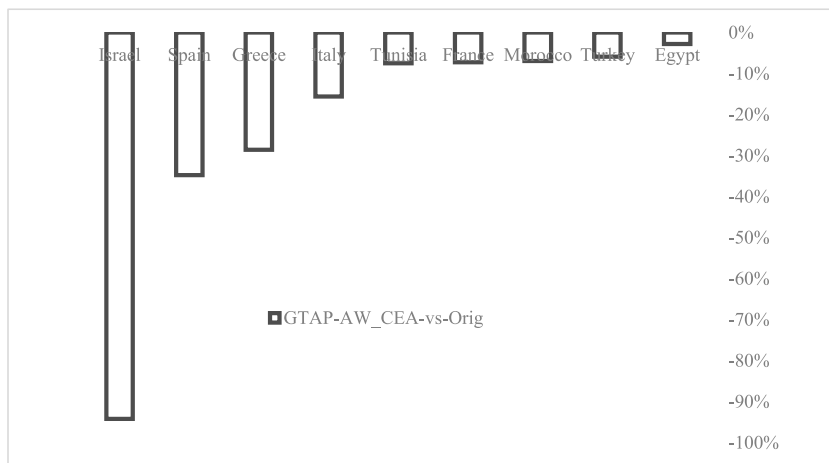


Fig. 6. Projected percent change in total water production in GTAP-AW with CEA versus the original model.

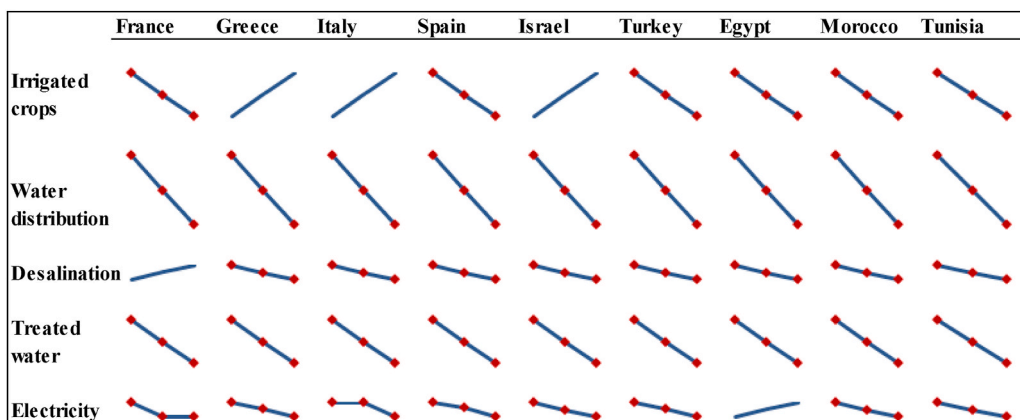


Fig. 7. Sensitivity analysis for different adoption shares of CEA in GTAP-AW\_CEA in 2050 SSP2-RCP4.5 vs. GTAP-AW (without CEA). The dotted lines represent a reduction in the change in the value of the indicator between 2014 and 2050 when CEA is applied. The non-dotted lines represent an increase.

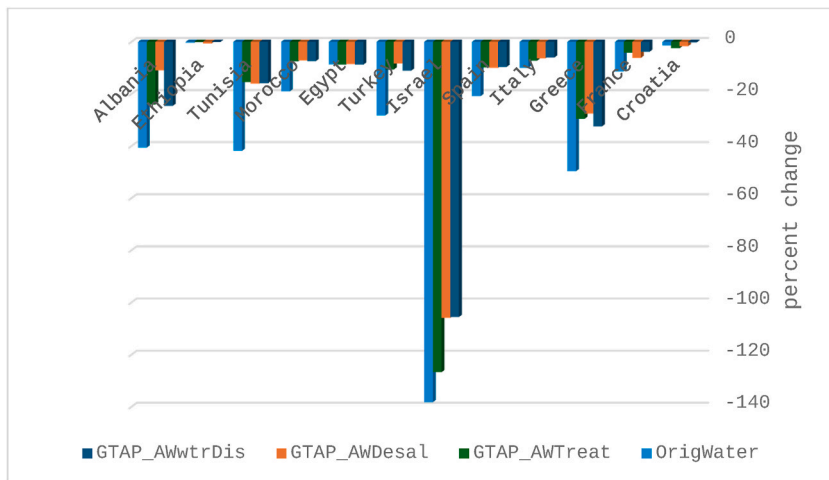


Fig. 8. CEA impact on Percent Change in Water Use by MSB Country in 2050 (Compared to 2014) under SSP2-RCP4.5 scenario.

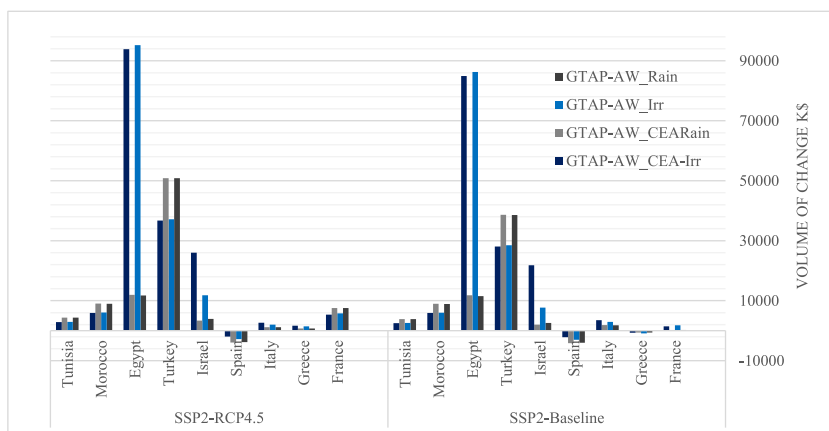


Fig. 9. The projected volume of change in irrigated and rainfed agriculture in the Mediterranean countries by scenario, 2014–2050.

rainfed crops compared to irrigated crops, stressing the vulnerability of food provision to CC impacts in this region and the importance of adopting CEA technologies. The two exceptions are Egypt, where 99 % of the crops are irrigated as of 2014, and Israel, where CEA investments are already in place. Furthermore, most countries show almost no yield reduction in the SSP2-RCP 4.5 compared to the SSP2-baseline. The projected changes volume is higher in SSP2-RCP 4.5 compared to the SSP2-baseline.

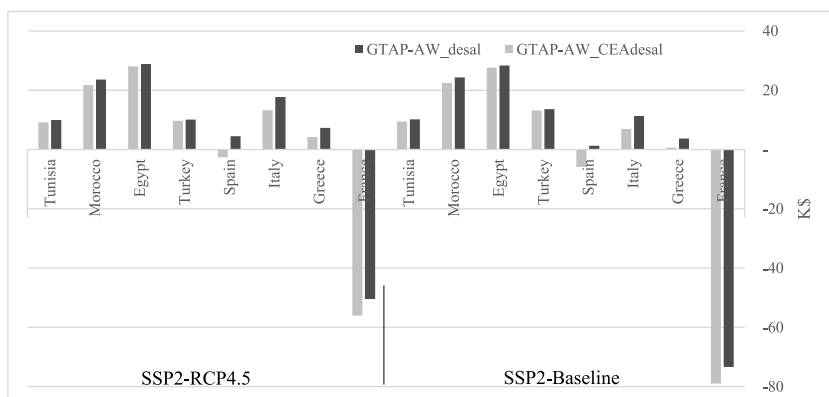


Fig. 10. The projected change in the desalination sector in the Mediterranean countries by scenario, 2014–2050.

Despite the expected reduction due to the mitigation costs in RCP4.5, there is still a growth or minimal change in the volume of both rainfed and irrigated crops sectors in most countries. To better explain the behavior in the different scenarios, a correlation test was imposed between the volume of change and the primary factors that were altered in the different scenarios. The volume of change in rainfed and irrigated agriculture (Fig. 9) is correlated with the GDP (correlation level greater than 0.6).

Comparing results for SSP2-RCP4.5 and SSP2-Baseline scenarios reveals distinctive patterns in the desalinated and treated water sectors (Figs. 10 and 11). The addition of nonconventional water industries and irrigated crops drives an increase in the volumes of the water industry in most countries under SSP2-RCP4.5 compared to SSP2-Baseline, stressing again the vital role of alternative water sources as a means of mitigating the CC-driven water scarcity. Adopting water-efficient CEA technologies reduces the need for desalination in all scenarios.

A similar pattern to desalination is observed for the treated water sector but at much higher volumes (Fig. 11).

The freshwater distribution sector reflects the highest increase in most countries, followed by the treated and desalinated water sectors. This trajectory follows the relative cost of capital investment required by each industry, meaning that the most economically feasible change will be implemented in the least capital-intensive sector, i.e., the production and distribution of fresh water. Out of the alternative water sources, treated water is less costly and more common than desalination. Water-efficient CEA technologies diminish the change in all water types and for all scenarios.

Next, we examine the change in electricity production by climatic scenario. To focus specifically on the change related to the mitigation and adaptation efforts, the results in Fig. 12 reflect the change compared to the values of the SSP2-Baseline. Although the share of agriculture in the GDP of most of the world regions is relatively low, the addition of alternative water sources and CEA as a means of adaptation is expected to alter electricity production and costs. However, the change in electricity costs also depends on the share of other electricity-intensive economic activities. In the SSP2-RCP4.5 scenario, the electricity production in GTAP-AW is lower than in the SSP2-Baseline. Energy-intensive CEA adds slightly to electricity consumption and offsets the reduction, calling for the need to produce clean electricity for energy-intensive CEA to prevent increased carbon emissions.

As the response to the scenarios among MSB countries is not uniform, Table 1 summarizes the cumulative impact of CEA on the food security index in Mediterranean countries. The significance is measured under three parameters: if the CEA adds to an increase in agricultural output under climate scenario (RCP4.5); if the CEA adds to a reduction in agricultural import under climate scenario (RCP4.5); if the CEA contributes to agricultural output when CC is considered at all. Overall, the CEA contributes to food security in all major countries of the Mediterranean. The response is more robust in the countries where the share of irrigated crops and skilled labor is higher.

Finally, the overall economic impact can be tracked through the change in regional GDP in SSP2-RCP4.5 compared to SSP2-baseline. Fig. 13 illustrates the percent change in the GDP in 2050 compared to the original model following the effect of CC, RCP mitigation, and CEA adaptation. While SSP2-RCP4.5 reflects the middle-of-the-road scenario implementing the costs of mitigation policy that affect GDP, the CEA technologies diminish the decline in GDP in SSP2-RCP4.5 and would create an absolute increase in GDP in SSP2-baseline. In Fig. 13, the decline in GDP under the climate scenario is more pronounced for all MSB countries when using GTAP-AW. This is because the modified model explicitly incorporates the costs associated with adopting non-conventional water sources. These adaptation costs are not accounted for in the original GTAP. As a result, the GTAP-AW model provides a more realistic representation of the economic impact of climate adaptation measures. The value of adopting CEA technologies varies among countries, contributing up to 4 percent of GDP.

To conclude, the results of the study stress the importance of analyzing the WEF nexus in the Mediterranean basin under the threat of CC with the explicit representation of alternative water sources and novel agricultural practices in the global CGE framework.

## 5. Discussion

Our study marks a pioneering effort in integrating alternative water sources and precise agriculture into a global neo-classical CGE model, particularly within the context of the Mediterranean Sea countries and adaptation to climate change. This research endeavors to understand the broader implications of these strategies on food security, water use, and electricity production.

The GTAP-AW model advances the well-established GTAP framework by explicitly representing desalinated and treated water as distinct economic sectors in addition to the water distribution industry. The three water-related and two agricultural sectors, along with electricity, industry, and other economic sectors, are characterized by their use of primary factors of production (capital, natural resources, labor, and land) and intermediate inputs. Then, the climate change projections according to SSP2-RCP4.5 were assessed, and the contribution of alternative water sources and CEA to cope with CC was evaluated, focusing on key economic indicators.

First, we investigate the impact of GTAP-AW to explicitly represent alternative water sources and the adoption of CEA on food security, water use, and electricity production compared to the original model. The results indicate that the availability of alternative water sources enhances the domestic production of grain crops in North Mediterranean countries. The adoption of high-skilled labor-intensive CEA technologies strengthens the comparative advantage of Italy, Israel, and Greece. These findings underscore the significant value of alternative water sources and precision agriculture technologies for the agricultural sector. In most countries, agricultural imports decline relative to the original model, suggesting that alternative water sources and CEA contribute to increased food security. Countries can reduce their reliance on imports by utilizing domestic water resources more efficiently and optimizing growing conditions through CEA, thereby decreasing vulnerability to global supply chain disruptions and price volatility.

Second, we investigate the role of alternative water sources and precise agriculture as means of adaptation to climate change. For this purpose, we compare the GTAP-AW outcomes for 2050 according to the SSP2-Baseline and SSP2-RCP4.5 with and without CEA. The results indicate that alternative water practices and controlled environment agriculture may bring about a positive trajectory in

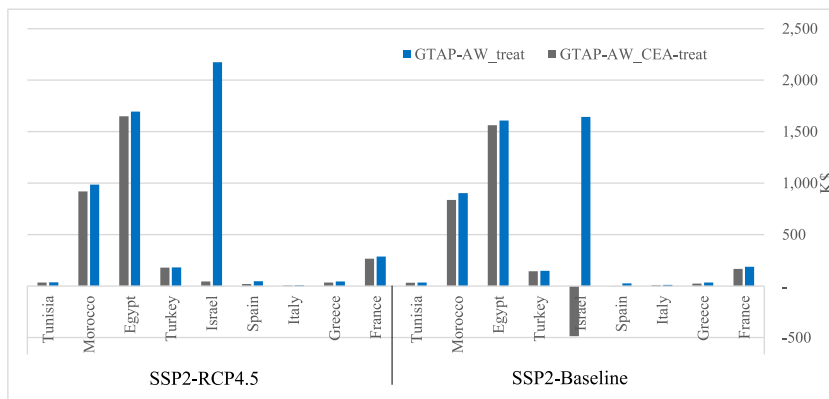


Fig. 11. Projected change in the treated water sector in the Mediterranean countries by scenario, 2014–2050.

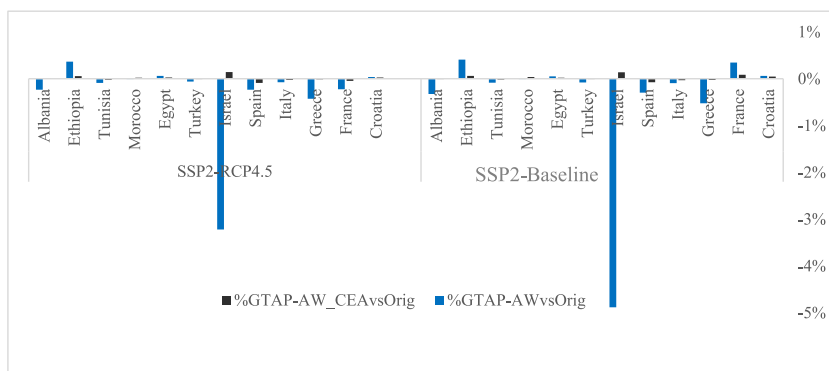


Fig. 12. The change in the electricity production in GTAP-AW vs the original GTAP model in the Mediterranean countries by scenario, 2014–2050.

**Table 1**  
The contribution of CEA to food security in the MSB.

MSB Country	Agricultural production under SSP2-RCP4.5 with CEA greater than in SSP2-Baseline	Agricultural production under SSP2-RCP4.5 with CEA greater than without	Reduction in agricultural imports in SSP2-RCP4.5 due to CEA	Overall contribution to food security <sup>a</sup>
Egypt	-	+	-	+
Spain	+	-	+	++
France	-	+	+	++
Tunisia	-	+	+	++
Turkey	-	+	+	++
Morocco	+	+	-	++
Italy	+	-	+	++
Greece	+	+	+	+++
Israel	+	+	+	+++

<sup>a</sup> The overall contribution to food security reflects the total positive impact in each region.

food security and the global economy, without notably affecting energy use.

The results clarify that in most of the MSB countries, the growth in agricultural production between 2014 and 2050 is mainly driven by rainfed crops as compared to irrigated crops, stressing the vulnerability of food provision to CC impacts in this region and the importance of adopting CEA technologies. Irrigated agriculture tends to have higher yields than rain-fed agriculture. This gap, identified in previous studies [6], continually increases with improved precision of irrigation technologies, fertilization practices and, ultimately CEA.

CC adaptation in food and water production is strongly correlated to the country’s GDP and the share of desalinated water out of total sources. Countries with a significant fraction of desalinated water have a unique advantage in adapting to water scarcity exacerbated by CC. By securing irrigation-water independently of natural water sources, they can support local agriculture and minimize reliance on imported food, thus increasing food security. Similarly, the changes in country’s electricity are correlated with its projected GDP in 2050. The possibility to use alternative water sources increases in the volumes of the total water supply in most

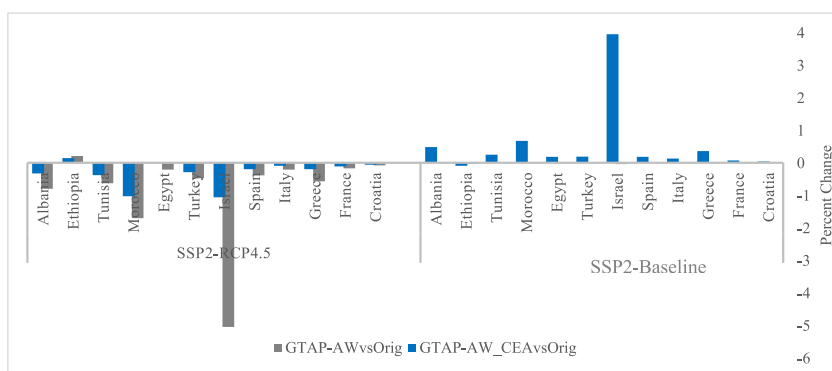


Fig. 13. Percent change in GDP in 2050 in GTAP-AW vs. original model by scenario.

countries under SSP2-RCP 4.5 compared to the SSP2-baseline, stressing the vital role of alternative water sources in mitigating the water shortage driven by the CC.

This study shows that alternative water sources and CEA can positively change CC adaptation and food security, although additional resources are needed to implement such measures. The value of adopting CEA technologies varies among countries, contributing up to 4 percent of GDP. The findings provide valuable information for decision-making processes related to sustainable agriculture and water practices in water-stressed countries like the MSB region, with implications for similar regions worldwide. These results reconfirm that cooperation between institutions, policymakers, and stakeholders is essential for managing water resources to mitigate CC impacts and support food security.

It is important to acknowledge that the first best solution to augmenting the water supply in South Mediterranean countries should concentrate on leaks from existing water infrastructure. Next, nations that invest heavily in desalination and climate-resilient agriculture demonstrate a strong capacity for climate adaptation. They can better respond to fluctuating weather patterns and water scarcity, which are direct impacts of climate change, by creating a stable supply of water for domestic and agricultural use. However, to increase seawater desalination and wastewater treatment high investment costs are involved. These important aspects are beyond the scope of this study.

To convey the direct link between precipitation and natural water sources, the follow-up study should investigate the role of alternative water sources while facing CC with explicit modeling of natural water as a primary factor of production, i.e., the endowment. Moreover, the study could be extended to the environmental impact of alternative water sources and precise agriculture. This would allow for a more comprehensive assessment of the trade-offs between food security and environmental sustainability.

Our findings underscore the critical role of alternative water sources and precise agriculture in adapting to climate change and enhancing food security in the Mediterranean region. These findings are robust across various assumptions. This study advocates for strategic investments in alternative water sources and precise agriculture as key measures to ensure food security in water-stressed regions, highlighting the necessity for collaborative efforts among institutions, policymakers, and stakeholders in sustainable water and agriculture practices.

#### CRedit authorship contribution statement

**Ruslana Rachel Palatnik:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Orna Raviv:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julia Sirota:** Visualization, Validation, Software, Formal analysis, Data curation. **Mordechai Shechter:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

#### 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.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wre.2025.100256>.

## Annex 1

Table A2

Population (in thousands) and share of Mediterranean population (in %) in 2020 and 2060, by countries and regional area

Countries	Population (in thousands)		Share of Mediterranean population (in %)	
	2020	2060	2020	2060
Egypt	107,465	174,311	19.0 %	25.4 %
Turkey	84,135	96,017	14.9 %	14.0 %
France	64,480	64,903	11.4 %	9.5 %
Algeria	43,452	63,554	7.7 %	9.3 %
Italy	59,501	48,233	10.5 %	7.0 %
Morocco	36,689	46,214	6.5 %	6.7 %
Spain	47,364	41,257	8.4 %	6.0 %
Syria	20,773	41,042	3.7 %	6.0 %
Jordan	10,929	16,131	1.9 %	2.4 %
Tunisia	12,162	14,512	2.2 %	2.1 %
Israel	8757	14,332	1.5 %	2.1 %
Palestine	5019	10,036	0.9 %	1.5 %
Libya	6654	8762	1.2 %	1.3 %
Portugal	10,298	8683	1.8 %	1.3 %
Greece	10,512	8506	1.9 %	1.2 %
Serbia	7358	5238	1.3 %	0.8 %
Lebanon	5663	4947	1.0 %	0.7 %
Bulgaria	6979	4656	1.2 %	0.7 %
Croatia	4097	3067	0.7 %	0.4 %
BiH	3318	2523	0.6 %	0.4 %
Albania	2867	2218	0.5 %	0.3 %
Slovenia	2118	1920	0.4 %	0.3 %
Macedonia	2111	1784	0.4 %	0.3 %
Kosovo	1671	1575	0.3 %	0.2 %
Cyprus	1238	1404	0.2 %	0.2 %
Montenegro	629	560	0.1 %	0.1 %
Malta	515	507	0.1 %	0.1 %
Southern and Eastern Shores	342,935	491,263	60.7 %	71.7 %
Northern Shore	222,147	194,053	39.3 %	28.3 %
Mediterranean	565,083	685,317	100 %	100 %

Source [1].

## Annex 2

## Splitting water and agriculture sectors

The methodological steps in GTAP to transform the database to include alternative water and irrigated crops include.

- Disaggregating the MSB countries from their regions into specific countries and values [57].
- Disaggregating the water and electricity sectors out of their industry groups [42,44,57,58].
- Splitting the water sector into three sub-sectors – freshwater, desalinated water and treated water [41].
- Splitting the GrainCrops sector into irrigated and non-irrigated crops [59].

The split was performed using the standard procedure of SplitCom application, in which original dataset tables were reformed to use sub sectors and represent multiple water values (Table A 3) and multiple agriculture values (Table A 4).

Data for the water split.

Table A 3

Regional disaggregation and share of water sources in the base year (2014) [41]; [58]; [42]; [44].

	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 %

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**Table A 3** (continued)

	Region/Country	Natural water	Desalinated water	Treated water
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 %

Data for the split grain crops sector into irrigated and rainfed grain crops.

**Table A 4**

Share of irrigated land, irrigated crops, and yield ratio by region [59].

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 %
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 %

### Annex 3

#### Data for 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 [35,47,60].

**Table A 5**

Projected accumulated change between 2014 and 2050 by country according to SSP2-baseline.

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 %

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**Table A 5** (continued)

Country/Region	Real GDP	Population	UnSkilled Labor	Skilled Labor	Physical capital	Land Cover (Cropland)
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 %

**Annex 4***Data for SSP2-RCPs*

The RCP4.5 scenario was based mainly on IIASA model results per the RCP assumptions put by IPCC [35,47]. The population and labour volumes were assumed to be similar to the SSP2 baseline data.

**Table A 6**

Projected accumulated change between 2014 and 2050 by country according to SSP2-RCP4.5

Country/Region	RCP	RCP 4.5		
		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 %

**Annex 5***Data for CEA scenario***Table A 7**

The data and method to calculate the % of feasible crops for CEA

Crops	% Crops 2014	% Growth 2050	% Hydroponic feasible	Total feasible	Reference
Wheat	0.12	0.06	0.00	0.06	
Maize	0.13	0.06	0.25	0.09	[53]

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Table A 7 (continued)

Crops	% Crops 2014	% Growth 2050	% Hydroponic feasible	Total feasible	Reference
Rice	0.03	0.04	0.50	0.05	[55]
Sugar beet	0.06	0.05	0.25	0.07	[54]
Soybean	0.05	0.00	0.25	0.01	[52]
Tropical Fruits	0.05	0.07	0.00	0.07	
Potato	0.03	0.03	0.50	0.04	[61]
Vegetables	0.17	0.14	0.75	0.27	(Chen P. , Zhu, Kim, Brown, & Huang, 2020) [62]
Pulses	0.03	0.00	0.50	0.02	[53]
Sunflower	0.01	0.00	0.00	0.00	
Sugarcane	0.09	0.12	0.00	0.12	
Temperate Fruits	0.03	0.02	0.00	0.02	
Olives	0.04	0.00	0.00	0.00	
Sorghum	0.01	0.01	0.50	0.01	[53]
Banana	0.01	0.01	0.00	0.01	
Groundnuts	0.05	0.00	0.00	0.00	
Fodder grasses	0.11	0.38	0.50	0.43	[53]
<b>Total</b>	<b>1.00</b>			<b>1.29</b>	

The percentage of the crop yield in the years 2014 & 2050 was based on AWESOME D2.3, WATNEEDS modeling report [56], and the hydroponic feasibility assumptions were based on the knowledge gathered in AWESOME WP5 on hydroponic and aquaponic practices and the cited references that were translated into the following grade-sections.

0	not feasible in the near future
0.25	feasible, in tests
0.5	feasible with minor growth in yield
0.75	feasible with medium growth in yield
1	higher (5–10 times) yield growth, like in lettuce

## Data availability

The authors do not have permission to share data.

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