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Virtual Water Scarcity Risk to the Global Trade System

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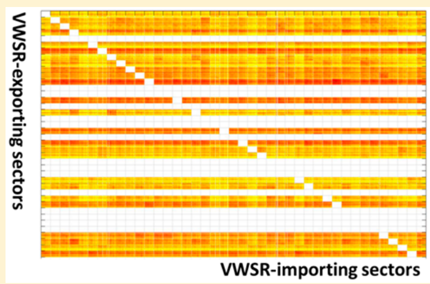
Supporting Information

ABSTRACT: Local water scarcity risk (LWSR, meaning potential economic output losses in water-using sectors due to physical water scarcity) can be transmitted to downstream economies through the globalized supply chains. To understand the vulnerability of the global economy to water scarcity, we examine the impacts of local water scarcity risk on the global trade system from 1995 to 2009. We observe increasingly intensified geographical separation between physical water scarcity and production losses due to water scarcity. We identify top nation-sectors in virtual water scarcity risk (VWSR) exports (indicating local water scarcity risk in each nation transmitted to foreign nations through its exports), including agriculture and utilities in major economies such as China, India, Spain, France, and Turkey. These nation-sectors are critical to the resilience of the global economy to water scarcity. We also identify top nation-sectors in virtual water scarcity risk imports (indicating each nation's vulnerability to foreign water scarcity risk through the global trade system), highlighting their vulnerability to distant water scarcity. Our findings reveal the need for nations to collaboratively manage and conserve water resources, and lay the foundation for firms in high VWSR-importing sectors to develop strategies to mitigate such risk.



INTRODUCTION

Water scarcity poses a significant risk to the global economy.[1] While water resources are usually managed locally, water-related issues have global origins and may exert global impacts.[2] From a local perspective, existing studies have quantified water scarcity of nations using various metrics, for example, the Falkenmark indicator,[3] basic human water requirements,[4−6] social water stress index,[7] and water stress indices defined as the ratio of water withdrawal or consumption to water availability.[8−11] To understand how foreign consumption drives local water use, an extensive body of research has investigated virtual transfers of water embodied in trade.[11−15] These studies have revealed that the economic activities of one nation may leave large imprints on the water use of distant countries. While virtual water trade has saved water globally, it has also increased water stress in some already water-scarce regions[11,16] and driven global biodiversity loss.[17] Moreover, sustainable water use has not been institutionalized in the global trade system.[18]

As nations are interconnected via international trade,[19] local water scarcity risk (LWSR) in producing nations, that is, the potential of directly losing economic outputs in water intensive sectors such as agriculture and power generation, can transcend national borders and lead to potential production losses in distant economies. As such, water scarcity risk (WSR) is increasingly perceived as a supply chain threat for industrial systems around the world.[20−22] Nations (or firms, industries, sectors) may be vulnerable not only to its own LWSR, but also to the LWSR facing its upstream suppliers that are located in foreign nations. In this context, local water resource management has become increasingly relevant to global industrial systems. Industrial and business decision-making will need to take into account these global connections to mitigate supply chain (or "virtual") water scarcity risk (VWSR).[12,23,24] Analyzing the impacts of LWSR on the global trade network can reveal vulnerable nations and sectors, and hence support policy and management decisions that protect those water resources critical to the global supply chains, thereby strengthening the resilience of the world economy to VWSR.

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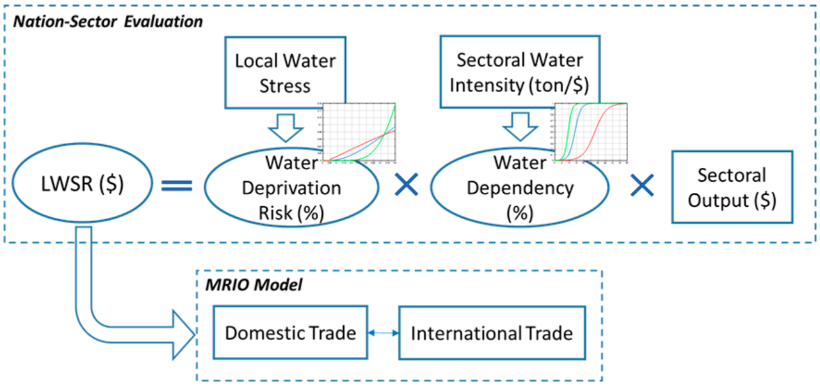

Figure 1. Graphical representation of our methodological framework. Rectangles represent real data and ovals represent estimated data. Exact functional images are shown in SI Figure S1.

This study, for the first time to our knowledge, evaluates the impacts of LWSR to the entire global trade system.

■ MATERIALS AND METHODS

In this study, WSR refers to potential output loss due to water scarcity, both directly (LWSR) and indirectly (i.e., VWSR). In this section, we develop a method to quantify LWSR and international VWSR linkages in the global economy.

In the evaluation of virtual water trade, a distinction has been made between the "bottom-up" (i.e., processed-based) approach and the "top-down" (i.e., input-output-table-based) approach.[11,25] The bottom-up approach takes into account the production processes of the main water-using products, and evaluates the virtual water content embodied in trade of those products. The shortcoming is that it cannot encompass all goods and services that indirectly use water through intermediate inputs. The top-down approach relies on the sectoral classification of input-output (IO) tables, and is therefore able to properly include all economic sectors in virtual water accounting. However, the relatively coarse sectoral classification in IO tables limits the scope of policy implications and may lead to inaccuracies in the accounting exercise.

Similarly, in quantification of water scarcity risks beyond the production site, one can start with either a bottom-up or top-down perspective. Recent studies based on the bottom-up approach have evaluated water scarcity risks transmitted through key water-using products, such as agricultural products[15] and electricity.[26] In these studies, consumers who source these products from water-scarce regions are deemed subject to water scarcity. The bottom-up approach benefits from specific descriptions of main water-using processes, but is unlikely to reveal the criticality of water to all products and services that are indirectly water-dependent.

Here we devise a top-down approach to evaluate water scarcity risks for all economic sectors, both directly and indirectly using water, in the global trade system. Besides borrowing from multiregional input-output (MRIO) models, additional complexities arise from this endeavor. The nation-sectors in the global trade system are subject to different degrees of water dependency and located in regions with different levels of water scarcity. To render consistent comparisons among the sectors, mathematical formula have to be used to convert relevant variables to monetary values, and the robustness of the result to parameter selection in this converting process should be assessed. In this section, we describe such as top-down method.

Figure 1 illustrates the key components of the framework and their relationship. We define LWSR of a sector in a nation (or a "nation-sector") as the relative potential of losing economic output due to water scarcity, by comparing annual consumptive freshwater use, the availability of surface and groundwater, and total output of each sector. For example, if a sector creates more output, consumes more freshwater, and is located at the more water-stressed region, its LWSR tends to be higher. We evaluate LWSR of a nation-sector in relative terms instead of absolute terms—the resulting metric thus measures the risk of output losses of a nation-sector facing water scarcity *relative* to such risks of other nation-sectors. This enables us to compare the vulnerability of nation-sectors due to the same local water scarcity.

Using data during 1995−2009, we first quantify LWSR for each nation-sector. We then evaluate impacts of LWSR transmitted to downstream sectors through reduced input supplies, using a global multiregional input-output (MRIO) model. Specifically, we evaluate both VWSR exports and imports of nations and sectors. The VWSR exports indicates the impact of LWSR in each nation on foreign nations through its exports. This helps us understand the importance of water scarcity in these countries to the global trade network. The VWSR imports indicates each nation's vulnerability to foreign water scarcity through the trade system.

LWSR Quantification. In water-stressed regions, economic activities in water-using sectors run the risk of not being supplied enough water to meet the requirement of production. If this occurs, a fraction of output would be lost, and the size of this fraction is determined by the degree to which the activity is dependent on water resources. In this way, we have conceived a pathway linking water scarcity to potential output loss for each economic sector, as in the following equation:

$$\mathrm{LWSR}_{k,c} = \mathrm{WDR}_c \times \mathrm{WD}_{k,c} \times x_{k,c} \quad (1)$$

where $\mathrm{LWSR}_{k,c}$, as described earlier, is the potential direct output loss (in monetary units) due to water scarcity of sector k in country c; WDR_c is *Water Deprivation Risk* in country c, measuring the fraction of potentially reduced water use due to water scarcity; $\mathrm{WD}_{k,c}$ is *Water Dependency* of sector k in country c, measuring the percentage output loss due to 1 percent of water deprivation; $x_{k,c}$ is the "benchmark" output (measured in dollars and adjusted for sectoral price changes

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across years) of the corresponding nation-sector without any water deprivation.

Since no direct data on WDR and WD exist, they need to be inferred from relevant variables. At this point, there are three points worth emphasizing. First, we do not aim to measure the absolute values of WDR and WD. Instead, they are measured in relative terms, and as a result, LWSR is also measured in relative terms. We are especially interested in the resulting rankings of nations and sectors (which allows for the identification of "hotspots"). Second, as mentioned earlier, one is concerned with the extent to which our main results depend on the parameters chosen for the above process. Therefore, we will conduct sensitivity analysis and discuss robustness. Third, the proposed method has the potential for adaption to data sources with higher resolution and even other environmental risks.

Below we explain the estimation of WDR and WD.

Water Deprivation Risk. The indicator WDR, lying in the interval[0,1], measures the expected fraction of reduced water use in a country due to potential water scarcity.

The water stressed index (WSI), expressed as the ratio of water consumption to potential water supply in a region, provide the most relevant information on the scarcity of water resources. Admittedly, high WSI does not necessarily lead to output loss, as a region can theoretically extract water as long as WSI < 1 and even do so when WSI > 1 while undermining environmental requirement and depleting water resources.[9] Nonetheless, without further systemic information regarding water supply to all sectors, it is expected that sectors in high-WSI regions are more likely to directly confront water scarcity.

Due to the above reasons, a function is used to convert WSI_c to WDR_c:

$$\mathrm{WDR}_c = f_{\mathrm{WDR}}(\mathrm{WSI}_c;\ \sigma) \tag{2}$$

where WSI_c is water stress index of country c, and σ is a parameter governing the heterogeneity of WDRs among countries (Supporting Information (SI) Figure S1A) and the function f_{WDR} is constructed from a probabilistic view as detailed in the SI.

A larger σ implies a greater difference of WDRs between a high-WSI and a low-WSI country. For the main results, we set $\sigma = 1$. SI Figure S2 plots WSIs calculated by this study and the resulting WDRs with different values of σ. Previous literature classified a region as subject to water scarcity if the ratio of water consumption to availability is over 20%, and significant and severe water scarcity if the ratio is over 30% and 40%, respectively.[9] As SI Figure S2 shows, when $\sigma = 1$, the countries with WSIs higher than 20% have WDRs over 1%. In addition, China has a WDR of 1.1% with a WSI of 16.6%, which is reasonable given its uneven distribution of water resources and regional water scarcity.[16] We will also calculate the results with σ ranging from 0.5 to 1.5 in the Sensitivity Analysis section. When $\sigma = 0.5$, only countries with WSIs higher than 40% (which are Malta and Spain) have WDRs higher than 1% and WDRs for other countries are negligible (SI Figure S2). When $\sigma = 1.5$, most countries (i.e., those with WDRs higher than 5%) have non-negligible WDRs.

SI Figure S2 further compares our evaluation with the global country-level water stress scores published by the World Resource Institute (WRI).[28] Most countries with WDR over 1% under $\sigma = 1$ are classified as subject to high water stress by WRI, except Denmark and France. This may result from the difference in water use estimations underlying this study[29−31] and the WRI score,[28] as well as the different definitions of water use for water scarcity evaluation (i.e., water consumption in this study versus withdraw by WRI). Furthermore, a few countries with notable water scarcity, such as Mexico, Australia and South Korea, are not captured by this study as having significant production risks, since the ratios of water consumption to exploitable water resources are low for these countries. Future studies may use data with higher spatial resolution to reveal WSR that is masked by country-level statistics. Thus, the comparison both testifies the risk quantification in this study, and points to its limitation and possible improvements.

Water Dependency. This indicator measures a sector's percentage economic output loss due to 1 percent of less water use compared with the "benchmark" condition. Its largest possible value is assumed to be 1, in which case water is completely not substitutable and output has to shrink in proportion to restricted water supply.

Water serves different functions in production of different sectors. As a result, it is impractical to comprehensive compare the various degrees of sectoral vulnerability to water restriction based on specific technologies. Following a recent study on water criticality,[32] we use water intensity, defined as water consumption for unitary sectoral economic output, to measure a sector's vulnerability to water restriction.

A function is used to convert sectoral water intensity (lying in$[0,+\infty)$) to sectoral water dependency (lying in $[0,1)$):

$$\mathrm{WD}_k = f_{\mathrm{WD}}(\mathrm{WI}_k;\ \alpha) = \frac{1}{1 + e^{-\alpha \mathrm{WI}_k}\left(\frac{1}{0.001} - 1\right)} \tag{3}$$

where WD_k and WI_k denote water dependency and water intensity of sector k, and the parameter α governs the cutoff value of WI above which WD rises rapidly toward 1 (SI Figure S1B).

A larger α implies a higher cutoff and therefore less nation-sectors classified as highly water-dependent. SI Figure S3 plots water intensity and the associated WDs, for the over 200 most water-intensive nation-sectors (among the 1400 ones) in the global economy, under $\alpha = 0.25$, $\alpha = 0.5$ (which is the value underlying the main results), and $\alpha = 0.75$. For each parameter value, the function in (3) leads to the results that highly water intensive nation-sectors have nearly maximum WD value (which is 1). For example, as labeled in SI Figure S3, although India's utility sector has higher water intensity (557 ton/\$) than China's agriculture sector (180 ton/\$), they are both treated as the most water dependent sectors with WD value very close to 1. On the other hand, for nation-sectors with very low or 0 water intensity, their WD values are at the minimum (i.e., 0.001), reflecting the general importance of water resources. Since the conversion from WI to WD is continuous, there is a range where the WD value declines quickly from the maximum to the minimum (SI Figure S1B and S3), and in this range, nation-sectors have WD between 0 and 1. Therefore, although more water-intensive nation-sectors are generally more water-dependent, the converting function is carefully chosen to admit the uncertainty for using water intensity to represent water dependency. When $\alpha = 0.5$, about 60 nation-sectors (or 4% of all nation-sectors in the global economy) have the maximum WD value (i.e., > 0.999), and 1170 ones (or 84% in total) have the minimum WD value (i.e., 0.001). As SI Figure S3 shows, when $\alpha = 0.25$ (0.75), less (more) sectors are classified as having the maximum WD value.

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Global Trade Modeling. Global trade among nation-sectors is described by the global multiregional input-output (MRIO) model. The global MRIO model records economic transactions within each nation and among nations at the sector level.[33] It has column balances, which mean that each sector's total input equals the sum of its intermediate inputs and value-added creation, as shown in eq 4. Each sector's total input also equals its total output.

$$x = eZ + v \quad (4)$$

In the above formulation, the $1 \times n$ vector x denotes total input of each sector; $1 \times n$ vector v indicates value-added creation of each sector; and $n \times n$ matrix Z represents economic transaction volumes among nation-sectors. Elements of the $1 \times n$ vector e are all 1.

Define an $n \times n$ matrix B which is the direct output coefficient matrix representing the allocation proportion of products from one nation-sector to all nation-sectors, as shown in eq 5. Equation 4 can then be written as the form of eq 6.

$$B = (\hat{x})^{-1}Z \quad (5)$$

$$x = v(\mathrm{I} - B)^{-1} \quad (6)$$

The $n \times n$ matrix $(I-B)^{-1}$ is known as the *Ghosh inverse* matrix,[33−35] each row of which indicates the total (sum of direct and indirect) outputs of sectors enabled by unitary value-added creation in the sector represented by this row. We use the *Ghosh inverse* matrix to evaluate impacts of LWSR on the global trade network, as shown in eq 7.

$$\Delta x = \mathrm{LWSR} \times (I - B)^{-1} \quad (7)$$

The vectorΔx represents directly and indirect output loss (i.e., WSR) of each nation-sector due to LWSR of all nation-sectors, and the vector LWSR represents LWSR of each nation-sector.

We can get a matrix ΔX by diagonalizing vector LWSR in eq 7, as shown in eq 8. Elements of each row of matrix ΔX indicate changes in economic outputs of each nation-sector due to LWSR of the particular nation-sector represented by this row. Elements of each column of matrix ΔX indicate changes in economic outputs of a particular nation-sector represented by this column due to LWSR of each row nation-sector.

$$\Delta X = \mathrm{diag}(\mathrm{LWSR}) \times (I - B)^{-1} \quad (8)$$

Suppose the world is divided into m nations; and let N be an $m \times m$ matrix, with each element n_{ij} standing for the impact of nation i's LWSR on nation j's economic production. We derive the element n_{ij} from elements of the matrix ΔX, as shown in eq 9.

$$n_{ij} = \sum_{\substack{k \in \mathrm{nation}i, \\ l \in \mathrm{nation}j}} \Delta x_{kl} \quad (9)$$

The element Δx_{kl} denotes the impact of nation-sector k's LWSR on nation-sector l's economic production.

VWSR exports for a nation, $\mathrm{VWSR}_i^{\mathrm{ex}}$, are calculated by eq 10, and VWSR imports for a nation, $\mathrm{VWSR}_i^{\mathrm{im}}$, by eq 11.

$$\mathrm{VWSR}_i^{\mathrm{ex}} = \sum_{i \neq j} n_{ij} \quad (10)$$

$$\mathrm{VWSR}_i^{\mathrm{im}} = \sum_{j \neq i} n_{ji} \quad (11)$$

We have used the Ghosh model instead of the Leontief model, because the former captures the supply push effects in the economy (i.e., primary input enables downstream production and consumption).[33,36−41] In contrast, the Leontief model measures demand-driven effects in the economy (i.e., final demand drives upstream production).[33] Water resources are essential factors for production in the economic system. Water scarcity directly influences the production of sectors in an economy, which indirectly restricts downstream production and consumption. Therefore, we use the Ghosh model in this study to evaluate the impacts of local water scarcity risk on the global trade system through supply push effects.

Although the Ghosh model has been criticized as a quantity model,[42−44] we find its formulation useful in our specific case, for the following reasons. First, the main implausibility of the Ghosh model comes from its assumption that sectoral inputs are perfectly substitutable.[43] In our study, perfect substitutability implies that downstream production losses only occur due to the direct reduction of input supplies, but not the resulting loss of usefulness of other inputs in the production process. Despite this, the results still imply sizable indirect water scarcity risk from trade. Second, the monetary value in this study serves as an indicator for *relative* importance of sectors or nations rather than precise measures for the values of economic losses. Thus, interpreting the Ghosh model as a quantity model in this study does not influence our main conclusions.

Herfindahl Index. To better reveal a nation's vulnerability to its VWSR import, we use the Herfindahl index, represented by Herf_i, to measure the concentration of VWSR imports for nation i.[45,46] If the origin of a nation's VWSR import is very concentrated, upstream production losses tend to occur simultaneously, and this reduces the nation's resilience to foreign water scarcity. Higher values of the Herfindahl index for a nation indicate higher concentration of its VWSR imports and thus greater vulnerability. The Herfindahl index is defined as

$$\mathrm{Herf}_i = \sum_{j \neq i} \left(\frac{n_{ji}}{\sum_{j \neq i} n_{ji}} \right)^2 \quad (12)$$

Data. Three types of data are required in this study: global MRIO data, consumptive water use of all sectors, and water availability of each nation.

MRIO Data. Scholars have recently developed many MRIO databases, for example, World Input-Output Database (WIOD),[47,48] Eora database,[49] GTAP database,[50] and EXIOPOL database.[51] The GTAP database does not have water use data, while Eora database (water use data in 2000[14]) and EXIOPOL database (water use data in 2000 and 2007[51]) only have water use data for limited time points. The WIOD has time-series water use data for households and sectors during 1995−2009.[27] Thus, for illustration of our methodology, we choose the WIOD (released on November 2013, with environmental satellite accounts) given its complete temporal coverage of water use data. However, the WIOD has a relatively coarse sectoral classification (with 35 sector for each country) and incomplete country coverage (with 40 countries/regions listed in SI Table S1 and the "Rest of World" regions for other areas). As a result, some water scarce countries in Middle East and North Africa are left out in this study. Future research may overcome this limitation by

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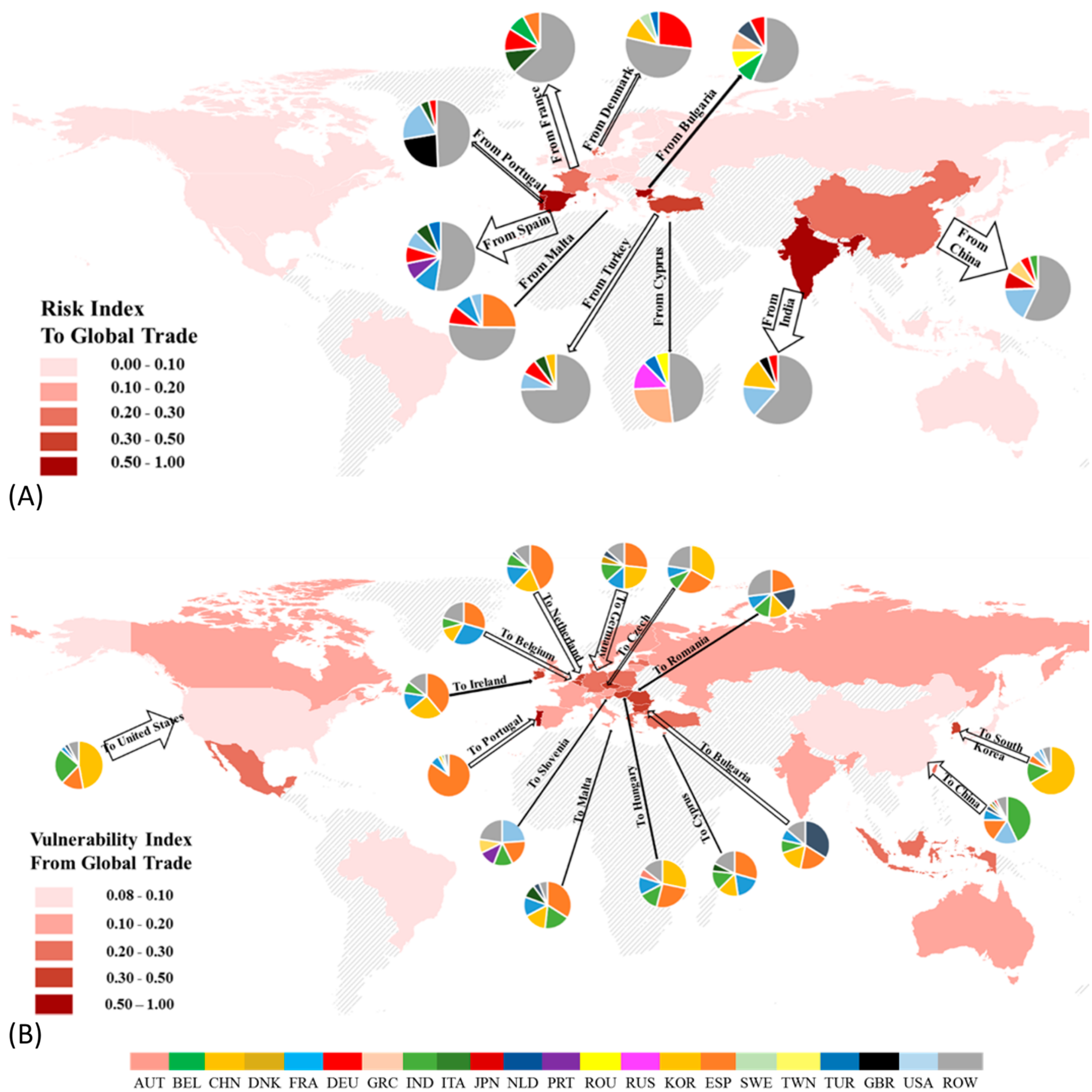

Figure 2. Virtual water scarcity risk (VWSR) exports (A) and imports (B) in 2009 by major nations. Arrow width is set in proportion to measures of risk. Risk indices (A) are VWSR exports normalized by the total output of the respective nations, and Vulnerability indices (B) are VWSR imports normalized by the total output of the respective nations. Hashed countries are not covered by WIOD individually. Meanings for country abbreviations are listed in SI Table S1.

integrating water resources data with MRIO databases with finer sectoral classification.

We choose the baseline as 2009 but also analyze time-series variation trends during 1995−2009 for the WIOD. In order to make results comparable across years, we convert all current-price MRIO data from the WIOD to ones in 1995 constant prices using the "convert-first-then-deflate" and double deflation methods from existing studies.[52,53]

Water Consumption. This study concerns the scarcity of blue water, which is the major water source for industrial production and households. Blue water use here means the consumptive use of surface and groundwater, the measure of which is rooted in the societal concern for water scarcity.[54] We use the indicator *blue water uses* from WIOD.[27] The underlying data come from previous sectoral evaluation of global water footprints.[29−31]

Water Availability. For annual water availability, we use the indicator "total exploitable water resource (km^3/year)" from FAO AQUASTAT,[8,9] instead of total renewable water resource as is commonly used in water stress evaluation,[8,9] to better reflect environmental requirements and technical and economic feasibility for water withdrawal. For some countries, data for annul exploitable water resources are lacking. For each country with missing data, we calculate the ratios of total exploitable water resource to total renewable water resource of the neighboring countries with complete data, and take the

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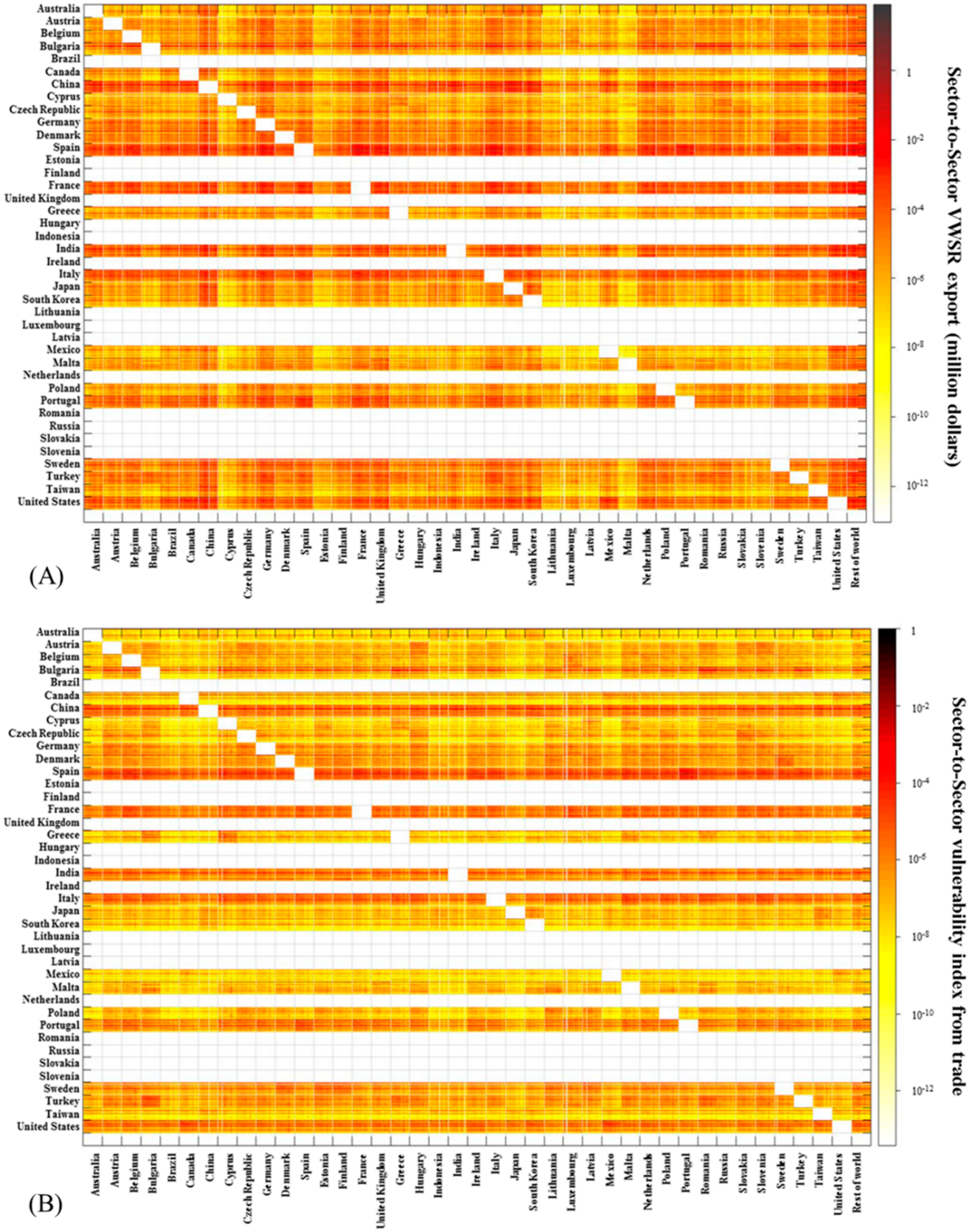

Figure 3. VWSR transmissions between nation-sectors (A) and sectoral vulnerability (irrespective of output size) from LWSR of foreign sectors (B). In each figure, rows and columns represent origins sectors and destinations sectors, respectively. Only the relevant nations are labeled. Each point in the heatmap represents the risk transmission from the row sector (i.e., the sector with physical water scarcity) to the column sector (i.e., the sector subject to VWSR).

average. We then multiply this average ratio by the total renewable water resource of the first country, deriving a proxy for its annul exploitable water resource which is comparable with existing data of other countries. Note that the data are not yearly water availabilities but rather annual averages averaged over decades. Thus, in this study, the change in nation-level

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WSI in different years is solely driven by the change in water consumption.

RESULTS

Separation between Physical and Virtual Water Scarcity Risks. Since 1995, the share of WSR due to trade (that is, the risk featuring separate nations with physical water shortage and production loss) has been steadily increasing until the fall in 2008 due to the global financial crisis (SI Figure S4). Such separation of physical and virtual WSRs is even more pronounced for most individual nations (SI Figure S5): compared with 1995, in 2009 a larger share of economic impact due to their LWSRs happens in foreign nations (SI Figure S5A), and a larger share of WSR affecting their economic systems physically originates from foreign nations (SI Figure S5B).

In 2009, approximately 7.3% of global WSR is transmitted through international trade (SI Figure S4). For a few nations, large portions of economic impacts of their LWSRs are associated with VWSR exports, such as Belgium (32%), Canada (26%), and Taiwan (26%) (SI Figure S5A). At the same time, there are 15 countries (in a total of 40) where all the WSRs for the economy are "virtual" (i.e., VWSR imports) (SI Figure S5B), since they are classified as not subject to LWSR due to extremely low WSIs. For over half of all the nations, VWSR imports occupy over 50% the WSRs threatening their economic production (SI Figure S5B), including nations with abundant water resources such as Russia, Brazil and Netherlands.

Mapping Water Scarcity Risk to Global Trade System. *Country Level Results.* We depict world maps of cross-border VWSR in Figure 2, revealing the distribution and transmission of water scarcity risks in the global trade system. Figure 2A and B focuses on VWSR-exporting (VWSR-importing) nations, where shades of color represent the VWSR export (import) per unit output of the corresponding countries. All country level statistics are provided in SI Table S1.

Figure 2A shows that VWSR originates in a relatively small number of nations. China, Spain, India, France, and Turkey can have significant impacts on foreign economies through VWSR exports. Although relatively large shares of such impacts remain domestic in these nations (SI Figure S5A), their international impacts are sizable and the WSR originating from these nations affect many other nations (Figure 2A). The VWSR-exporting nations are the world's top economies[55] and major commodity exporters in the global market. The combination of these factors and their domestic water stress (particularly in Spain and India[56]) can lead to significant impact in the global economy. To better understand the VWSR irrespective of the economic size, we measure the VWSR export for unitary output (i.e., normalizing each nation's VWSR by its total output), as illustrated in Figure 2A by the risk index to global trade. Then Spain, Malta, India, Portugal, Bulgaria and Turkey merge as the most risky nations for global trade, in that the production for unitary economic output tends to put more risk on the global trade system through insufficient water supply.

From 1995 to 2009, absolute values of exported VWSRs in major nations increased (SI Figure S6A). Notably, China has risen from the sixth largest VWSR exporter in 1995 to the first in 2009 (SI Figure S6B). This is mainly due to China's accession to the World Trade Organization (WTO), enabling it to become the "world factory" to supply large amounts of intermediate goods to other nations. Meanwhile, the rankings of European nations slightly dropped. The pattern above reflects the changing landscape of the world economy during this period, as well as increasing water stress in major exporting countries.

Figure 2B shows the impacts of foreign WSR to nations through imports, namely, VWSR imports. In contrast to the relatively concentrated distribution of VWSR exports, VWSR imports are more widespread in the global economy. As such, the interconnectedness of nations via trade can enable local water scarcities to exert global impacts. In particular, United States, Germany, China, France, and Japan are large VWSR importers. They are major commodity importers in the global market, making their economies sensitive to LWSR of foreign, upstream suppliers. To get rid of the effects of the economies' sizes, we calculate vulnerability indices from foreign WSR, by normalizing nations' VWSR imports by their total outputs. As Figure 2B shows, the economies of Portugal, Belgium, Malta, Bulgaria, and Netherlands are most vulnerable to VWSR imports.

Historically, absolute values of imported VWSRs in major nations increased from 1995 to 2009 (Figure S6C). In particular, the relative importance of China as a VWSR importer rose significantly from 1995 to 2009 (SI Figure S6D), due to China's increasing participation in the world economy.

Sector Level Results. The heatmaps in Figure 3 visualize the sector-to-sector VWSR transmission in the global trade system. These figures help illustrate general patterns of VWSR distribution in the global trade system, with the resolution of nation-sectors. Furthermore, one can identify hotspots from the heatmaps (i.e., the most important sector-to-sector relationships) by singling out the darkest points. Generally, the distributions of VWSR appear to spread over a variety of sectors in the global economy, both in terms of total risk transmission (Figure 3A) and vulnerability of the importing sectors (Figure 3B). This underscores the underpinning role of water resources in the modern economy, and stands in contrast to the relatively narrow focus on water-food or water-energy nexus featured in previous bottom-up analyses.

The top 100 links in Figure 3A and B are listed in the SI Table S2 and S3 respectively. We can find sectoral VWSR exports (SI Table S4) (imports (SI Table S5)) by summing up row (column) values of Figure 3A, and sectoral vulnerabilities from trade irrespective of output size (SI Table S6) by summing up column values of Figure 3B. Similar to results at the country level, the destinations of VWSR span broadly while the origins are relatively concentrated. Water scarcity to agriculture, energy and material production in a few water-stressed countries, such as Spain, India and China, can affect a variety of manufacturing sectors around the world through trade linkages.

The transmission of VWSR in the global trade system can be divided into two types with different implications for mitigation. The impact from the *Agriculture, Hunting, and Forestry* sector to various other sectors mainly occurs through direct trade. For example, if the exporting nation reduces its agricultural outputs under water scarcity, the food sectors of the importing nations may be supplied with less inputs and consequently suffer production losses. However, there is one obvious option to mitigate such risk: the importing nations may simply resort to the global market and switch to producers elsewhere, if the transportation costs and price fluctuations are not significant.

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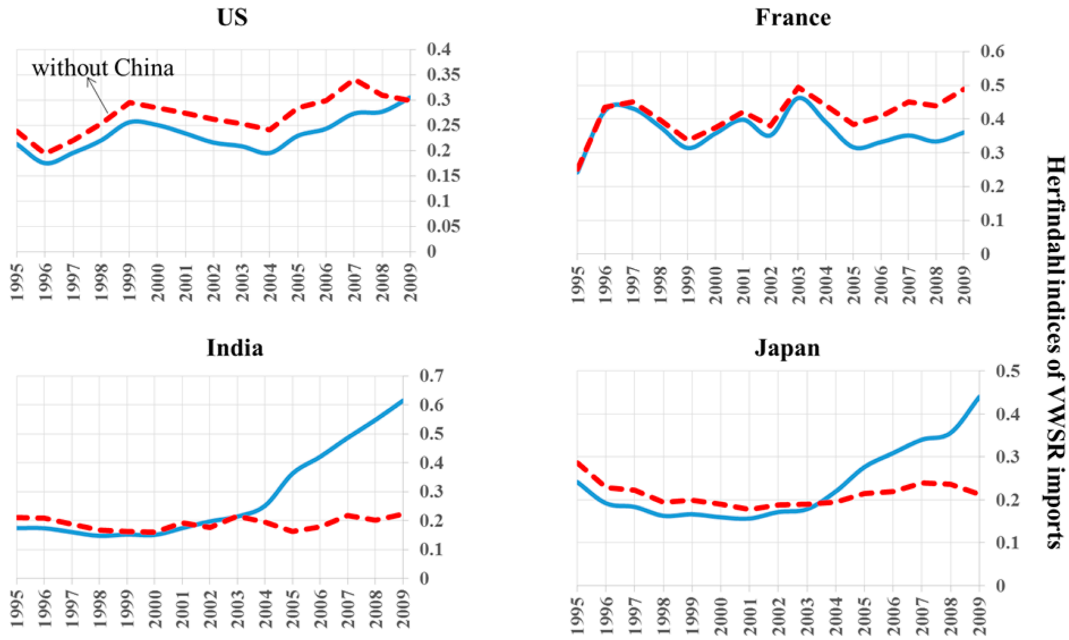

Figure 4. Trends of Herfindahl index for VWSR import concentration from 1995 to 2009, for four typical countries. Blue solid lines are for actual data, and red dotted lines indicate hypothetical trends with the exclusion of Chinese imports. Trend lines for all countries are presented in SI Figure S8.

On the other hand, the VWSR originating from the *Electricity, Gas, and Water Supply* sector can travel in the global trade system in a different way. Rather than through direct trade, such VWSR is transmitted in the industrial system largely organized in a transboundary fashion. SI Figure S7 shows transmission paths from Spain and China's *Electricity, Gas, and Water Supply* sectors to a few other manufacturing sectors. For example, the VWSR is transmitted from Spain's *Electricity, Gas and Water Supply* sector to Germany's *Transport Equipment* sector through several intermediate sectors, including Spain's *Transport Equipment*, *Basic Metals and Fabricated Metals*, and *Rubber and Plastics* sectors. Thus, the water-energy nexus in Spain, through water scarcity, may result in production losses in its multiple industrial sectors, which can in turn affect Germany's automobile production that sources key inputs from Spain. Crucially, this type of risk cannot simply be mitigated by markets: the intermediate inputs can have distinct designs, perform specific functions, and be supported by detailed contracts between the trading partners, without any "global market" to provide substituting products.[57] In this case, the WSR faced by the upstream suppliers are directly linked to downstream producers.

Measuring the Concurrence of Water Scarcity Risks. In addition to VWSR imports, we also evaluate the concentration of upstream trade partners for each nation to better reveal the vulnerability of nations to foreign WSRs. Higher concentration of suppliers to a system implies lower resilience, which refers to the ability of a system to continue functioning in the face of external shocks.[58] For example, if a nation imports products from just a few upstream nations - which are likely to experience water scarcity simultaneously - the downstream nation will be at high risk. We measure the concentration of upstream nations using the Herfindahl index,[45,46] where a higher Herfindahl index indicates higher vulnerability of a nation to foreign WSRs.

Figure 4 shows the historical trends of Herfindahl index for U.S., France, India, and Japan, both with and without inclusion of trade with China (we thank for an anonymous referee for adding the second series). The trends for all nations are in SI Figure S8. The rising importance of China in international trade can lead to opposite effects: it could diversify a nation's importing sources and thus make it more resilient against VWSR imports, or make a nation too dependent on Chinese imports and less resilient against VWSR imports. It is an empirical question which situation really occurs. In a certain year, if a nation's Herfindahl index with the inclusion of Chinese is lower (higher) than the one without, trade with China should have increased (decreased) the nation's resilience against VWSR imports.

We observe that China's rising importance has contributed to the diversification of VWSR and thus lowered the vulnerabilities for many of the world's major economies including US, France, Germany, Denmark, Britain and Indonesia (Figure 4 and SI Figure S8). However, the opposite has occurred for India and Japan (Figure 4). For these two countries, the gap between the trends including Chinese trade (the solid line) and the trend excluding Chinese trade (the dotted line) has widened significantly since 2003, indicating the increasing dependence on Chinese imports may have lowered their resilience to water scarcity.

Sensitivity Analysis. We analyze the robustness of nation-sector rankings to the selection of parameters. We change the value of α, the parameter governing the heterogeneity of WDRs among nations (eq 2), and σ, the parameter governing the cutoff level of water intensity for high water dependency (eq 3). Therefore, we recalculate the model for each of more than 10 000 (α,σ) pairs. We focus on sectoral rankings for LWSR (SI Figure S9A), VWSR exports (SI Figure S9B), and VWSR imports (SI Figure S9C). In each case, the Kendall correlation coefficients with the benchmark case presented above (where $\alpha = 0.5$ and $\sigma = 1$) are calculated for all (α,σ) pairs. When this coefficient is close to 1 (as illustrated in the green areas), the sectoral rankings for the relevant variable differ very little from the benchmark case.

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While the evaluations for sectoral LWSR and VWSR exports are only modestly robust, the robustness for sectoral VWSR imports is surprisingly high. Therefore, the identified top vulnerable nation-sectors to foreign water scarcity should carry more weight. This pattern is rooted in the systematic nature of the VWSR import estimation, as opposed to the single-point evaluation of LWSR and thus VWSR export. As we vary the value of the (α,σ) pair, for some nation-sectors, the probabilities of water deprivation and degrees of water dependency can change dramatically, rendering their LWSR and VWSR export estimations sensitive to the parameters. In contrast, the vulnerability of VWSR-import hotspots comes from a large number of foreign nation-sectors as origins with direct output loss (i.e., LWSR), and the inaccuracies in these single estimations tend to cancel out when added together through the entire trade system.

■ DISCUSSION

International trade transfers local water scarcity to distant economies through globalized supply chains. Our quantification reveals the changing nature of WSR in the global economy: more of it involves one nation facing a physical water shortage and yet another nation risking the subsequent production loss. This implies that the economic incentives for local water management are increasingly inadequate compared with the need of the world economy. We then identify critical nations and sectors whose local water scarcity may have significant ramifications for distant economies through the trade-connected global economy. We show that *Agriculture, Hunting, Forestry and Fishing* and *Electricity, Gas, and Water Supply* sectors in China, Spain, India, and France, and *Chemical and Chemical products* sectors in China and India, are critical to maintaining the robustness of the global trade system to WSR. As such, decision makers may want to focus on these "hotspots" for mitigating the transmission of VWSRs.

Our study also identifies critical nations and sectors with high vulnerability to foreign water scarcity. These include *Food, Beverages, and Tobacco* sectors in the U.S., Netherland, Germany, and China, *Transport Equipment* sectors in the U.S. and Germany. They are large importers of VWSRs. We also identify nation-sectors that are vulnerable to distant water scarcity controlling for economic size, such as *Food, Beverages, and Tobacco* sectors in Portugal and Netherlands. These nation-sectors are relatively small in economic size, but are highly vulnerable to water scarcity disruptions in the upstream supply chain. As such, this study informs governments, firms, and policy makers in these vulnerable nation-sectors of the supply chain risks they face, enabling them to develop strategies to mitigate the potential impacts (e.g., diversifying the upstream suppliers of their supply chains).

Our method has enabled the search for major origin–destination pairs for VWSR transmission at the sector level. Destination firms may pay attention to water scarcity issues in the origin nation-sectors. For example, firms in the *Electrical and Optical Equipment* sector in China need to be aware of and may develop strategies to mitigate the potential impacts to their supply chains due to water scarcity in India, which could constrain production in the upstream *Chemical and Chemical Products* sector. This highlights a potential opportunity for nations to collaboratively manage and conserve the critical upstream water resources. Countries already work together on transboundary management of physical water resources; this study points to the possibility that countries may now want to consider similar cooperation to protect scarce water resources that are upstream of their consumers in the supply chain, although it remains to be seen if such action at the country level would be politically feasible.

Critically, our study develops a complete methodological framework to quantify how local production shocks are transmitted to distant economies through the global trade system. This framework may be employed to understand how international trade transmits other production risks (e.g., weather shocks, deforestation, and even government policies) to the global economy and develop policies to mitigate such risks. This study highlights the importance of understanding teleconnections in the global trade system and quantifying local water scarcity implications for distant consumers. However, future work is needed to evaluate how decision makers, who typically only have jurisdiction within their own country, can address these nonlocal water scarcity risks. Future research would benefit from a study with firm-level data, since companies may be the best equipped to operationalize actions to mitigate upstream water scarcity risks to their supply chains.

Last but not least, two methodological limitations are noteworthy. First, our current framework provides only a snapshot of vulnerability across the global economy, but not insights on the changes of production patterns if a local production disruption (such as a drought) occurs. Recent progresses on IO modeling based on information theory has attempted to overcome this limitation.[59] In future work, such methods may be incorporated into our framework if computational capacity allows. Second, as mentioned in the discussion for sector level results, production disruptions can be transmitted differently through the transactions of homogeneous goods (such as agricultural products) and those of industrial intermediate inputs.[57] Future research may take this aspect into account to improve the accuracy of VWSR evaluation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b04309.

Detailed explanations, figures and data (PDF)

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