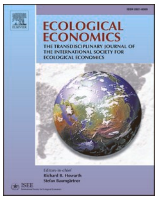
Ecological Economics 211 (2023) 107904

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon



Analysis

Macroeconomic impacts of water allocation under droughts. Accounting for global supply chains in a multiregional context

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ARTICLE INFO

Keywords:
Climatic change
Water drought
Integrated management
Input-output
Non-linear optimization
Supply chains

ABSTRACT

Water allocation policies play a key role in determining the impact of drought events on the macroeconomic system. Economic agents may find it difficult to modify their production structure immediately, and will therefore try to maintain current production and commercial patterns. The study takes this behavior into account and combines a Multi-Regional Input-Output model with a Non-Linear Programming optimization model to assess the macroeconomic impacts of localized droughts on a global scale. It analyses their propagation through interconnected supply chains, and it also evaluates the implications of different water allocation policies in terms of GDP impacts, with a large regional and sectoral detail. Our results show that the policy-regime chosen greatly determines the extent of the economic impacts, both in the directly affected region and in third countries. When the drought affects only agriculture, that negative economic impacts can be mitigated by adjusting production and trade. In contrast, when water availability is reduced uniformly across all economic sectors in the drought-stricken region, economic losses spread across the globe.

1. Introduction

Rising temperatures and the continuous expansion of water demand due to population and economic growth will impact water availability in most regions (UNESCO, UN-Water, 2020), resulting in major socioeconomic and environmental impacts (IPCC, 2022). Adaptation to climate change has therefore received increasing attention in the scientific debate in recent years. From a macroeconomic perspective, the most common approaches to analyze water scarcity problems have been Computable General Equilibrium (CGE) models (see Calzadilla et al. (2016) for a review; Borgomeo et al. (2018); Kilimani et al. (2018)) and Input-Output (IO) models (Freire-González, 2011; Pagsuyoin and Santos, 2015; Qu et al., 2018; Freire-González et al., 2018; Garcia-Hernandez and Brouwer, 2020).

A strand of the literature has addressed the potential of instruments to reduce pressure on water resources. The analyzed measures include water pricing policies such as taxes on the water used by sectors (Berrittella et al., 2008; Llop, 2008; López-Morales and Duchin, 2011; Cazcarro et al., 2020), subsidies (Cazcarro et al., 2020), transfer of water rights (Goodman, 2000; Gómez et al., 2004), improvements in water saving technologies (Llop, 2008; López-Morales and Duchin, 2011; Calzadilla et al., 2011; Osman et al., 2016; Distefano and Kelly, 2017), desalination (Baum et al., 2016) or wastewater reuse (Cazcarro et al., 2016; López-Morales and Rodríguez-Tapia, 2019). According to this literature, the proposed instruments could be effective means to alleviate the economic consequences of water scarcity.

However, apart from the climatic risks of progressive evolution, climate change has led to an increase in the frequency and magnitude of droughts, which are forecasted to increase further once global warming exceeds 1.5 °C (IPCC WGII, 2018). As regards to their economic impacts, droughts behave quite differently than climate induced water scarcity (Van Loon and Van Lanen, 2013; Berbel and Esteban, 2019), leading to extreme water shortages that can affect multiple economic sectors in a short period of time (Van Loon et al., 2016). Besides, in a context of uncertainty generated by climate change, the variability in drought patterns greatly exacerbates pre-existing water scarcity (Kiem et al., 2016). The increasing frequency and intensity of drought periods has encouraged adaptation and mitigation behaviors by stakeholders in water-stressed zones (Berbel and Esteban, 2019), yet in some cases the implemented measures have failed to improve or have even aggravated the scarcity problem. For instance, Perry et al. (2017) reported evidences on the adoption of modern irrigation technologies in numerous

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https://doi.org/10.1016/j.ecolecon.2023.107904
Received 23 June 2022; Received in revised form 19 May 2023; Accepted 20 May 2023
Available online 28 May 2023
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countries, and found no documented examples of substantial water savings. The reason is a rebound effect that entails the expansion of irrigated land —unless limits are implemented—, and the shift to higher value but more water-intensive crops. Thus, in the face of drought, these instruments alone are likely to fall short of balancing demand and supply. With an insufficient provision of water resources, withdrawal restrictions become inevitable and water allocation policies play a key role in determining the impact of the disruptive event on the macroeconomic system. Thus, it is necessary to assess the macroeconomic consequences of a reduction in the water availability in order to improve the design of allocation policies that minimize economic losses.

At a regional, multiregional, or national level, several studies have examined water-induced supply-side disruption of economic activities, such as in Canada (Eamen et al., 2020; Garcia-Hernandez and Brouwer, 2020), Catalonia (Freire-González, 2011), Mexico (López-Morales and Duchin, 2011, 2015), the US (Pagsuyoin and Santos, 2015), and the UK (Freire-González et al., 2018), among others. These studies, however, are national in scope and often overlook or simplify the international dimension, which is necessary to determine the propagation of the effects of water shortages to other countries through international markets.

In this sense, the literature assessing the macroeconomic implications of water disruptions by analyzing the effects on a global scale is less extensive. Our paper belongs to this line of research, contributing to the literature on water management using a world-wide perspective. Thus, the main objective of the study is to evaluate the short-term global economic impacts of implementing different supply-side policies based on resource redistribution to address a supply shock such as drought. Concretely, we provide various case studies that serve to analyze the macroeconomic effects of localized droughts, i.e., in China, India, South Europe and Middle East, comparing their consequences in terms of production and value added in their own territories and in the rest of the world. An early work in this line was conducted by Berrittella et al. (2007), who examined the effects of water supply restrictions in a world-wide context and found a decrease in global welfare due to constrained production. They determined regional winners and losers resulting from changes in trade patterns. However, they do not differentiate allocation of industrial water use to its different users and rely on some stylized assumptions, like the existence of a perfect water market, with costless water transportation within each of the macro-regions considered. Roson and Damania (2017) combined projections on water availability under climate change with a CGE model differentiating 15 sub-regions of the world and found that a strong reallocation of water could completely mitigate its global impact in terms of GDP. Koopman et al. (2015) analyzed water supply restrictions in agriculture affecting the Netherlands and other EU countries, using the GTAP-W model, and distinguishing between rainfed and irrigated land. They found that cross-sectoral and cross-country substitution effects are able to diminish the final impacts on agriculture, but in parallel they increase indirect impacts in non-agricultural sectors. However, they focus exclusively on agricultural water use assuming only irrigation water is restricted. Our paper evaluates the implications of different water distribution policies with a large regional and sectoral detail. Moreover, the analysis considers water shortages in agriculture and also examines the case where all economic sectors suffer from water shortages.

With this aim we combine an existing global Multi-Regional Input-Output (MRIO) and a non-linear programming (NLP) model (Oosterhaven and Bouwmeester, 2016). Standard demand- and supply-side (MR)IO models have been considered to be unsuited to simulate the impacts of a disruptive event in the supply side of the economy since they are not able to take spatial substitution effects into account, due to the assumption of fixed trade coefficients (Oosterhaven, 2017). Thus, we depart from standard IO analysis (Leontief, 1941; Miller and Blair, 2009), and take account that during an extreme event economic agents (e.g., households, businesses and governments) will try to maintain productive and commercial patterns since they do not have much room to reorient the current production structure (Oosterhaven and Bouwmeester, 2016). This approach combines the simplicity of IO models with the plausibility of CGE models to estimate the impacts of a supply shock in the short-run, allowing for the inclusion of substitution effects that better capture the response of economic agents. The methodology has already been used to examine the effects of other disruptive events in the economy (Bouwmeester and Oosterhaven, 2017; Oosterhaven and Többen, 2017; Bonfiglio et al., 2021, 2022).

The paper is structured as follows: Section 2 presents the methodology and data used and describes the scenarios under analysis. Section 3 examines the direct impacts of drought on the Gross Domestic Product (GDP) in the regions facing water scarcity, as well as the induced impacts trough trade. It examines how an extreme water disruption is spread along production and trade chains to different sectors and regions. Section 4 presents the discussion of main findings, and Section 5 closes the paper with some concluding remarks.

2. Methodology and data

2.1. Data

In our analysis we employ the 3.7 version of EXIOBASE[1] (Stadler et al., 2019). It provides information on the economic linkages among 163 sectors in 49 areas (44 countries and 5 aggregated regions) matched with multiple social and environmental satellite accounts. Concretely, we use the information for the year 2016. For several reasons, EXIOBASE appears as an optimal MRIO database for conducting environmentally-related analysis. First and foremost, EXIOBASE has an environmental and resource focus. It follows the UN System of Environmental-Economic Accounting (SEEA) guidelines (European Commission et al. 2012), providing harmonized and cross-country comparable high level of sector detail for those economic activities that put a significant strain on natural resources. This is particularly relevant when dealing with the impacts of water restrictions, since agriculture is the most water intensive sector in the world, accounting for 70% of the global water consumption (World Bank, 2020). Therefore, the level of detail of EXIOBASE for the different agricultural branches is key in our analysis. Second, it allows the evaluation of drought impacts at a macro-scale. The country coverage of the database, which includes 27 EU countries and 16 non-EU major economies, accounts for approximately 90% of the world's GDP. It also distinguishes between 5 different rest of the world regions, providing a better picture of these areas in the global economic structure. Lastly, it offers consistent long and up-to-date series as suggested by Tukker and Dietzenbacher (2013).

For our empirical application, several industries have been combined into major economic sectors, according to the Statistical Classification of Economic Activities (also known as NACE) (European Community, 2008), while keeping disaggregated those activities that are highly water intensive, namely agriculture, natural resources extraction and energy production.[2] The resulting MRIO matrices provide information for 33 aggregated sectors for each of the regions. Adding low water intensive industries was preferable than aggregating countries together, as information regarding bilateral trade patterns would have been lost. The correspondence of these sectors with the original data of EXIOBASE is shown in Table A.1 of the Appendix.

To model the initial direct economic losses for the sectors bearing the water shortage in the drought-affected areas, it is necessary to estimate how reductions in water availability translate into aggregate production

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[1] See https://www.exiobase.eu/index.php/about-exiobase.

[2] Although we attempted to work with the EXIOBASE database as disaggregated as possible, that is, keeping all sectors (163) and regions (49), it was proven to be computationally unfeasible when applying the NLP methodology explained in Section 2.3.

losses for each of the economic sectors. In order to obtain more accurate estimations of these direct effects we use the output-water elasticities calculated by Roson (2019) for several economic sectors in different world regions, which quantify the percentage change in the sectoral output due to a relative change in the water resources consumed by each industry. These elasticities can be found in the Appendix, Table A.2.

The consumptive water use is measured by the water consumption data that indicate the volume of water withdrawn by each sector that evaporates or it is incorporated into the products. We consider both the consumption of blue water –fresh surface and groundwater–and green water –precipitation stored in the soil as moisture or in the plants– (Hoekstra et al., 2011). Starting from the regular water consumption, the introduction of elasticities in the model makes it possible to establish the direct production losses for those economic sectors facing water shortages. The resulting constraint is explained in more detail in Section 2.3.

2.2. Scenarios

A total of eight scenarios, described below, have been designed to address our main objective. For its definition we have chosen relevant economic areas, that are also prone to drought and subject to an increasing risk of suffering water shortages due to climate change.

The areas facing severe drought risk have increased over the last century in five continents with the exception of Oceania, being Asia the one that has the highest growing tendency (Wang et al., 2014). In this sense, we have selected four major zones trying to evaluate the heterogeneous effects that a drought in key regions for food security and highly vulnerable to climate change would involve in the short run. The first two drought scenarios considered in this article are located in Asia and correspond to the countries with the highest global water consumption in this region, i.e., China (CH) and India (IN). According to FAOSTAT (2022), China and India together represent around 50% of total water withdrawal in Asia (China 22.7% and India 28.95%) and over 70% of their agricultural value added is produced under irrigation conditions. On the one hand, India is classified as a lower middle-income country by the World Bank, has a large rural population (67% on total population) and presents low agricultural and industrial water use efficiencies (FAOSTAT, 2022). Its index of water stress (SDG 6.4.2. indicator amounts to 66.5%), suggests that adaptation measures to the existing water scarcity problem have been proven insufficient. In the 1960s, the government subsidized energy consumption for water pumping, which led to serious overexploitation of the country's aquifers. Most of these subsidies are still in place, and farmers pay a flat rate or electricity is simply provided free of charge. Thus, water tables continue to decline at very high rates in many Indian districts (Famiglietti, 2014; Richey et al., 2015). On the other hand, China is an upper middle-income economy, more than 70% of its cultivated land is irrigated and also faces serious problems with groundwater depletion in the most arid areas of the country (Sun et al., 2022).

In addition to Asia, the risk of drought in Europe is also growing significantly (Hoerling et al., 2012; Spinoni et al., 2017). With 34.8% of the land at severe risk of drought, the climate model projections point almost uniformly towards an increase in drought in the continent in the coming decades, in particular in South Europe (SE) (Forzieri et al., 2014; IPCC, 2022). Projections indicate that in the case of severe drought, the decrease in water availability will occur not only in one country, but in several regions simultaneously (Wang et al., 2014). For instance, it has been observed that the drought regime in SE is different from that of the rest of Europe (Hanel et al., 2018; Cammalleri et al., 2020). Thus, our third scenario simulates a water shortage in SE, and comprises the countries of Spain, Italy, Portugal, Greece, Malta and Cyprus. This is a developed region with a long-standing tradition of agricultural production and trade. Therefore, a drought in this region may notably affect international markets.

Finally, we have also considered the Middle East region (ME) to illustrate the distribution of a water-supply disruption through the global supply chains. It includes Turkey and Rest of the World Middle East.[3] Most of these countries are totally reliant on aquifers, and the overexploitation has lead, as in China and India, to a serious depletion of the groundwater tables. The increased use of desalination and wastewater resources has been largely insufficient to alleviate the problem of water scarcity. Thus, the critical water stress (489%) and the weight of agricultural water use in total water withdrawal (90%) are matter of concern in this territory (FAOSTAT, 2022). Most ME countries have adapted to this situation by increasing their imports of agricultural products, and it is forecasted that population growth will intensify the dependence on international trade (Antonelli et al., 2017).

Apart from selecting the zones, the reduction in water availability in these regions must be defined, together with the sectors that will confront the water shortages. To make the results comparable, we assume that the total water availability in the region facing the drought has been reduced by 5% in all scenarios. This percentage is derived from Pagsuyoin and Santos (2015), who found that drought monitoring occurs when the available water supply is reduced by around 5–10% of usual consumption levels. Although somewhat more conservative, this is also in line with the works of Freire-González et al. (2018) and Garcia-Hernandez and Brouwer (2020).

As for the sectoral composition of water shortage, in a first set of scenarios we simulate the water reduction in the affected region is entirely borne by the agricultural sector.[4] The reasons are clear: from the large number of factors that influence agricultural production (e.g., soil quality, pests, diseases, weather, or agricultural practices), when predicting the impacts of climate change, droughts are one of the main factors affecting crop yields — it is estimated that they explain more than 60% of the output declines (Li et al., 2009). Moreover, agriculture accounts for 70% of direct water consumption worldwide (World Bank, 2020). Therefore, it is unsurprising that in the case of a severe drought, the most affected sector will be agriculture.

Nonetheless, economic policies can regulate water availability in the different economic sectors. Thus, we formulate a second set of scenarios in which the regulator induces a uniform reduction in water availability across all sectors of the economy (i.e., all sectors of face the same 5% reduction). With these two sets of scenarios we can further explore how different water allocation arrangements may affect the economic impacts (both direct and indirect) of a drought.

2.3. Economic model

For the assessment of extreme drought episodes both at a sectoral and national level we use a Multiregional Input-Output approach combined with a NLP model. In a context of globalized economies, inputs, natural resources and final products are increasingly interconnected through international trade and global supply chains. Any economic assessment must therefore take into account the interdependencies between the different regions and industries, in order to properly understand how disruptive events may spread through the economy. Failing to incorporate this interconnectedness in the modelling framework can inevitably lead to suboptimal economic analysis and inefficient policy design.

The multiregional input-output model considers all the intermediate exchanges among industries as well as the final demands of countries and sectors (consumption, investment, public expenditure and exports). Let's define the equilibrium equation that represents the world economy

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[3] Rest of the World Middle East comprises the countries of Bahrain, Egypt Arab Republic, Iran Islamic Republic, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen Republic.

[4] Agricultural sectors correspond to the Exiobase codes from i01.a to i01.l, shown in Table A.1.

comprised by i sectors and r countries.

$$\mathbf{x} = \mathbf{Ze} + \mathbf{Yu} \tag{1}$$

where $\mathbf{x} = (x_i^r)$ is the vector of output, with x_i^r being the total output of industry i in region r, $\mathbf{Y} = [y_i^{rs}]$ is the matrix of total final demands of countries in which y_i^{rs} is the final demand of products of industry i in region r made by region s and $\mathbf{Z} = [z_{ij}^{rs}]$ the multiregional matrix of intermediates. Each representative element of $\mathbf{Z}$, z_{ij}^{rs}, informs on the volume of input i of country r that is used in the production of product j in country s. $\mathbf{e}$ and $\mathbf{u}$ are vector of ones of dimensions rxi and s, respectively.

Departing from Eq. (1), we apply the NLP model introduced by Oosterhaven and Bouwmeester (2016) to evaluate the economic impact of water scarcity scenarios. This approach allows for the inclusion of spatial substitution effects unlike standard IO models (Oosterhaven, 2017, 2022, Chapter 8).[5] The microeconomic assumption behind this method is that, during a disruptive event, economic agents (i.e., households, firms and governments) will try to follow the pre-established production and commercial patterns as closely as possible. In sum, the model simulates that in the immediate aftermath of a natural disaster economic actors will try to continue doing "business as usual". This is achieved by minimizing the difference in the information gain between the post-event and pre-event economic situation, the latter referred with the superscript "*ex*" and is taken from the original MRIO table as structured in [1]. Thus, the objective function takes the following form:

$$Min \sum\nolimits_{ij}^{rs} z_{ij}^{rs} \left(ln \ \frac{z_{ij}^{rs}}{z_{ij}^{rs,ex}} - 1 \right) + \sum\nolimits_{i}^{rs} y_i^{rs} \left(ln \ \frac{y_i^{rs}}{y_i^{rs,ex}} - 1 \right) + \sum\nolimits_{j}^{s} v_j^s \left(ln \ \frac{v_j^s}{v_j^{s,ex}} - 1 \right) \tag{2}$$

where z_{ij}^{rs} denotes the purchases of sector j in region s from sector i in region r, y_i^{rs} the final consumption of products of industry i in region r made by region s, and v_j^s the value added generated by sector j in region s valued at market prices (i.e., GDP). The objective function in [2] is minimized subject to several constraints. Consistently with the information gain measure, the objective function does not treat negative values. Thus, the first restriction imposes that all economic transactions must be semi-positive. Second, the market remains in the short run equilibrium, that is, supply equals demand for each industry and region:

$$\sum_{s,j} z_{ij}^{rs} + \sum_{s} y_i^{rs} = x_i^r, \forall i, r \tag{3}$$

Third, it is assumed cost minimization under Walrass-Leontief production function, per sector and region:

$$\sum_{r} z_{ij}^{rs} = a_{ij}^{*s} x_j^s \text{ and } v_j^s = c_j^s x_j^s, \forall i, j, s \tag{4}$$

where $a_{ij}{}^{*s}$ are the input coefficients, i.e., the intermediate inputs of sector i necessary to produce a unit of output j in country s, regardless of the region of origin, and c_j^s are the coefficients determining the VA per unit of output. They are calculated from the original MRIO table as $a_{ij}{}^{*s} = \sum_r z_{ij}^{rs,\ ex} / x_j^{s,\ ex}$ and $c_j^s = v_j^{s,\ ex} / x_j^{s,\ ex}$, with $\sum_i a_{ij}{}^{*s} + c_j^s = 1 \ \forall \ j, s$. Note that Eq. (4) introduces the possibility of spatial substitution between inputs from one region for those from other regions.

Fourth, to model the composition of local final demand, a similar approach of cost minimization under a Walrass-Leontief utility function is assumed:

$$\sum_{r} y_i^{rs} = p_i^{*s} y^s, \forall i, s \tag{5}$$

where $y^s = \sum_i^r y_i^{rs}$ is the total regional final demand and $p_i{}^{*s}$ the package coefficients that denote the need of products of industry i to meet the final demand of region s regardless of the region of origin. Similar to Eq. (4), this constraint introduces the possibility of spatial substitution between final products from one region for those from other regions. These coefficients are calculated from the original MRIO table as $p_i{}^{*s} = \sum_r y_i^{rs,\ ex} / y^{s,\ ex}$, where $\sum_i p_i{}^{*s} = 1, \forall \ s$.

Finally, to model the direct production losses induced by the drought in the affected region, we include an additional constraint translating the water reductions for the sectors bearing the water shortage into percentage production losses.

$$\frac{x_k^q - x_k^{q,ex}}{x_k^{q,ex}} \leq -\gamma_k^q \ \delta_k^q, \forall q, k \tag{6}$$

where $x_k^{q,\ ex}$ is the total sectoral output from the original MRIO tables, δ_k^q the output-water elasticities and γ_k^q the water scarcity parameter (i.e., the percentage (in positive) by which the quantity of available water is restricted as a consequence of the drought), for sector k coping with the water shortage in the affected region q. Since we are to assess two different policy choices in the scenarios simulated (agricultural vs uniform), that is, either the water shortage in the affected region is fully borne by the agricultural sector or the water restrictions are uniformly allocated to all sectors that use water as an input, the water scarcity parameter needs to be scaled accordingly for each policy choice:

$$\gamma_k^q = \frac{W^{q,ex} \times \alpha}{\sum_k w_k^{q,ex}}, \forall q, k \tag{7}$$

where $W^{q,\ ex}$ is the total amount of blue and green water consumed in the affected region q by all sectors, $w_k^{q,\ ex}$ the amount of blue and green water consumed by sector k bearing the water restriction in the affected region q, and α the factor by which the total quantity of available water is reduced in the affected region as a consequence of the drought (i.e., 5%). $W^{q,\ ex}$ and $w_k^{q,\ ex}$ are also obtained from Stadler et al. (2019). Thus, the numerator in Eq. (7) represents the reduction in available water resources (i.e., the water shortage) in the affected region due to the drought and the denominator the total amount of water consumed by the sectors that will have to deal with the water restrictions. Eq. (7) therefore establishes the proportion of the water shortage each sector must assume based on the water it consumes. Note that for the uniform case $W^{q,\ ex} = \sum_k w_k^{q,\ ex}$, so the water scarcity parameter for each sector is just $\gamma_k^q = \alpha$. In contrast, when water shortages are only imposed on agriculture, agricultural sectors end up bearing water reductions ranging from 5.1% to 5.8%, depending on the case analyzed.

The optimal solution of minimizing [2] subject to [3]–[7] provides the post-drought MRIO tables that best resemble the pre-event economic situation.

Once we have obtained the post-event MRIO tables based on the NLP model, we calculate the VA embodied in all the flows among countries and sectors for the base MRIO tables (pre-event) and for all the scenarios considered (post-drought).[6] To that aim, first, we rewrite the model expressed in Eq. (1) as a function of the Leontief inverse, $\mathbf{L} = [l_{ij}^{rs}]$:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{Ly} \tag{8}$$

where $\mathbf{A} = \mathbf{Z}\widehat{\mathbf{x}}^{-1} = \left[a_{ij}^{rs} \right]$ is the matrix of (intermediate) input co-

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[5] See also Koks et al. (2019) for a comparison of the outcomes of a supply-shock case-study between the two most widely used demand-driven MRIO models and the NLP and another optimization approach (MRIA model).

[6] Since the solution of the NLP model returns a new matrix of intermediates **Z** along with a new vector of value added (**v**) and a new matrix **Y**, it is possible to derive the corresponding matrix of intermediate input coefficients **A** for each of the scenarios and to carry out the embodied analysis with all "post-drought" elements. Hence, the "post-drought" matrices of input coefficients present a new allocation of input requirements where spatial substitution has taken place (and the same applies for the matrix of final demands, as the NLP also allows for spatial substitution of final products).

efficients and $\mathbf{y} = \mathbf{Yu}$ the vector of total final demands.[7] Each representative component of $\mathbf{L}$, $l_{\mathrm{ij}}^{\mathrm{rs}}$, indicates the output of sector *i* of country *r* directly and indirectly incorporated in each unit of the final demand of industry *j* in country *s*. Second, we define a vector $\mathbf{c} = \left(c_j^s\right) = \left(\frac{v_j^s}{x_j^s}\right)$ that represents the VA per unit of output and its corresponding diagonalized form $\widehat{\mathbf{c}}$. Pre-multiplying [8] by $\widehat{\mathbf{c}}$, and applying the breakdown of final demands[8] based on the industry-region final allocation ($\mathbf{Y}^*$), as in Cazcarro et al. (2012), we obtain matrix $\mathbf{Q} = [q_{\mathrm{ij}}^{\mathrm{rs}}]$ as:

$$\mathbf{Q} = \widehat{\mathbf{c}}\mathbf{L}\mathbf{Y}^* \tag{9}$$

Matrix $\mathbf{Q}$ consists of block matrices $\mathbf{Q}^{\mathrm{rs}}$, with each element q_{ij}^{rs} showing the VA generated in county *r* and sector *i* that directly and indirectly meets the final demand of industry *j* in country *s*. $\mathbf{Q}$ can be analyzed from the producer (Eq. 10) and the consumer perspectives (Eq. 11). On the one hand, we obtain the VA associated to the production of all industries in country *r* regardless of the destination of this production, i.e., direct VA as in [10]. On the other hand, we get the VA generated by the consumption of country *s* independently of the origin of the flow, or embodied VA in [11].

$$\sum_{s}\mathbf{i}'\mathbf{Q}^{\mathrm{rs}}\mathbf{i} = \sum_{s\neq r}\mathbf{i}'\mathbf{Q}^{\mathrm{rs}}\mathbf{i} + \mathbf{i}'\mathbf{Q}^{\mathrm{rr}}\mathbf{i}, \forall r \tag{10}$$

$$\sum_{r}\mathbf{i}'\mathbf{Q}^{\mathrm{rs}}\mathbf{i} = \sum_{r\neq s}\mathbf{i}'\mathbf{Q}^{\mathrm{rs}}\mathbf{i} + \mathbf{i}'\mathbf{Q}^{\mathrm{ss}}\mathbf{i}, \forall s \tag{11}$$

Defining $\mathbf{i}$ as a vector of ones of dimension *i*, from Eqs. (10) and (11) we can obtain three expressions. First, $\mathbf{i}'\mathbf{Q}^{\mathrm{rr}}\mathbf{i}$ ($\mathbf{i}'\mathbf{Q}^{\mathrm{ss}}\mathbf{i}$) indicates the VA generated in the production of goods and services in country *r* (*s*) and consumed domestically. Second, $\sum_{s\neq r}\mathbf{i}'\mathbf{Q}^{\mathrm{rs}}\mathbf{i}$ is the VA embodied in exports from *r*. And finally, $\sum_{r\neq s}\mathbf{i}'\mathbf{Q}^{\mathrm{rs}}\mathbf{i}$ represents the VA embodied in the imports of country *s*.

Finally, we compare the base scenario ($\mathbf{Q}^{ex}$ and its associated indicators) with the different drought simulations ($\mathbf{Q}^{post}$ and its associated indicators). In this way it is possible to obtain the VA relative change for all economic transactions between sectors and countries from both the consumer and producer perspective that are triggered by the water restrictions in each scenario:

$$\mathbf{Q}_{\omega}^{change} = \frac{\left(\mathbf{Q}^{post,\omega} - \mathbf{Q}^{ex}\right)}{\mathbf{Q}^{ex}}, \forall\omega \tag{12}$$

where $\mathbf{Q}^{ex}$ is calculated as in [9] from the original MRIO tables and $\mathbf{Q}^{post,\omega}$ are obtained from the matrices and vectors returned by the optimal solution of the model in each scenario ω. Fig. 1 shows the different stages followed in the framework adopted. The NLP model is solved in GAMS (Brooke et al., 1998), using the IPOPTH solver, which implements an interior point optimization algorithm suitable for large-scale nonlinear programming problems.

3. Results

3.1. Drought impacts in global value added

The aggregated economic impacts under the different simulations are illustrated in Table 1, which presents the VA change in the drought-affected areas and the VA change in the non-affected areas. It shows that all the drought scenarios involve global VA losses, with the reduction ranging from −0.47% to −0.01%. The strongest global impact is estimated to occur when the water endowments are reduced uniformly to all sectors of the Chinese economy. Similarly, our results also point to substantial losses of global VA if the drought in China is fully borne by the agricultural sector (−0.17%). This should not be surprising considering that China is one of the world's leading economies, and its agriculture has a non-negligible weight in the productive structure of the country (see Appendix, Fig. A.1). Furthermore, reduction of global VA is also considerable when a drought in the Middle East or in South Europe involves a uniform reduction of water across industries (−0.16% and −0.15%, respectively), due to the greater weight of manufacture and services in these regions in comparison to China and India (Appendix, Fig. A.1). These initial results indicate the relevance of two aspects for the proper quantification of the impacts of a shock at the global level: the role of the drought-prone region in the production chains and the importance of the productive specialization in the areas affected by the drought.

The drought-affected areas experience the largest decrease in VA, which is common to all the regions under diminishing access to water resources. The loss in VA would be larger if water availability were restricted to all economic sectors compared to agriculture. More specifically, drops in VA in the scenarios where the water restrictions affect uniformly to all economic sectors would reach more than 2.5 percentage points, regardless of the area considered. These VA losses would be mostly driven by the fall of domestic demand in the region suffering from water restrictions, and to a lesser extent by a reduction in external demand. However, the effect of reduced exports as a determinant of falling VA in drought-affected areas would be relevant for the case of the Middle East (Table 1).

Table 1 also shows that a drought not only involves economic effects for the region disrupted, but it also has indirect impacts in other areas of the world, both positive and negative. These cascade effects spread to other regions in the short term through interconnected supply chains, showing that a supply shock caused by a drought induces vulnerability at the global level. This has also been found in other studies analyzing the effects of different natural disasters (Arto et al., 2015; Mendoza-Tinoco et al., 2017). In this respect, the use of multiregional input-output models is essential to assess how these indirect effects are distributed (Arto et al., 2015; Bouwmeester and Oosterhaven, 2017; Zhao et al., 2021).

Interestingly, we can see that imposing water restrictions to only the agricultural sector would generate an overall gain outside the drought-affected areas, except in the case of India. In contrast, results are dramatically different when the drought impacts all sectors of the economy uniformly, as we can observe that in this case aggregate economic losses outweigh the potential gains. In all the scenarios considered, losses outside the drought-affected area account for roughly 10% of the overall drop in global value added, being slightly higher for the uniform water allocation scenario in the Middle East. The largest fall in value added outside the drought-affected borders would take place if China were to experience water restrictions in all sectors, due to its prominent role in global supply chains. In this scenario, the indirect economic impacts spread to non-affected areas would translate into aggregate losses in VA of −0.05%.

3.2. Value added changes in the drought-affected areas

Table 1 also depicts the percentage loss of VA in the drought-affected regions from the producer perspective (see Eq. 10), breaking it down into the domestic loss and the loss embodied in exports.

It shows that India is the most vulnerable region to a drought. If agricultural water availability were limited, the fall in the VA associated to the production activities in India would reach −2.2%. This is completely explained by the intense drop of the domestic VA, generated in India to meet its own domestic final demand (see Table 1). India's trade flows performance contrasts with that of other areas. Concretely, water restrictions in agriculture involve moderate drops in exports (Table 1) and increases in imports for all areas considered except India

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[7] ^ denotes expressing the vector as a diagonal matrix and $^{-1}$ the inverse.

[8] $\mathbf{Y}^*$ consists of block diagonal sectoral matrices of countries, whose blocks, $\mathbf{Y}^* = [\widehat{\mathbf{y}}^{rs}]$, are diagonal matrices of final demand of region *s* on *r*.

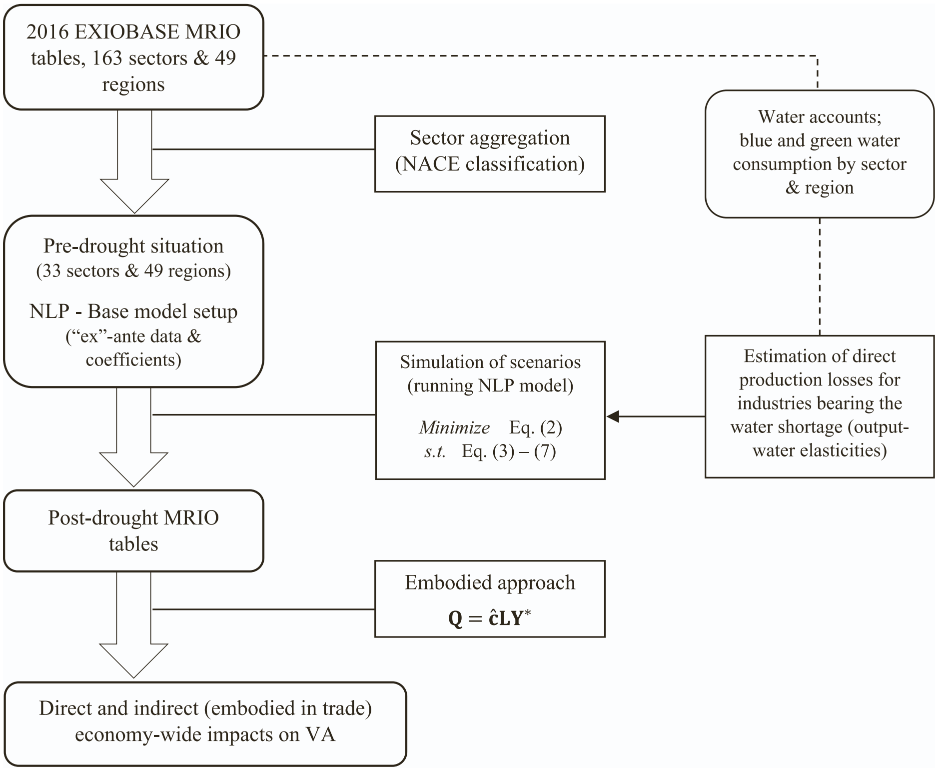

Fig. 1. Methodological framework.

Table 1
Impact of the water allocation policy options on global VA.

Drought-affected area	China		India		South Europe		Middle East	
Drought-affected sector/s	Agri	All	Agr	All	Agri	All	Agri	All
Global VA change	−0.17%	−0.47%	−0.07%	−0.10%	−0.01%	−0.15%	−0.02%	−0.16%
VA change in the drought-affected area (producer approach)	−1.21%	−2.95%	−2.15%	−3.01%	−0.22%	−2.60%	−0.36%	−2.89%
Domestic VA	−1.3%	−2.8%	−2.6%	−3.1%	−0.2%	−2.9%	−0.3%	−3.0%
% of the global VA change	98%	73%	97%	80%	82%	77%	65%	62%
VA embodied in exports	−0.5%	−3.6%	0.3%	−2.4%	−0.2%	−1.6%	−0.4%	−2.7%
% of the global VA change	7%	18%	−2%	10%	25%	13%	39%	27%
VA change outside the drought-affected area	0.01%	−0.05%	0.00%	−0.01%	0.00%	−0.02%	0.00%	−0.02%
% of the global VA change	−5%	9%	5%	10%	−7%	10%	−4%	11%

Source: own elaboration based on EXIOBASE v.3.7.

(for the VA embodied in imports see Fig. A.4 in the Appendix). Even though India's exports of agricultural products would significantly shrink, the increase in sales of other sectors such as mining, manufacture and chemicals to other countries would offset the potential economic losses, with a net increase in exports of +0.3% (Table 1). Since agricultural production in India represents 15.7% of its GDP and accounts for 12.1% of its exports (see Figs. A.1 and A.2 in the Appendix), this could point to an internal reallocation of water resources from agriculture to less water-intensive sectors, but with higher returns in international markets. Conversely, the VA embodied in India's imports would plummet by 2.76% (Fig. A.4), as a result of the cut back on foreign purchases of non-agricultural products from most countries, amounting to an aggregate loss in VA for its suppliers of −9.6 b€.

On the contrary, under the uniform policy scenario, both the domestic VA and the trade flows would be negatively impacted in all areas, with exports and imports decreasing (see Table 1 and Fig. A.4). The drop of exports would be particularly intense in China (−3.6% in Table 1), which would have to deal with losses in VA resulting from the contraction of their international sales of −13.1 b€. In this case the drought would affect a sector with a marked dynamism in recent decades, the machinery and transport equipment industries (Caporale et al., 2015). In the Middle East, the drop in exports under the uniform scenario (−2.6% in Table 1) would be mostly driven by the large economic losses in the mining and quarrying industries, a sector that represents more than 50% of the total exports in the region (see Fig. A.2 in the Appendix). As for the reduction in the VA embodied in imports, Fig. A.4 shows that it would be smaller if China were to allocate the water shortage uniformly across sectors (−0.72%), in comparison to the other areas considered (where it would fall between 2% and 2.5%). Although China would notably increase its purchases of foreign agricultural products (e.g., a 10% increase in imports of paddy rice, 9% in cereals or 11% in sugar cane), it would also significantly shrink its imports of services and mining and quarrying products. Table 1 also shows that in South Europe and the Middle East regions the negative economic impacts could be much larger if the policy choice to allocate water were to affect all economic sectors uniformly (−2.60% and – 2.89%, respectively) compared to impose water restriction only to agriculture (−0.22% and – 0.36%, respectively). This can be explained by the reduced share of agriculture in their productive structure in comparison to China and India as shown in Fig. A.1 of the Appendix.

3.3. Cascade effects: Impacts on value added outside the drought-affected areas

We can go deeper into the analysis by evaluating the country-wise impacts in Figs. 2 and 3, which display the generalized losses in value added in each country under the agricultural and uniform scenarios, respectively. As it can be appreciated, the largest indirect economic impacts in the regions that do not experience the drought would happen if water disruptions took place in China, both for the agricultural and uniform policy alternatives. If a drought in China were to be managed by restricting water to the agricultural sector, it would induce winners and losers worldwide (see Fig. 2). Although the global aggregate impact from Table 1 may appear negligible (+0.01%), this is explained because the VA would increase in approximately half of the areas of our study, whereas it would fall in the rest. Countries in Asia and Pacific, Australia, India and South America would be in the first cluster, contributing to an aggregate economic gain outside the Chinese borders of around +7.8 b€. The increase in their exports, mostly sells of wheat and other cereals, vegetables, fruit, farming products and food products such as meat to China, would be behind these economic gains. This means that China would import the agricultural products that it would not be able to produce domestically due to the water shortages. This result is particularly significant in a context of changing food consumption patterns and growing income in China (Zhou et al., 2015). In the second group, with aggregate VA losses amounting to −2.7 b€, we find Japan, Germany, the Middle East, Korea and Russia. These countries, among the top Chinese trading partners in 2016 (World Bank, 2016), would notably reduce their exports to China.

Water shortages in India borne by the agricultural sector would trigger aggregate losses in other regions equivalent to −2.67 b€, with Middle East, China, Germany and Russia being the most negatively affected. However, it would also lead to economic gains outside its borders of around +0.67 b€. Hence, economic losses in third-countries due to the contagion of a drought taking place in India and managed by restricting water to agriculture would outweigh the potential economic benefits. In contrast, the indirect impacts induced by a drought in South Europe and the Middle East would be smaller. First, the negative indirect impacts triggered by water shortages in the agricultural sector in South Europe would amount to −0.53 b€, which would be mostly borne by Germany and UK. The gains would be of around +1 b€, with countries in Asia, Africa and South America benefiting the most. These areas would mostly sell cereals, vegetables and farming products to Spain, Italy or Greece, historically specialized in trading Mediterranean products (Duarte et al., 2021), which would replace domestic goods with other imported commodities. Second, for the case of agricultural water shortages in the Middle East, losses in other countries would be equivalent to −0.84 b€ (specially in Russia and Germany) and benefits to +1.3 b€ (mostly by countries in Asia and Pacific, Africa, South America and India). These findings lead us to affirm that when a drought affects only to agriculture, substitution and complementarity relationships throughout global supply chains appear. This is reflected in the existence of winners and losers as a result of the transmission of the economic impacts of the water restrictions all over the world.

Fig. 3 displays the generalized losses in value added in each country under the uniform water allocation scenarios. First, if water shortages affected every Chinese sector, considerable negative impacts would happen in the VA of every region in the world. These would be particularly large in Asia and Pacific, the US, the Middle East, Latin America and Africa, with global VA losses amounting to −26.8 b€. Only Taiwan and Germany would seem to benefit from this water allocation policy during a drought in China. This reflects the importance of China in global value chains and the transmission of the economic consequences of a drought impacting all its sectors. Similarly, considering the scenario in which all the economic sectors in India were affected by the drought, the value added associated to the production of goods and services would fall in most countries, especially in the Middle East, given the intense drop in exports of mining and quarrying products to India. Thus, we find that a drought in some of the Asian Giants (China or India) could indirectly impact on one of the main sectors in the MENA region, mining and quarrying (Lopez-Calix et al., 2010), reducing their demand and hence the export flows from the Middle East and North Africa.

In the event of a drought in South Europe, water constraints in all economic sectors would also trigger economic losses all over the world. These would amount to −9.4 b€, and would be particularly intense in their Eastern European neighbors, due to the decrease in the VA associated to their domestic production, but also to the deceleration of the trade flows. As an example, the VA in Bulgaria would fall over −0.1%, mostly due to the decrease of mining, quarrying and transport exports to the drought-affected areas, specially Italy. Other non-European areas such as the Middle East, the United States, Asia and Pacific and Africa would also experience economic losses. These results demonstrate the importance of trade links within Europe, as well as of the agreements in the context of the Euro-Mediterranean partnership.

Finally, we can consider the case of the drought in the Middle East as an exception, since water restrictions affecting all the sectors would not only involve large economic losses in most countries, but also significant economic gains in some regions. For example, Indian exports would drop −0.44%, mainly due to the flows of non-metallic minerals, machinery and financial intermediation services to the Middle East. However, looking at absolute figures, economic losses in the US, Japan, India and Asia and Pacific would account for most of the global fall in VA (−10.8 b€). Conversely, there would be areas where the VA would notably grow, contributing to a global gain in VA of +2.6 b€. This is the case of Norway, Africa, Russia, Latin America, Brazil, Canada and Mexico. The export increase would contribute to the improvement in national VA, with growth rates ranging between 0.34% and 0.11%. These regions would step in to satisfy the demand of mining and quarrying products that would be left unmet by the Middle East if it were to allocate water uniformly across sectors.

4. Discussion

In sum, our results show that under a water disruption in a given region, economic impacts not only occur in nearby countries, but also in very distant areas. Sectoral policies affect regions differently and the behavior of countries may have divergent geographical effects. We have seen that if the drought affects only agriculture, the negative economic impacts outside the affected area can be offset by gains in VA resulting from increases in agricultural production in some regions. Thus, under this scenario, there would be scope for changes in production and commercial patterns in order to compensate for the reduction in agricultural production in the drought-affected area. Latin America, Africa, Asia and the Pacific or some Eastern European countries could respond and meet the demands for the products constrained by the drought bottlenecks. Most of them are developing regions specialized in sectors located in the first stages of the production chain. This would be particularly important for the affected regions in the first place, as it would help mitigate the direct impact on local consumption by purchasing agricultural products from international markets. To give some estimates, Table 2 presents the impacts on global agricultural VA under the different scenarios, disaggregated by the VA change in the affected and in the non-affected areas. It shows that if South Europe and the Middle East were to restrict water only to agriculture, the gains in agricultural VA in the non-affected areas would mostly compensate for the agricultural production losses in these regions, covering 91.69% and 78.41% of the agricultural loss in VA, respectively. For India and China these numbers would be different, however, given their weight in global agricultural production. As it can be appreciated, increases in agricultural production in non-affected areas could only offset approximately 40% of the loss in agricultural VA in these regions if these were to withdraw water solely from this sector. On the contrary, when the drought affects every branch of the economy, if no action is taken, the

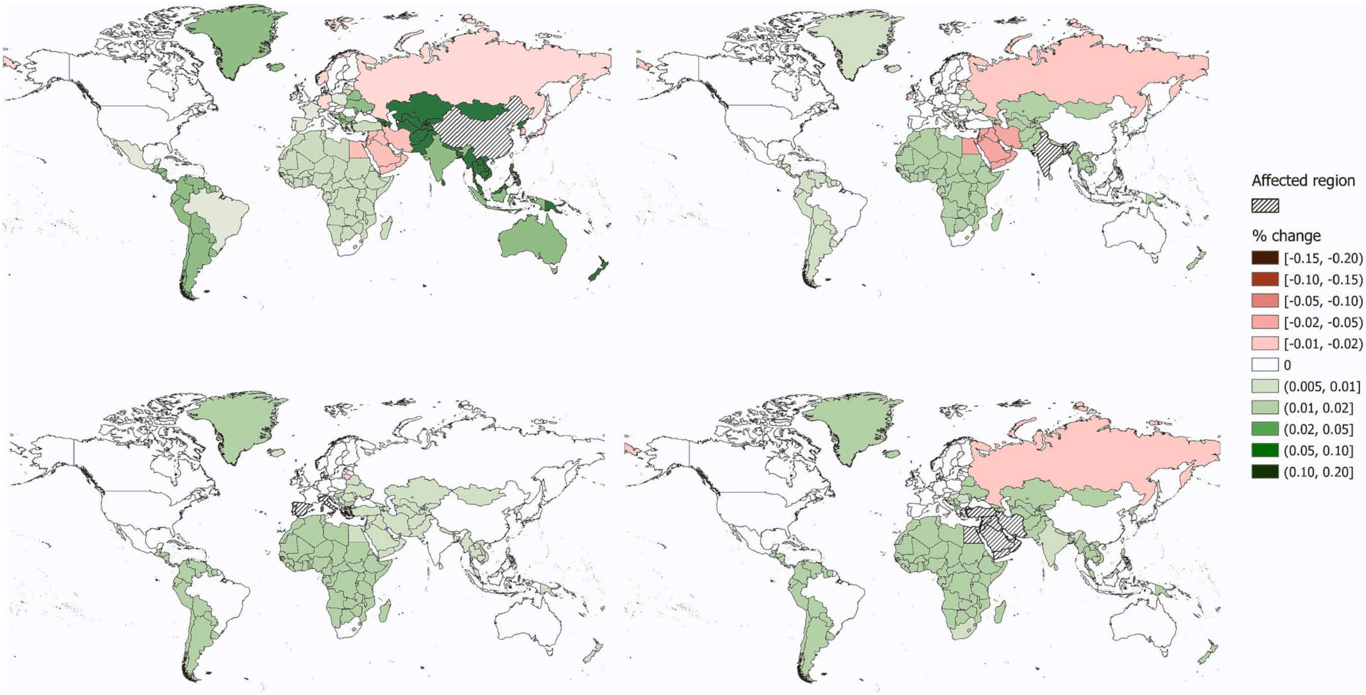

Fig. 2. VA percentage change outside the drought-affected regions caused by a 5% reduction of water available in agriculture.
Source: own elaboration based on EXIOBASE v.3.7.

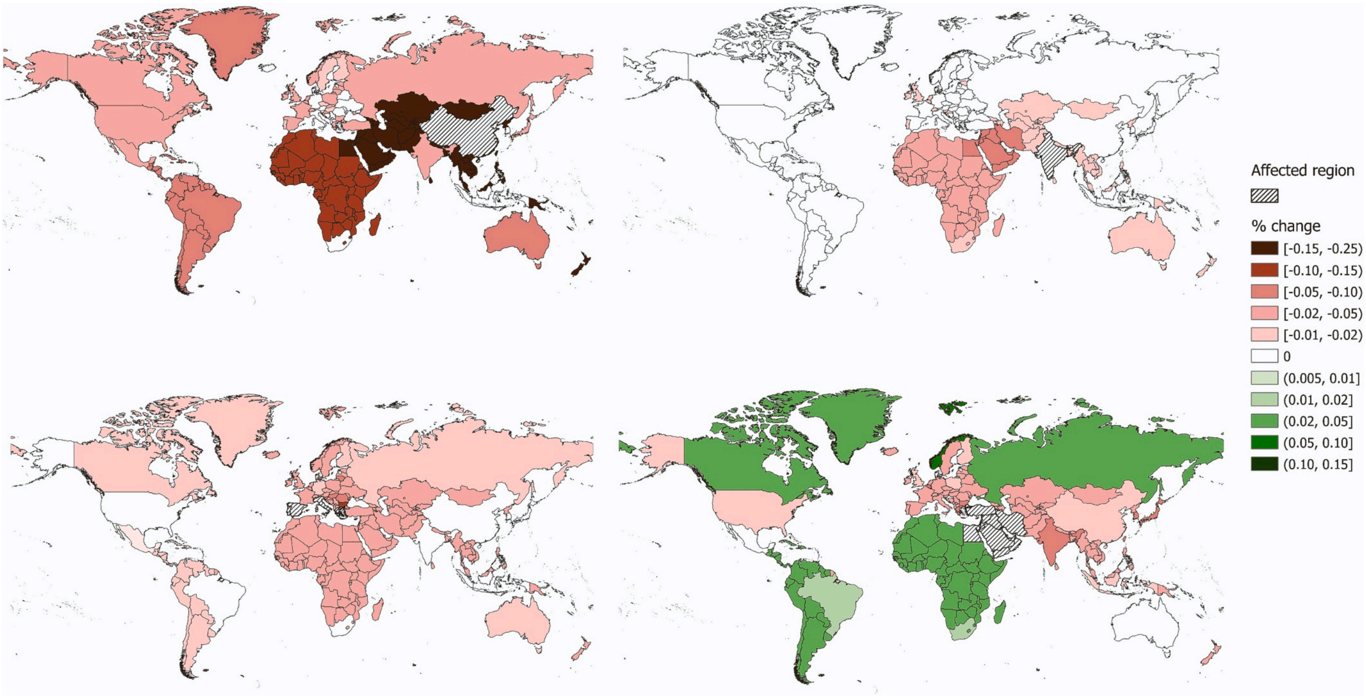

Fig. 3. VA percentage loss outside the drought-affected regions caused by a 5% reduction of water available in all sectors.
Source: own elaboration based on EXIOBASE v.3.7.

Table 2
Impact of the water allocation policy options on agricultural VA.

	China		India		Med EU		Middle East	
	Agri	All	Agri	All	Agri	All	Agri	All
Agricultural VA loss in the drought-affected area (b€)	−30.19	−28.48	−9.07	−8.86	−2.77	−2.30	−5.05	−4.92
Agricultural VA gain outside the drought-affected area (b€)	11.68	0.67	3.78	2.39	2.54	0.15	3.96	−0.39
Net aggregate loss (b€)	−18.51	−27.81	−5.29	−6.47	−0.23	−2.15	−1.09	−5.31
% of loss covered by the non-affected regions	38.68%	2.35%	41.67%	26.97%	91.69%	6.52%	78.41%	−7.92%

Source: Own elaboration based on EXIOBASE v.3.7.

economic losses may spread all over the world. In this case, the intense disruption in global supply chains of intermediate inputs induced by the affected area would not allow third-countries to adapt and shift production to meet the demands of their domestic and international markets, leading to generalized losses. In this situation, certain competitive behaviors, such as an export embargo, may appear,[9] aggravating further the damage generated by the water restrictions. Comparing it with the agricultural scenario, we can see from Table 2 that a uniform reduction in the affected region would dramatically limit the response capacity of the non-affected areas in increasing their agricultural production. Although with a uniform water allocation policy China would deal with lower VA losses in its agricultural sector (−28.48 b€), third-countries would not have much scope for increases in agricultural production, ending up covering only a very tiny percentage of those agricultural VA losses in China (2.35%). A similar pattern would be observed in South Europe, and even more damaging indirect effects would take place in the Middle East (where there would be a net loss in agricultural VA in non-affected regions). One explanation to this limited response capacity can be that a uniform water reduction would induce negative impacts in all economic sectors of the affected region, some of which are essential intermediate inputs in agricultural production (e.g., pesticides, chemicals fertilizers or agricultural equipment). Thus, a supply shortage from these products would interrupt agricultural and farming production activities in third-countries that require these inputs from the affected region, weakening their capacity to temporarily increase production. Further, the production reduction in certain sectors of the affected region, such as manufacturing of food products and services, would not allow these industries to increase their purchases of agricultural products from abroad as much as they would if the water restriction only affected agriculture.

These results are remarkable and highlight the importance of managing water not as a regional but as a global resource, since specific water allocation policies adopted in one region may have dramatic and undesired economic consequences in non-affected areas through interconnected markets and supply chains. This is in line with the results of Koopman et al. (2015), and Baldwin and Freeman (2022), and confirms the need to better understand the structure of these global supply chains to better adapt to and recover from supply shocks. It is thus essential to consider the role of each economic sector in global supply chains when designing drought management strategies, identifying those key industries that may transmit large economic impacts through backward linkages (by changes in the demand of products purchased abroad) and those that may induce negative impacts through forward linkages (by changes in the supply of products sold abroad). Moreover, the results also evidence that placing the water restrictions in agriculture may induce smaller effects abroad but would concentrate the impacts in the affected region, creating a significant domestic distortion in this sector.

5. Conclusions

In this paper we assess the macroeconomic consequences of water restrictions generated by droughts. This analysis is particularly relevant in a context of climate change, given the potential increase in the frequency and magnitude of drought events and the growing water competition among economic sectors. In order to capture the fact that during a period of drought, agents may have difficulties in adapting their productive and commercial structure to the new conditions of water scarcity, we use an existing MRIO and NLP modelling. We simulate two different water policy allocation regimes in areas prone to water shortages, namely, China, India, the Middle East and South Europe.

The results are significant and may have several policy implications. First, we find that the size and magnitude of the global economic impacts of drought would largely depend on the role of the affected country in the world's economy. We have seen that the water shortages in China induce the largest impact on global VA, regardless of the water allocation choice. Second, the economic structure of the region facing the water shortage, in combination with the policy regime chosen, would also greatly determine the scope of the economic impacts, both in the affected and in the non-affected areas. Our estimates show that whereas India would be the most affected country in terms of aggregate loss in VA if it were to place the water restrictions only to agriculture, under this policy choice the aggregate negative economic impacts of water shortages in the countries of South Europe and the Middle East would be negligible. In contrast, if the latter were to restrict the water endowments uniformly across all sectors, their economic impacts would be of similar magnitude to those of the other water-stressed areas. India is a predominantly agricultural country in comparison with the other analyzed scenarios, whereas manufacture and services have a greater weight in South Europe and Middle East economies. This highlights the importance of considering the economic structure of a region when designing the water allocation policy.

Third, our results also reveal the role of trade in shaping the transmission of the macroeconomic impacts of a drought to the non-affected areas through global supply chains and interconnected markets. We have seen that if the policy choice is to manage the water shortage by constraining water to only the agricultural sector, the common pattern among the affected regions would be to increase their imports (mostly of agricultural products to compensate for their own losses) while reducing their foreign sales of domestic products. Hence, although some countries would be negatively impacted by the cutbacks on exports from the affected regions, the increase in imports would induce other economies to step in, increase their production levels and try to meet the demands of agricultural (and non-agricultural) products that are left unmet by the affected region, experiencing net gains in their VA. This is the case of China, South Europe and the Middle East regions. Instead, India would exhibit a very distinct behavior, as it would need to increase its exports of non-agricultural products, while cutting back on imports, in order to compensate for the large economic losses in the agricultural sector. For the scenarios where water endowments are reduced uniformly across sectors, India, South Europe and the Middle East would significantly reduce their exports and imports, thus inducing negative spillover effects to other countries through the contraction of both their sales and purchases in international markets. In this case, China seems to be the

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[9] As an example, in response to the Russian invasion of Ukraine, which has reduced the world's wheat supply, and given the forecast of low harvests due to a current heat wave, India has recently banned exports of most grains in order to guarantee its domestic demand (https://www.nytimes.com/2022/05/14/world/asia/india-wheat-export-ban.html, accessed May 19, 2022)

region deviating from the norm, as it would cut back on its exports much more than it would on its imports, propagating these negative effects to other countries through shortages in its supply rather than by reducing its demand.

And finally, the water allocation criteria in the affected region would play a primary role in determining the capacity of the world's economy to respond to such disruption. This is the key message to be drawn from this paper. Our results show that if the drought affects only to agriculture the negative economic impacts outside the affected area can be mitigated by gains in VA resulting mainly from increasing agricultural production in other regions. There would be thus room for maneuver in international markets and scope for changes in the production levels of third countries to partially compensate for the contraction of agricultural production in the drought-affected area. Latin America, Africa, Asia and the Pacific or some Eastern European countries could respond and meet the demands for the products constrained by the drought bottlenecks. This would be particularly important for the affected regions, as they could mitigate the direct impact on local consumption by purchasing agricultural products from international markets. On the contrary, a uniform water allocation policy would induce negative economic impacts worldwide. In this case, the intense disruption in global supply chains of all sectors would not allow third-countries to adapt and shift production to meet the demands of their domestic and international markets, leaving little room for substitution and complementary capacities to take place. However, withdrawing water endowments only to the agricultural sector during a drought, though more efficient in terms of aggregate VA, would impose intense economic losses in this sector and create large sectoral disparities within the affected region. Further research is thus needed to explore different allocation options, so that efficiency and equity can be combined. In this respect, the uniform scenario could be considered as an upper bound estimate of the negative impacts of drought, since it does not consider the water efficiency of the different sectors.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

Acknowledgments

This publication is part of the R&D project PID2020-118268RB, funded by MCIN/AEI/10.13039/501100011033. The research is also supported by the Spanish Ministry of Education (grant FPU20/00182), and the Catalan Government (grant 2021 SGR 00570). We also thank two anonymous referees for their insightful comments.

Appendix

Table A.1
Correspondence between MRIO sectors and aggregated sectors used in the study.

Exiobase code	Aggregate sector
i01.a	Cultivation of paddy rice
i01.b	Cultivation of wheat
i01.c	Cultivation of cereal grains n.e.c
i01.d	Cultivation of vegetables, fruit, nuts
i01.e	Cultivation of oil seeds
i01.f	Cultivation of sugar cane, sugar beet
i01.g, i01.h	Cultivation of plant-based fibers and other crops
i01.i–i01.l	Farming
i01.m, i01.o	Wool, silk-worm cocoons and other animal products nec
i01.n	Raw milk
i01.w.1, i01.w.2	Manure treatment (conventional and biogas)
i02	Forestry, logging and related service activities
i05	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing
i10–i14.3	Mining and quarrying
i15.a–i15.d	Processing of meat products
i15.e	Processing vegetable oils and fats
i15.f–i15.i	Processing of other food products
i15.j	Manufacture of beverages
i15.k	Manufacture of fish products
i16	Manufacture of tobacco products
i17, i18, i19	Manufacture of textiles and leather products
i20–i22	Manufacture of wood products, paper and printed matter
i23.1–i25	Manufacture of refined petroleum, chemicals and plastics
i26.a–i26.e	Manufacture of other non-metallic mineral products
i27.a–i28	Manufacture of basic metals and fabricated metal
i29–i37.w.1	Machinery, transport equipment and other manufacturing n.e.c
i40.11.a–i41	Electricity, gas and water supply
i45, i45.w	Construction
i50.a–i55	Wholesale and retail trade, Hotels and restaurants
i60.1–i64	Transport, storage and communication
i65–i74	Financial intermediation, renting and related business activities
i75, i80, i85, i99	Public administration, Education, Health and extra-territorial organizations
i90.1.a–i95	Other community, social and personal service and household activities

Table A.2
Industrial output elasticity of water.

Sector	Exiobase code	South Europe	Middle East	India	China
Rice	i01.a	0.765	0.836	1.167	0.832
Wheat	i01.b	0.759	0.821	0.956	0.893
Cereals	i01.c	0.767	0.833	1.054	0.939
VegFruit	i01.d	0.714	0.747	0.800	0.720
Oilseeds	i01.e	0.702	0.800	0.869	0.795
Sugar	i01.f	0.707	0.773	0.859	0.819
OthCrops	i01.g, i01.h	0.685	0.716	0.695	0.687
OthAgr	i01.i–i01.o, i01.w.1, i01.w.2, i02, i05	0.682	0.718	0.762	0.700
Extraction	i10–i14.3	0.682	0.701	0.689	0.681
P.Food	i15.a–i15.k	0.675	0.676	0.676	0.675
Textiles	i17, i18, i19	0.675	0.676	0.676	0.675
LightMan	i16, i20–i22	0.675	0.676	0.678	0.675
HeavyMan	i23.1–i37.w.1, i45, i45.w	0.675	0.677	0.678	0.676
Utilities	i40.11.a–i41	0.681	0.695	0.691	0.683

Source: Elasticities based on Roson (2019).

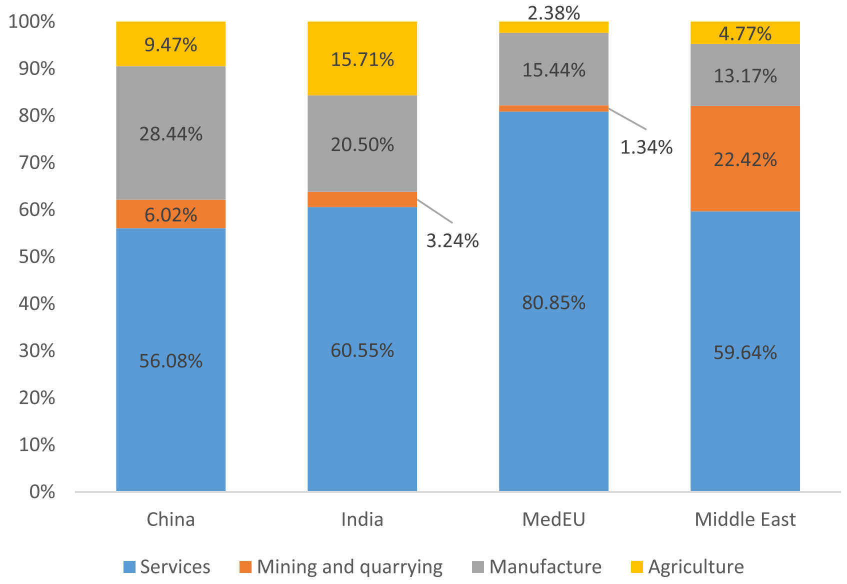

Fig. A.1. Sectoral composition of GDP by affected region.

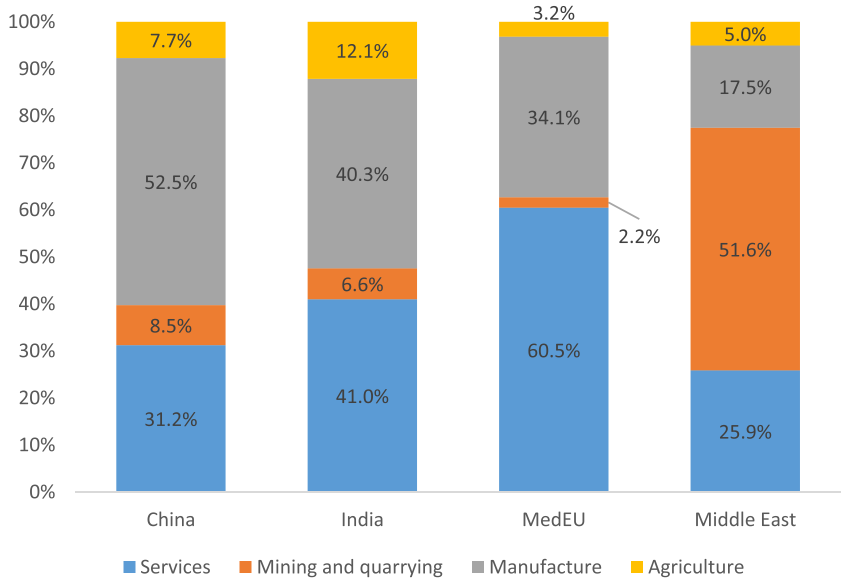

Fig. A.2. Sectoral composition of exports by affected region.

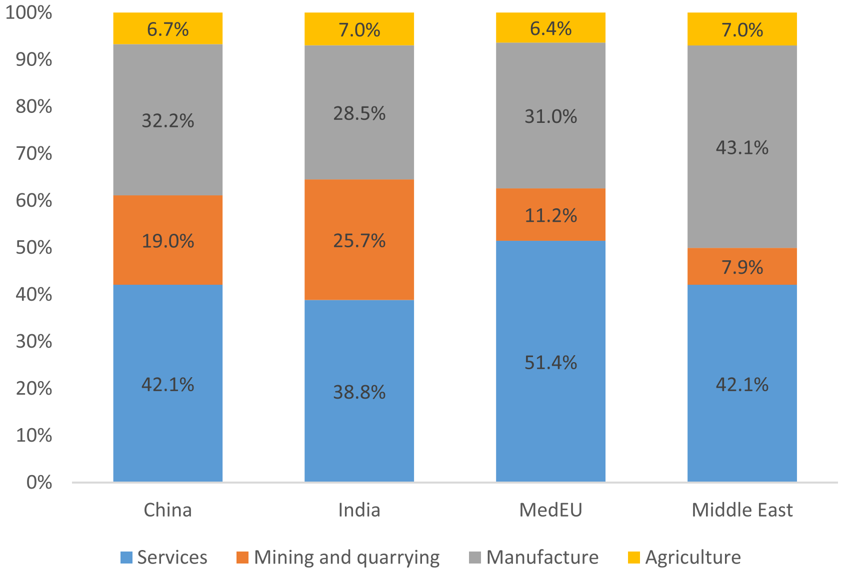

Fig. A.3. Sectoral composition of imports by affected region.

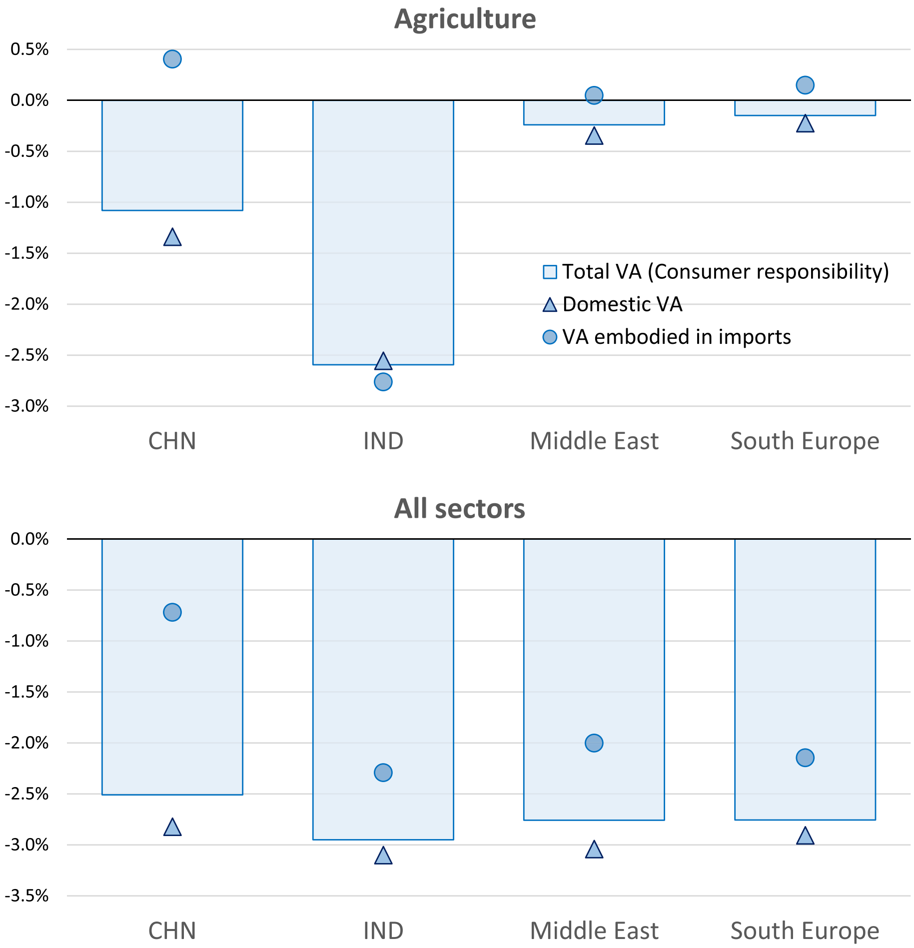

Fig. A.4. VA percentage change from the consumer approach (Eq. 11) in the drought-affected regions caused by a 5% reduction of water supply.
Source: own elaboration based on EXIOBASE v.3.7. Note: Upper panel: Water reductions in agriculture (agriculture scenario). Lower panel: Water reductions in all sectors (uniform scenario).

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