



Proceeding Paper

# Macroeconomic, Food and Energy Security Implications of Water Dependency under a Changing Climate: A Computable General Equilibrium Assessment <sup>†</sup>

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<sup>†</sup> Presented at the ICSD 2021: 9th International Conference on Sustainable Development, Virtual, 20–21 September 2021.

**Abstract:** Water, food and energy are three interconnected fundamental needs. Climate change potentially hinders the security of all of them, acting as a threat multiplier. Accordingly, this paper addresses the consequences of two climate scenarios in the 2030 horizon: specifically, it addresses the highest and lowest representative concentration pathway (RCP), 8.5 and 2.6; the relative changes in freshwater availability; and their sectorial and macroeconomic impacts. Furthermore, it addresses the importance of developing the simulations through a dynamic computable general equilibrium (CGE), which, uncommonly, explicitly considers the water endowment as a factor for both the irrigated agriculture and the energy sector. The results highlight that both the activation of the water–energy link and climate-induced freshwater availability changes have significant impacts on the simulation outcomes, even in the short-term horizon of 2030. Moreover, it reveals that water scarcity issues are expected to arise in the Middle East, leading to significant food security issues, as well as to significant consequences for the behaviour of the energy sector. Indeed, while we would expect that dependency on a scarce resource would lead to security issues, the Middle East energy sector appears to not straightforwardly behave as a resource attractor, likely due to its economic relevance both within the region and internationally.

**Keywords:** water–food–energy nexus; computable general equilibrium models; climate change; water modelling



Citation: Bardazzi, E.

Macroeconomic, Food and Energy Security Implications of Water Dependency under a Changing Climate: A Computable General Equilibrium Assessment. *Environ. Sci. Proc.* **2022**, *15*, 1. <https://doi.org/10.3390/environsciproc2022015001>

Academic Editors: Cheyenne Maddox and Lauren Barredo

Published: 30 March 2022

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## 1. Introduction

Food and energy are two basic needs, fundamental for both sustainable development and the general thriving of the humankind [1,2]. Both are part of the concept of a water–energy–food nexus, an idea that stresses the notion of interconnectedness and the necessity of addressing the reciprocal influences between resources [3,4]. Historically, resource security studies were developed through separate assessments, but after the introduction of the nexus there was an increasing recognition of the fundamental need to account for influences and externalities to properly address security assessment issues [5–7].

Hence, there is a growing need for instruments able to perceive the connections between these factors. This work contributes to the nexus research field, improving a dynamic computable general equilibrium (CGE), ICES [8,9], expanding the explicit connection between water as an endowment and irrigated agriculture, which is usually well-addressed in the general equilibrium modelling literature, with water as an endowment also for the energy sector, an uncommon trait in CGEs [10,11].

Hence, there are two main aims of this study: on the one hand, it evaluates the relevance of the methodological modification in CGEs to implement a direct connection

between water and energy and have a better perception of the nexus in the models. On the other hand, it assesses the consequences of freshwater availability changes relative to two RCPs in the 2030 horizon in terms of food, energy security and macroeconomic impacts. The freshwater availability assessment highlights Middle East as a particularly vulnerable area, being the only region subject to freshwater constraints in this timeframe. Thus, the last section focus on the analysis of sectoral and macroeconomic consequences relative to water scarcity in this specific region.

Accordingly, Section 2 describes our materials and methods, Section 3 presents the results, Section 4 discusses the findings, and Section 5 draws the conclusions.

## 2. Materials and Methods

The model used to develop the simulations was specifically adapted to have a comprehensive view of the water–energy–food nexus in a CGE, particularly focusing on the usually overlooked water dependency of the energy sector and the consequent competition between irrigated agriculture and energy for water. Indeed, while several CGEs explicitly address the link between water resources and irrigated agriculture in the models (e.g., [12–14]), very few explicitly expressed the link for the energy sector, e.g. [15,16], and without explicit acknowledgement of the nexus issue per se, the resulting sectoral competition issues, or its implications in climate change assessments.

The main idea was, therefore, to create a model that could perceive the connections to water for both sectors, highlighting the eventual competition and security issues in its simulations, especially in a context of climate-induced water constraints. Accordingly, the framework was built following a common methodological approach in the literature [14,17] and by implementing an almost Leontief configuration for the water endowment substitution with other endowments as in [18–20], to stress the importance of water endowment in the production processes. The economic values of water were assigned based on [21] for irrigated agriculture and on [22,23] for the energy sector. The main description of the changes is shown in Figure 1. For a detailed description of the methodology, we refer to [11].

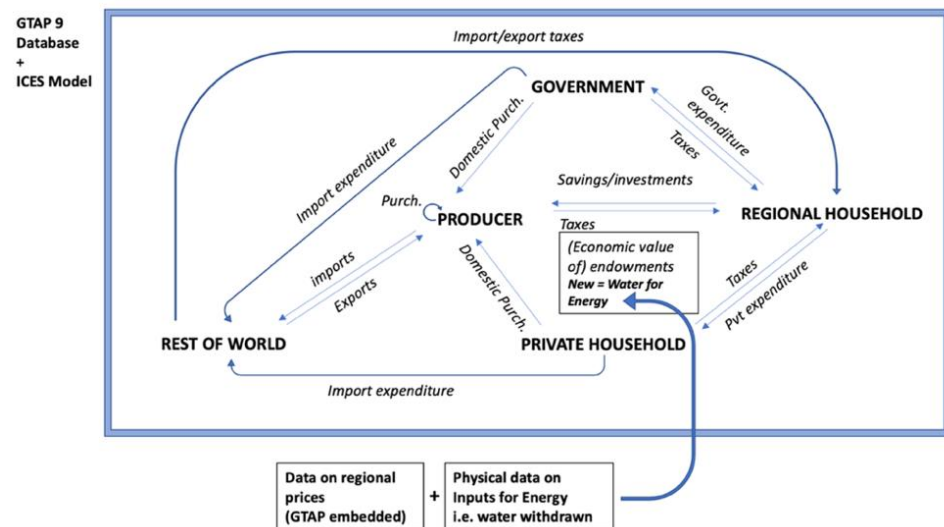


Figure 1. Representation of the main methodological changes (based on [11,24]).

For simplicity and data availability reasons, the simulations were carried out in a 10-region and 5-sectors aggregation (Regions: OECD Europe, OECD Americas, OECD Oceania, other Europe–Eurasia regions, Asia, China, India, the Middle East, Africa, and Latin America. Sectors: irrigated agriculture, rainfed agriculture, energy, industries, and services) from the database GTAP9 [25]; with base year 2011. Therefore, the framework was updated to explicitly model the water–energy link and assess how much this can influence future expectations in terms of food and energy security as well as the implications of

a climate change assessment itself. This feature, in particular, allows for a more precise analysis of the impact of eventual shocks on the prices, output, consumption, and security in the relevant sectors, as well as the overall macroeconomy.

Therefore, the experiments carried out in this paper aim to address the macroeconomic and security consequences of the mitigation and adaptation of a socio-economic pathway (SSP) [26–28], the SSP2, combined with freshwater changes expectations relative to two representative concentration pathways (8.5 and 2.6) in the 2030 horizon. The focus is particularly targeted towards the analysis of how the climatic and social projections will affect freshwater availability and security, the resulting production and consumption of food and energy and the general regional macroeconomic expectations. In particular, the main experiment aims to simulate the impacts of water withdrawal changes generated by two different RCPs [29], RCP 8.5 and 2.6, and their consequences against a baseline that replicates the economic and population growth of the SSP2 based on IIASA's projections [30,31]. The experiment was carried out twice, i.e., before and after the introduction of a direct connection between water endowment and the energy sector, to underline and quantify the importance of an explicit representation of the elements of the nexus in the model.

Concerning the climatic shock calibration, the supply of water was computed using the FAO AQUASTAT Database [32] values for the total average renewable water resources for the period 2008–2012, which were projected following the changes in the median regional total runoff variable from ISIMIP [33,34] for the RCPs: 8.5 and 2.6 (highest and lowest paths). Climate forcing was addressed through GFDL-ESM2M, bias correction target through EWEMBI, and the hydrological model was H08; no social or CO<sub>2</sub> cross fertilization was assumed. Considering the uncertainty relative to the physical data projections (e.g., [35,36]) to properly evaluate the issue, we should have adopted a multi-model calibration approach. Nevertheless, the present work only uses one of the physical model compositions and two climate scenarios as a complete multi-model assessment was out of the scope of the present work. Furthermore, in this context, we assumed that there were no significant changes in the regional water withdrawal levels. Indeed, even if technological changes or economic and demographic pressures could result in variations in the regional amount of water withdrawn when compatible with the freshwater availability, the lack of data availability and the short-term characteristics of the 2030 horizon led us to assume that regional water withdrawal levels were static, even if there is space for the development of more detailed scenarios in future studies.

### 3. Results

#### 3.1. Baseline Results

The baseline calibrates the scenario through the total factor productivity, based on GDP trends and the population growth in SSP2. This leads to changes in sectoral production, as shown in columns one and four of Table 1. To quantitatively understand the importance of the water–energy link, the data are reported for before and after the activation of the water–energy link (top and bottom parts of the table).

In general, there could be a potential food security issue for OECD America, OECD Oceania, Other Europe–Eurasia and China, which decreases their irrigated agriculture internal demand (qdp) and significantly increases its foreign demand (qpm) in both specifications. This implies a shift towards a more internationally dependent provision of the good, which could lead to potential security issues. Nevertheless, this is not necessarily the case. For example, China is the region with the highest rainfed production potential; therefore, a strong reduction in and dependency on irrigated agriculture does not necessarily have to be interpreted as a risk of food security.

**Table 1.** Water-dependent output and domestic and foreign household demand between now and 2030. (Model with and without the activation of the water–energy link).

| Only Irrigated Agriculture       |                       |        |        |        |        |        |
|----------------------------------|-----------------------|--------|--------|--------|--------|--------|
| Region                           | Irrigated Agriculture |        |        | Energy |        |        |
|                                  | qo                    | qpm    | qpd    | qo     | qpm    | qpd    |
| OECD Europe                      | 42.47                 | 10.69  | −7.31  | 24.35  | 165.94 | 67.11  |
| OECD America                     | 28.68                 | 92.72  | −12.88 | 18.09  | 207.10 | 68.85  |
| OECD Oceania                     | 24.33                 | 9.74   | −9.93  | −13.87 | 207.55 | 36.43  |
| Other Eu Eurasia                 | 56.16                 | 39.63  | −22.62 | 64.15  | 151.36 | 106.08 |
| Asia                             | 91.37                 | 36.10  | 15.70  | 232.75 | 73.86  | 151.64 |
| China                            | 181.64                | 131.75 | −35.16 | 556.43 | −43.97 | 224.84 |
| India                            | 223.57                | −15.89 | 59.25  | 794.33 | −61.41 | 361.19 |
| Middle East                      | 30.00                 | 5.49   | −17.91 | 46.17  | 90.97  | 59.83  |
| Africa                           | 84.10                 | 16.93  | 16.26  | 178.18 | 135.33 | 146.86 |
| Latin America                    | 50.43                 | 28.15  | −1.66  | 43.71  | 215.90 | 119.13 |
| Irrigated Agriculture and Energy |                       |        |        |        |        |        |
| Region                           | Irrigated Agriculture |        |        | Energy |        |        |
|                                  | qo                    | qpm    | qpd    | qo     | qpm    | qpd    |
| OECD Europe                      | 61.85                 | 3.01   | 0.90   | 28.17  | 39.67  | 6.18   |
| OECD America                     | 93.31                 | 76.77  | −6.65  | −32.02 | 285.53 | −25.35 |
| OECD Oceania                     | 18.66                 | 39.20  | −13.57 | 117.12 | −21.12 | 0.12   |
| Other Eu Eurasia                 | 33.76                 | 77.50  | −17.92 | 106.42 | 98.01  | 84.68  |
| Asia                             | 78.77                 | 66.13  | 22.52  | 286.79 | 99.68  | 109.67 |
| China                            | 201.99                | 215.23 | −40.55 | 81.39  | 531.08 | 48.04  |
| India                            | 199.70                | 37.39  | 51.02  | 754.62 | −60.23 | 237.81 |
| Middle East                      | 22.89                 | 27.13  | 0.25   | 74.18  | 63.94  | 51.87  |
| Africa                           | 68.04                 | 69.61  | 28.44  | 183.06 | 149.08 | 127.73 |
| Latin America                    | 42.59                 | 58.48  | 1.29   | 111.50 | 82.31  | 67.96  |

The activation of the water-energy link produces significant changes in the production and import dynamics of both sectors. For example, in the active scenario, OECD Europe produces more, increases its domestic demand, and reduces its foreign demand in irrigated agriculture, i.e., endowment competition between sectors influences regional specialization choices and leads to a decrease in food security risks in the region. The strong effects of the activation of the water–energy link can also be detected in the energy sector. Indeed, for example, the Other Europe–Eurasia region significantly increase their energy production in the energy-dependent model. On the other hand, OECD America and China drastically reduce their energy production with respect to the inactive scenario, signalling a potential withdrawal of water from energy to be redistributed to agriculture and potential energy security issues. Focusing on the scenario with the water–energy link activated, the most significant potential security issue arises in OECD America, which decreases its energy output and domestic demand for goods, a strong signal of increasing energy insecurity in the region. Less strong, but still significant, is the energy security issue in China, which is expected to substantially increase energy requests from abroad, making the country more dependent on political agreements and eventual external shocks. The production behaviours of these regions are coherent with the fact that both OECD America and China have high-water-intensive energy production structures; therefore, the greater security

issues when accounting for water dependency can be explained by the technological and production configuration of these regions.

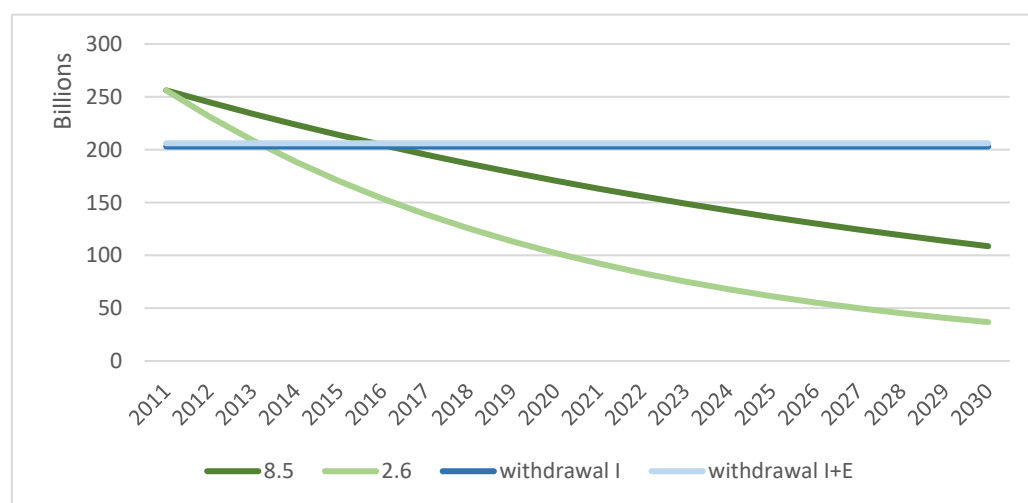
### 3.2. Freshwater Limit Assessment

To evaluate the eventual climate-induced freshwater scarcity, the amount of regional available freshwater was projected according to the expected median runoff variation under RCP 8.5 and 2.6 between now and 2030 (Table 2). These quantities were then compared to the levels of water withdrawal, considering only irrigated agriculture and agriculture and energy, assuming no technological changes and no fluctuations in the regional withdrawal levels. Under these conditions, most of the regions will not face a water availability problem between now and 2030. The only exception is the Middle East. Indeed, in this region, the water withdrawal level is too high with respect to the changes in the availability of in the 2030 horizon.

**Table 2.** Freshwater withdrawal coherency assessment (10<sup>12</sup>) m<sup>3</sup>/yr.

| Regions        | Freshwater Available |          |          | Water Withdrawn (I. + E.) | Water Withdrawn (I.) | Diff AV-W (I. + E.) 8.5 | Diff AV-W (I. + E.) 2.6 | Diff AV-W (I.) 8.5 | Diff AV-W (I.) 2.6 |
|----------------|----------------------|----------|----------|---------------------------|----------------------|-------------------------|-------------------------|--------------------|--------------------|
|                | 2011                 | 2030_8.5 | 2030_2.6 |                           |                      |                         |                         |                    |                    |
| OECD Europe    | 2.59                 | 2.75     | 2.82     | 0.15                      | 0.09                 | 2.60                    | 2.66                    | 2.66               | 2.73               |
| OECD America   | 7.36                 | 7.62     | 8.62     | 0.50                      | 0.26                 | 7.12                    | 8.12                    | 7.36               | 8.36               |
| OECD Oceania   | 1.32                 | 1.58     | 1.73     | 0.069                     | 0.064                | 1.51                    | 1.67                    | 1.51               | 1.67               |
| OtherEuEurasia | 5.73                 | 4.98     | 6.68     | 0.26                      | 0.17                 | 4.72                    | 6.42                    | 4.81               | 6.52               |
| Asia           | 8.38                 | 7.04     | 14.1     | 0.70                      | 0.69                 | 6.34                    | 1.34                    | 6.35               | 1.34               |
| China          | 2.84                 | 5.89     | 12.5     | 0.54                      | 0.43                 | 5.35                    | 1.19                    | 5.46               | 1.20               |
| India          | 1.91                 | 3.96     | 8.40     | 0.75                      | 0.71                 | 3.21                    | 7.65                    | 3.25               | 7.69               |
| Middle East    | 0.26                 | 0.11     | 0.037    | 0.21                      | 0.20                 | -0.097                  | -0.17                   | -0.094             | -0.17              |
| Africa         | 2.84                 | 1.96     | 3.26     | 0.23                      | 0.22                 | 1.73                    | 3.04                    | 1.74               | 3.04               |
| Latin America  | 17.8                 | 6.78     | 141      | 0.16                      | 0.14                 | 6.62                    | 141                     | 6.63               | 141                |

Accordingly, Figure 2 shows that water withdrawal for the Middle East reached unsustainable levels in 2014 in the 2.6 scenario and in 2017 in the 8.5 scenario. When also accounting for the energy threshold, the actual results are from one year before for both RCPs, i.e., 2013 and 2016, respectively. The next section will present the results of a simulation that accounts for feasible withdrawal in the region.



**Figure 2.** Water availability vs. withdrawal (two models) for the Middle East in the two RCPs (m<sup>3</sup>/yr).

### 3.3. Economic Results of the Introduction of Water Climate Constraints in Middle East

The Middle East is the only significantly water-constrained region in the 2030 horizon. Therefore, the water scarcity simulation was calibrated to incorporate water withdrawal reductions that were compatible with the levels of available freshwater in the region. These simulations entailed the following impacts of sectorial output and GDP growth for the Middle East (Table 3).

**Table 3.** Irrigated Agriculture., energy and GDP % changes in the Middle East in three scenarios.

| IRR.AG.ONLY | Baseline |        |       | 8.50     |        |       | 2.60     |        |        |
|-------------|----------|--------|-------|----------|--------|-------|----------|--------|--------|
|             | Irr. Ag. | Energy | GDP   | Irr. Ag. | Energy | GDP   | Irr. Ag. | Energy | GDP    |
| 2015        | 13.15    | 13.50  | 16.83 | 13.11    | 13.47  | 16.77 | −3.84    | 14.12  | 16.51  |
| 2020        | 6.72     | 10.53  | 12.61 | −12.01   | 11.84  | 10.14 | −37.83   | 17.30  | 5.30   |
| 2025        | 2.73     | 7.73   | 9.65  | −19.88   | 10.00  | −0.03 | −39.87   | 13.05  | −9.15  |
| 2030        | 4.79     | 8.15   | 10.24 | −18.17   | 8.83   | −2.84 | −38.48   | 8.27   | −11.66 |
| 2011–2030   | 30.00    | 46.17  | 59.03 | −34.74   | 51.92  | 24.92 | −77.89   | 63.83  | −1.54  |
| IRR.AG + EN | Irr. Ag. | Energy | GDP   | Irr. Ag. | Energy | GDP   | Irr. Ag. | Energy | GDP    |
| 2015        | 12.84    | 14.29  | 16.82 | 12.84    | 14.29  | 16.82 | −4.30    | 15.04  | 16.58  |
| 2020        | 5.48     | 16.91  | 12.54 | −12.57   | 18.53  | 11.63 | −38.72   | 22.10  | 8.81   |
| 2025        | 0.70     | 16.51  | 9.66  | −20.25   | 18.33  | 5.92  | −41.47   | 18.73  | 0.56   |
| 2030        | 2.52     | 11.88  | 10.26 | −18.87   | 12.42  | 4.52  | −41.37   | 11.15  | −0.69  |
| 2011–2030   | 22.89    | 74.18  | 58.97 | −36.16   | 80.21  | 44.37 | −79.88   | 85.38  | 26.69  |

Concerning the results of the irrigation-only model (top part of the table), the constraints of available water, as expected, had significantly negative impacts on irrigated agriculture. Significant impacts on GDP growth were also detectable, which decreased in both water-constrained scenarios with respect to the base year.

In the energy-dependent scenario, both sectors are significantly impacted by water dependency and water scarcity. Nevertheless, while agriculture and GDP follow relatively straightforward patterns—i.e., the lower output/economic growth, the more the freshwater availability is constrained—the energy sector has a peculiar behaviour. Indeed, there are two unexpected trends in the energy sector. On the one hand, the activation of the water–energy link increases sectoral production. This could be explained by the fact that the Middle East has a low water intensity in the energy sector with respect to other regions, which creates international incentives that specialise in this sector, despite the dependency on an additional factor. On the other hand, the higher the water constraint the greater the increase in energy production, even in the water-dependent model. This can also be explained by the international role that Middle East energy plays, as well as from the fact that, in a context of possible factor allocation shifts between sectors, the constrained resources are preferably redirected towards the most economically valuable sector. Accordingly, the results show a clear regional choice in shifting the available water from agriculture to energy production. Nevertheless, it is significant that this trend is not enough to guarantee the achievement of the expected baseline GDP growth, which almost halves in the worst water scarcity scenario, i.e., RCP 2.6.

### 4. Discussion

Water, food, and energy are strictly interrelated, and the results presented in this paper clearly signal the importance of addressing all the links between them when performing macroeconomic and climate change impact assessments. Climate-induced water constraints can be a significant threat in terms of agricultural and energetic security, as well as in terms of macroeconomic growth, even when considering the relatively short-term period of the

2030 horizon. The simulations developed in this paper show how significantly future expectations can depend on the structure of the modelling framework e.g., the presence of connections between factors and sectors. Therefore, it is crucial that we use tools that can perceive the links between the subjects of the nexus to perceive important and otherwise undetected feedback. Concerning the entity of the impacts that climate-induced freshwater availability changes can have on sectoral productivity and GDP, it is clear that, even in the short term, they are not negligible. This is particularly true for the Middle East, which is already severely water constrained, an issue that strongly affects its macroeconomic expectations and production decisions. Moreover, it appears that the connection between energy and water can lead to conclusions that are not straightforward. Indeed, instead of bringing out security issues connected to scarcity in the new energy sector, the water–energy link suggests that it would instead start to act as a resource attractor, exacerbating security issues in the agricultural sector that are already accounted for. The prioritization of energy production in the region is coherent with the regional production structure and its international role as an energy producer. Another peculiar finding can be detected in the GDP results for the Middle East. As such, while climate freshwater changes lead to a decrease in macroeconomic growth, regardless of model specifications and scenarios, the results suggest that a clear explanation of the water–energy connection reduces the overall GDP losses in the region. This is relatively counterintuitive, although it is coherent with the economic value and importance of the energy sector for the region as well as its role as international referent producer.

## 5. Conclusions

From the results of this paper, two conclusions can be drawn. First, from a methodological point of view, having models that can perceive the interconnections between the elements of the nexus is crucial for developing macroeconomic and climatic scenario assessments. Secondly, water, food and energy can clearly be influenced by climate change and the relative freshwater availability constraints, which can potentially hamper their provision and security. Indeed, this study showed how the expected freshwater constraint relative to different climate scenarios can significantly shape the international and domestic provision of agriculture and energy, as well as limiting the economic growth of the regions facing water scarcity, e.g., Middle East. Nevertheless, the simulations also highlight the complicated implications of the explicit connection between water and energy, especially concerning the repercussions of water scarcity in the Middle East. Indeed, the results shows that energy–water dependency does not necessarily imply losses in the new water-dependent sector. As such, energy seems to behave as a resource attractor, exacerbating security issues in the competing agricultural sector. Moreover, it suggests that GDP losses due to water scarcity could be less strong than those expected without any explicit connection between energy and water, likely due to the role of the region as an energy production hotspot, the competition/international specialization issues and its technological structure.

**Funding:** This research received no external funding.

**Data Availability Statement:** Part of the data presented in this study are openly available in SSP Public Database Version 2.0 from IIASA at DOI:10.1016/j.gloenvcha.2014.06.004 and DOI:10.1016/j.gloenvcha.2015.02.012; Part of the data are available in Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) at <https://doi.org/10.5880/PIK.2020.004>; Part of the data presented in this study are available from the Center for Global Trade Analysis at Purdue University's Department of Agricultural Economics. Restrictions apply to the availability of these data, which were used under license for this study. A general description of the Data can be found at: <https://doi.org/10.21642/JGEA.010103AF>; The data that support the findings are restricted since they were produced using data under license, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC).

**Conflicts of Interest:** The authors declare no conflict of interest.

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