Impacts of Local Resource Scarcity Risk on Global Trade Network

by

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

CGE – Computable General Equilibrium

HDI – Human Development Index

IIM – Inoperability Input-Output Model

I-O – Input-Output

MRIO – Multi-Regional Input-Output

PPI – Policy Potential Index

UNEP – United Nations Environment Programme

WaSSI – Water Supply Stress Index

WAVE – Water Accounting and Vulnerability Evaluation

WDI – Water Depletion Index

WIOD – World Input-Output Database

WSA – Water Scarcity Assessment

WSP – Water Scarcity Probability

WTA – Withdrawal-To-Availability

Abstract

Local resource scarcity risk can transcend beyond national borders through international trade activities. However, there lacks a system-based approach to evaluate such risk posed from local resource scarcity to the trade-connected global economy. Using water resource as an example, this research develops a probabilistic framework to examine the impacts of local resource scarcity risk on the global trade network. Impacts of both country-level and basin-level local water scarcity risk on the global trade network are evaluated based on the data from Eora database, AQUASTAT database, and Water Footprint Network. The results identify top country-sectors in virtual water scarcity risk exports, including agriculture in major economies including Colombia, USA, Italy, France and Spain, which are critical for the resilience of the global economy against water scarcity risks. The results also identify top country-sectors in virtual water scarcity risk imports, showing the vulnerable sectors to local water scarcity risks of upstream suppliers. In addition, the basin model identifies the importance of local water scarcity risks of international basins, which indicates a need in peaceful cross-border cooperation to mitigate water scarcity risks. Overall, these findings provide implications to policy makers and corporate executives in developing strategies for mitigating water scarcity risks.

Introduction

The global economy has become more interdependent than ever[1], so as the interactions between the economy and the natural environment[2]. Existing studies have evaluated the environmental impacts of the global trade network[3-5]. The interactions between the economy and the natural environment are bi-directional, and local environmental challenges can result in cascading impacts to other parts of the world through the global trade[6-8]. However, little attention has been paid to the impacts of environmental challenges on the global trade network, quantifying which can support policy decisions to enhance the resilience of the global trade network against environmental challenges. However, there still lacks a systems-based decision-support tool to evaluate the consequences of such environmental challenges.

This thesis recognizes the above mentioned research gap, and aims to develop a probabilistic network-based analytical framework to quantify the impacts of natural resource scarcity risk on the global trade network. This work focuses on water resource due to its significant scarcity risks and publicly available data on the global scale. A framework was developed to assess both country-level and basin-level local water scarcity risk during the course of this thesis. It was demonstrated using publicly available data from Eora database, AQUASTAT database, and Water Footprint Network.

A manuscript based on the national risk model has been submitted for publication.

Water Scarcity Risk

Water is one of the most important natural resources on earth. Living beings must have water to survive, and socioeconomic activities also depend on water uses. Economic and population growth will continuously require more water for agricultural, industrial and domestic uses[9]. However, climate change, uneven water resource distribution, and population growth have posed great risks to the ability to fulfill the increasing water demand[10]. In fact, the World Economic Forum listed water crises as one of the most significant global risks in its Global Risks 2016 report[11]. Water is hence treated as an economically strategic resource, more than an essential natural resource[12].

In the complex global trade network, the impacts of local water scarcity risks often go beyond geographic boundaries. In fact, water scarcity is increasingly perceived as a supply chain threat for industrial systems[13]. Existing water scarcity metrics focus both on the availability and withdrawal of local water resources, with implications in the ecological footprints of anthropogenic activities. However, previous studies overlooked the trans-boundary passing effect of water scarcity in the global supply chains. Analyzing the impacts of local water scarcity risk on the global trade network can reveal the most vulnerable nations, sectors, and trade links facing the potential water scarcity risks, from either its local region or its upstream suppliers. Such analytical method could help form strategies in water conservation, especially in ensuring the resilience of the global economy against water scarcity risks.

In existing studies, different indices and models have been developed to assess the global water scarcity. Water scarcity was quantified mostly in two methods, one based on Human Water Requirements and the other based on Water Resources Vulnerability.

The Human Water Requirements method describes freshwater scarcity as a function of available water resources and human population[14-16]. These figures are generally expressed in terms of annual per capita water and mostly at the national scale. The logic behind their development is simple: if the amount of water that is necessary to meet human demands is known, then the water that is available to each person can serve as a measure of scarcity. Ohlsson[17] further developed this concept by taking into account Human Development Index (HDI), arguing that the capability of a society to adapt to difficult scenarios is a function of the distribution of wealth, education opportunities, and political participation.

The Water Resources Vulnerability method considers both the water demands and physical water availability[18-21]. Under this concept, various indices have been developed. The Water Supply Stress Index (WaSSI) assesses the relative magnitude of freshwater withdrawn and actual renewable water resources[22]. Pfister et al.[23] define WTA (Withdrawal-To-Availability) as the ratio of annual freshwater withdrawals to hydrological availability at the grid scale. They further consider the variation factor in precipitation distribution to calculate the Water Stress Index after non-linear transformations. Berger et al.[24] refine the concept by introducing the Water Accounting and Vulnerability Evaluation (WAVE) model. In their model, the Water Depletion Index (WDI) denotes the vulnerability of drainage basins to freshwater depletion based on physical blue water scarcity, which is based on the effective water consumption and actual renewable freshwater in each watershed. These existing studies provide useful information to identify key watersheds or nations facing significant local water scarcity risks. However, they cannot capture how the water scarcities affect human society.

Global Trade Network

The global economy has become increasingly interconnected and interdependent. The make of any modern product could involve a global supply chain where materials are sourced and values are added from any corner of the world. For example, an iPod, distributed by a U.S.-based company, is assembled in China from hundreds of parts that are sourced from around the world[25]. To quantify the complex global trade network, two predominantly used models are developed: Input-Output (I-O) Model and Computable General Equilibrium (CGE) Model.

A Computable General Equilibrium (CGE) model consists of a set of equations describing producers' and consumers' preference and a detailed actual economic database. By adding neo-classical assumptions about elasticities in production and consumption, CGE models are often used to estimate how an economy might react to changes in policy, resource, technology or other external factors[26]. The structure of

CGE models allows for the possibility of input substitution and imported goods for regionally products. Rose and Liao performed a case study for an earthquake-induced water supply disruption in Portland using a regional CGE model[27]. They used a questionnaire survey regarding individual responses as model inputs and simulated the induced sectoral and regional economic impacts of that earthquake. However, CGE models assume facile return to equilibrium in the near future, which may fail to well represent the real case. Besides, the redundant assumptions made in CGE models often undermine the credibility of such simulation.

Traditional Input-Output (I-O) analysis first developed by Nobel Laureate Wassily Leontief[28] uses a set of sectorally disaggregated economic accounts in a single country to quantify inputs from all industries to each individual industry and the subsequent uses of the output of each individual industry by all industries. By coupling environmental indicators, I-O analysis can be used to illustrate both the direct and indirect environmental impacts within the economy-wide activities[29, 30].

In the light of increasingly intensified economic interdependence among countries via growing international trade, Multi-Regional Input-Output (MRIO) model has gain its popularity in characterizing the global trade network and analyzing the environmental implications including greenhouse gas emissions, water, and energy use[31-36]. Essentially, an MRIO model consists of national economic input-output tables that are inter-linked by trade flow tables showing the value of imports and exports by countries and industries. It allows quantifying the interconnections among industries of countries through product flows.

Existing MRIO studies on environmental impacts mostly focus on the accounting of environmental responsibility to final consumers[37-42]. Such consumption-based approach follows the upstream of the supply chains and assigns emissions from upstream manufactures to their final customers[43]. An alternative income-based approach follows the downstream of the supply chains[44]. The rationale behind it is that downstream emissions are enabled by primary suppliers. Thus, the consumption-based approach can evaluate the economic activity due to changes in final demand, while the income-based approach can assess the economic performance due to changes in primary input.

Risks and Global Trade Network

Previous studies used different approaches to examine the impacts of potential risks or disasters on the economies, in which MRIO models are often used to quantify the economic outcomes and deficiencies. Some studies create assumed scenarios to simulate the incidents, while some use *ex post* numbers to estimate the losses caused by the events.

Nansai et al. developed the Mining Risk Footprint to quantify the mining risk affecting a national economy through its consumption of critical metals[45]. They use the Policy Potential Index (PPI) after linear transformation to quantify the mining risk of a certain mining country x. The use of proxy index for mining risk captures the opinions of managers and executives regarding the effects of policies in jurisdictions.

However, the use of such index does not take into account the physical constraints of the natural resources, as the risks of capitalizing certain natural resources depend on both the societal use side and the natural stock supply side. In addition, this index is subjective itself and does not distinguish different kinds of natural resources.

Based on Leontief Input-Output Model, the Inoperability Input-Output Model (IIM) was developed to analyze the economic system dysfunction due to the inability of a sector to perform its intended functions[46]. Santos and Haimes later expanded this model to examine the holistic economic losses resulted by demand reduction from two sectors after the “9/11” attack[47, 48]. Crowther and Haimes assessed the effects on the total economy of slowing down port operations and delaying commodities to sectors by port security[49]. The model used the shippers not demanding the goods as a demand reduction to ports. Anderson et al. applied IIM to the risk analysis of the 2003 Northeast Blackout[50]. The perturbations of the blackout were used to create an *ex post* case study that regards the power outage as unfulfilled electricity demand.

Most of the current IIM applications focus on static losses caused by disruption in demand reduction. Some studies also estimated the losses due to inoperability from the supply side. Crowther and Haimes calculated the cascading consequences of an assumed 10% loss of power output as unrealized supply[49]. Their study ranked the sectors according to both percentage and absolute economic loss.

However, Dietzenbacher and Miller argue that the IIM model is a straightforward application of the standard I-O model[51]. They proved that the IIM model is essence identical as the standard I-O model in math, with only difference in introducing unnecessary “new” matrices. Nevertheless, the publications of IIM have drawn relevant attention to an application of I-O models to analyze holistic economic impacts from disasters.

To the author’s knowledge, current studies focusing on economic losses caused by risks are limited in the way to assessing the losses: they are either exogenous from an assumed scenario, or an *ex post* statistics to estimate the losses caused by an event. In addition, none of the existing studies has been explicitly focused on the risks posed by water scarcity. A precautionary study on potential risks can better inform the policy makers in advance of the resource scarcity incident while reflecting the reality.

Conceptual Framework

The study evaluates the potential impacts posed by local water scarcity risks on the global trade network. Figure 1 uses a value chain example to show the two kinds of water scarcity risks – local water scarcity risk and virtual water scarcity risk. Local water scarcity risk is defined as the relative potential of losing value-added due to water scarcity for each sector in each region, which takes into account the direct water use and value-added of the sector, as well as the hydrological water availability of the local region. A sector faces higher local water scarcity risk if it uses more freshwater, generates higher value-added, and has less access to available water. As the primary input sector faces water scarcity risk, its deficiency in delivering the output would cause trouble to its downstream sectors, transferring the risks along the supply chain. The virtual water scarcity risk is then defined as the potential total output losses of a sector due to local risks transferred from other sectors.

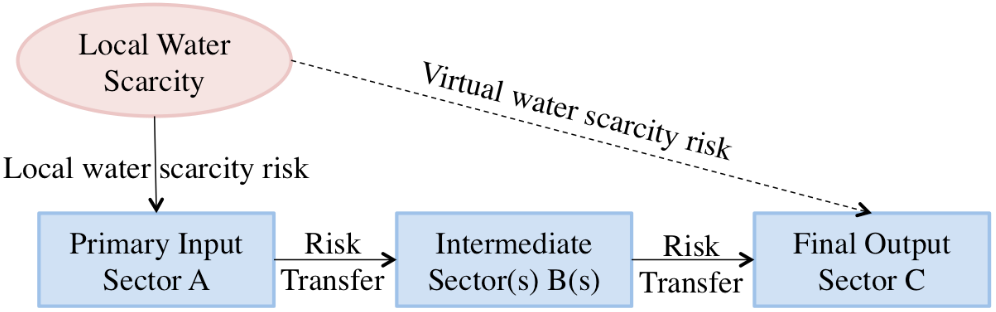

Figure 1 The conceptual framework of local and virtual water scarcity risks using a value chain example

Methods and Data

The analytical framework comprises two major components: Water Scarcity Assessment and Multi-Regional Input-Output Analysis (Figure 2). The Water Scarcity Assessment part uses sectoral direct water use and local water resource availability as model inputs to generate relative sectoral local water scarcity risks as model outputs. The MRIO part then takes the assessed relative local water scarcity risks as model inputs to calculate the holistic economic potential losses due to local water scarcity risks. Each of the two components has its own independent model inputs and outputs. When new data and methods related to particular components become available, this probabilistic network analysis framework could be flexibly updated by only changing the corresponding components.

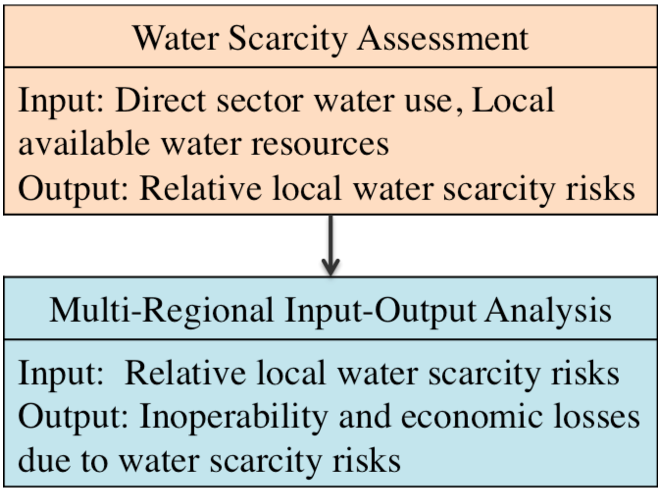

Figure 2 The two components of the analytical framework: WSA and MRIO

The water scarcity for each sector is assessed with respects to both the location's local water availability and the sectoral water use intensity. Generally, the more the amount of water needed for delivering unitary goods or services of a sector, the more vulnerable it is to local water scarcity. On the other hand, the likelihood of water scarcity is estimated according to the ratio of water use pattern and local water availability. Regions with higher water consumption and lower water availability are more likely to encounter water scarcity.

Various forms of water availability information exist in terms of level of resolution, while the most popular two levels are grid-based water basin level[52] and country level[53]. Recognizing the availability of data, this thesis has developed two water scarcity assessment methods – one based on water basin availability, and the other one based on national water availability.

The global trade network is characterized by the Multi-Regional Input-Output (MRIO) model. Once a sector is affected by local water scarcity, its inability to perform intended function would have impacts on other sectors across the world through the global trade network. Income-based I-O Model using primary input deficiency as model inputs then quantifies the economic losses to all sectors in the world. The finest resolution of the global MRIO model is on the country-sector level, which limits the corresponding model input have to be on the same country-sector level.

Water Scarcity Assessment

Water availability. The total renewable water resources include the amount of water generated inside a country and the amount of water entering this country. When water basin information is available, a country’s water availability can be aggregated by each catchment area of its sovereignty. If a water basin falls completely under one country’s territory, then the water resource can be directly added up to the country’s total water availability. If a water basin covers more than one country, then the basin is divided up into smaller sub-basin according to the sovereignty of each area. The water availability of each sub-basin is disaggregated from the original basin based on the area of each sub-basin. Therefore, the available water resource of country *i* is

$$A_i = \sum\nolimits_m I_k + \sum\nolimits_n \left(\frac{a_{i,p}}{a_{i,p} + \sum_x a_{l,p}} E_p\right) \text{ for country } i, \text{all basin} \tag{1}$$

where A_i (km^3/year) represents the total renewable water resources of country i, I_k (km^3/year) represents the renewable water resources of basins that are fully country *i*'s sovereignty, $a_{i,p}$ (km^2) represents the area of the sub-basin of the international basin *p* that is country *i*'s territory, $a_{l,p}$ (km^2) represents the area of the sub-basin of an international basin *p* that is outside of country *i*'s territory, E_p (km^3/year) represents the renewable water resources of an international basin *p*.

Country-level water stress. Water stress is commonly portrayed as the ratio of total annual freshwater withdrawals to hydrological availability[23]. Water uses were measured as consumptive use, rather than direct withdrawals, of ground and surface water (blue water use)[52, 54, 55]. Water stress indices are hence calculated after normalization for specific geographic regions, usually at country level or basin level.

$$WTA_i = \frac{U_i}{A_i} = \frac{\sum_j U_{i,j}}{A_i} \text{ for country } i, \text{all sector} \tag{2}$$

where WTA_i stands for the used water to availability ratio for country i, U_i represents the annual total consumptive freshwater use of country i, and $U_{i,j}$ denotes the annual water consumption of sector *j* in country i. A_i (km^3/year), the total renewable water resources of country *i*, come from the national-level data in the national risk model, and from the aggregated basin-level data in the basin risk model.

Sector-level water stress. Little literature has brought up the sector-wide water scarcity. The major difficulties lie in identifying the amount of available water resources for a given industry, since information on consumptive freshwater use is easier to gather or estimate. To assess the water stress posed by different sectoral uses based on their water use patterns, a few factors need to be taken into account, given that those sectoral WTAs are used to characterize the relative probability of a water supply shortage to each sector eventually.

1) A country's WTA should represent the average of its all sectors' WTAs and household WTA to some extent. A country's WTA is defined as the ratio of its total freshwater withdrawals to its hydrological availability. Likewise, a sector's WTA is defined by the ratio of its water consumption to its accessible water resource. Therefore, a country's WTA should somewhat represent the overall average of its all sectors' WTAs as opposed to the aggregated WTAs;
2) It is meaningful to compare one country's WTA to another country's WTA. Each country has its own portfolio of water consumption and availability. The rational of the defined WTA depicts the ability of a region's natural water resource to meet the demand driven by human activities. Then the comparison of these country's WTAs should directly involve each country's natural resource

fulfillment;

3) It is meaningful to compare one sector’s WTA to another sector’s WTA within the same country. Different sectors have different water use intensity and total water use. An important factor here to consider is that the sector that uses more water should have higher value of WTA and eventually higher risks of water shortage happening. More sophisticated probability models may be developed to identify the relations between water use and water shortage risk. However, it is the relative risk instead of absolute risk that matters to the purpose of this study. A single linear model may fulfill the purpose of preliminary study;
4) It is meaningful to compare the same sector’s WTAs from one country to another country. Even for a given sector, different countries may apply different technologies and hence have different water use pattern. In addition, from the natural resource perspective, available water resources differ from countries. Generally, countries that are more water use-intensive and availability-constrained should have higher WTAs for a given sector.

The proposed method to evaluate sector-level WTAs satisfy the above mentioned criteria with a water resource distribution assumption that each sector should be allocated the same amount of water to generate unitary output. The household domestic use (D_i) is excluded from the country’s available water resource to calculate the country’s sectoral available water resources:

$$A_i^* = A_i \frac{\sum_j U_{i,j}}{\sum_j U_{i,j} + D_i} \tag{3}$$

where A_i^* (km^3/year) denotes the effective water resource availability for sectoral uses. Then the WTA for sector *j* in country *i* is:

$$WTA_{i,j} = \frac{U_{i,j}}{A_i^* \frac{x_{i,j}}{\sum_j x_{i,j}}} = \frac{U_{i,j}/x_{i,j}}{A_i^*/\sum_j x_{i,j}} \text{ for country } i, \text{sector } j \qquad (4)$$

In the second form, $U_{i,j}/x_{i,j}$ denotes the water use intensity (km^3/\$ million output) for sector *j* in country *i*. $A_i^*/\sum_j x_{i,j}$ represents the amount of available water resources (km^3) for unitary output (\$ million) of country *i*. Therefore, the WTAs are unitless indicators.

Sector-level Water Scarcity Probability (WSP). The Probability is the measure of the likeliness that an event will occur, and quantified as a number between 0 and 1. The higher the probability of an event, the more certain we are that the event will occur. The event here in this study is the occurrence of 1 km^3 water shortage of the industry demand that cannot be satisfied. However, it is the relative value instead of absolute value that is of this study's interest. It makes more sense to capture the relationships among all the sectors as opposed to best estimate the probability of water shortage.

1) WSPs should be non-negative and no greater than 1;
2) The higher one industry's WTA is, the higher the WSP will be. WTA depicts the ratio of water use over its availability. Apparently, if a sector is more water-intenve or located in a country where water resources are less available, the water shortage is more likely to happen;

3) For WTA greater than 1, meaning water withdrawal is higher than local availability, water shortage is happening or most likely to happen;
4) A variation factor with regards to local precipitation should be taken into account. The Kolmogorov-Smirnov test shows that log-normal distribution generally fits better for precipitation. If the precipitation of a watershed deviates more than another, even though they have the same annual precipitation, the place with higher deviation is more likely to have water shortage;
5) In addition to physical water scarcity, socio-economic parameters are also relevant to freshwater shortage, particularly in less developed countries. The cause-effect chain from precipitation via withdrawal to final consumption is highly complex. To calculate the relative probability of water shortage, social indicators such as Human Development Index (HDI) can be taken into account. Higher HDI may reduce the probability of water shortage impacting the industry. However, higher HDI can also correlate with more water demand and thus water resource is scarcer. Thus, the relationship between the socio-economic factors and water scarcity risks is obscure.

To provide a first attempt to evaluate the WSPs, the proposed method uses a simple linear normalization with regards to the highest sector-level WTA. This method fulfills basic criteria 1) to 3), while future study could also take into account criteria 4) to 5).

$$WSP_{i,j} = \frac{WTA_{i,j}}{\max(WTA_{i,j})} \tag{5}$$

However, this way may distort the relationships between a small number of sectors like agriculture that have really high WTAs and the majority of sectors with low WTAs.

Relative economic losses. Relative economic losses of sectors due to local water scarcity is measured by the amount of value added creation for 1 tonne of water used, based on the notion that sectors more dependent on water resources tend to lose more value added from local water scarcity.

$$L_{i,j} = \frac{V_{i,j}}{U_{i,j}}\ for\ country\ i, sector\ j \tag{5}$$

where $L_{i,j}$ (\$ million/km^3) is the relative economic loss of sector *j* in country *i* due to local water scarcity, $V_{i,j}$(\$ million) represents the value added creation of sector *j* in country *i* in a given year, and $U_{i,j}$ (km^3) stands for the annual water use of sector *j* in country *i*.

Scarce water. The scarce water (SW) of sector *j* in country *i* ($SW_{i,j}$) is the product of its WSP and water use:

$$SW_{i,j} = WSP_{i,j} \times U_{i,j}\ for\ country\ i, sector\ j \tag{6}$$

Relative sectoral local water scarcity risks. Quantifying the risks usually involves multiplying the relative risk probabilities and certain weights. For example, in the WAVE model, Berger et al[24] developed a concept named risk of freshwater depletion determined by multiplying the effective water consumption in each basin with its corresponding water depletion index. The risk they assessed was associated with water depletion. Therefore, the weight in relative risks is effective water consumption. In this study, the risk we evaluate is the relative economic loss in primary inputs caused by water shortage. Thus, the weight is the value added of each sector and the probability is the WSP illustrated earlier of each sector. In this way, the discrepancy caused by arbitrary industry classification could be avoided.

$$Relative\ Loss\ \left(\Delta V_{i,j}\right) = L_{i,j} \times SW_{i,j} = \frac{V_{i,j}}{U_{i,j}} \times WSP_{i,j} \times U_{i,j} = WSP_{i,j} \times V_{i,j} \quad (7)$$

Multi-Regional Input-Output Model

The supply-side Ghosh MRIO model demonstrates the production behaviors in a forward direction within the supply chain of a given industry[56, 57]. Thus, it can illustrate how all sectors would operate with water scarcity impacting the primary input sector. The demand-side Leontief MRIO model is another predominantly used form of MRIO, which can be used to illustrate the losses that result from the water-supply sectors not demanding the essential commodities needed for operation when the water-supply sector provides a reduced output of water commodity. For the purpose of this thesis, supply-side Ghosh MRIO model best fits the interests.

In a supply-side MRIO model, each sector’s total input equals to the sum of its intermediate inputs and value-added creation. The balanced matrix equation is as follows:

$$x = e\,\boldsymbol{Z} + v \quad (8)$$

Assume that the global economy is divided into n nation-sectors. The 1×n vector x means total input of each sector; 1×n vector v indicates value-added creation of each sector; and n×n matrix $\mathbf{Z}$ represents economic transaction volume among nation-sectors. Elements of the 1×n vector e are all 1.

Define an n×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 equation (9). Equation (8) can then be written as the form of equation (12).

$$\boldsymbol{B} = (\hat{x})^{-1}\,\boldsymbol{Z} \tag{9}$$

$$\boldsymbol{x} = \boldsymbol{x}\,\boldsymbol{B} + \boldsymbol{v} \tag{10}$$

$$\boldsymbol{x}\,(\boldsymbol{I} - \boldsymbol{B}) = \boldsymbol{v} \tag{11}$$

$$\boldsymbol{x} \ = \boldsymbol{v}\,(\boldsymbol{I} - \boldsymbol{B})^{-\mathbf{1}} \tag{12}$$

Let $\widetilde{\boldsymbol{v}}$ represents the primary input deducted from the loss caused by water scarcity and $\widetilde{\boldsymbol{x}}$ represents degraded production output due to supply-side disturbance.

Then

$$\widetilde{\boldsymbol{x}} = \widetilde{\boldsymbol{v}}(\boldsymbol{I} - \boldsymbol{B})^{-1} \tag{13}$$

Losses in total output are the differences between $\boldsymbol{x}$ and $\widetilde{\boldsymbol{x}}$:

$$\Delta\boldsymbol{x} = \boldsymbol{x} - \ \widetilde{\boldsymbol{x}} = \boldsymbol{v}\,(\boldsymbol{I} - \boldsymbol{B})^{-\mathbf{1}} - \ \widetilde{\boldsymbol{v}}(\boldsymbol{I} - \boldsymbol{B})^{-1} = (\boldsymbol{v} - \widetilde{\boldsymbol{v}})(\boldsymbol{I} - \boldsymbol{B})^{-1} \tag{14}$$

Let $\boldsymbol{G} = (\boldsymbol{I} - \boldsymbol{B})^{-1}$ and $\Delta\boldsymbol{v} = \ \boldsymbol{v} - \widetilde{\boldsymbol{v}}$

$$\Delta\boldsymbol{x} = \ \Delta\boldsymbol{v} \ \times \ \boldsymbol{G} \tag{15}$$

If the $\Delta\boldsymbol{v}$ vector is diagnalized into a matrix, then the final results are also in matrix form.

$$\Delta\boldsymbol{X} = \widehat{\Delta\boldsymbol{v}} \times \boldsymbol{G} \tag{16}$$

Element Δx_{ij} means the impacts on total output of sector *j* (column) from sector *i* (row) as sector *i* faces risks posed by local water scarcity. The sum of each row elements is equivalent to the $\Delta\boldsymbol{x}$ vector.

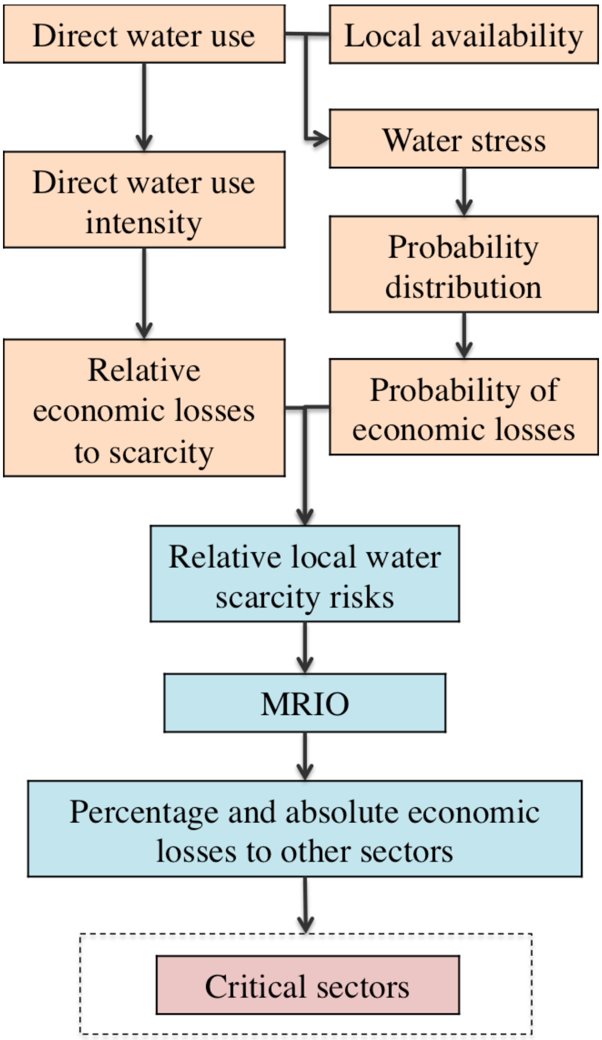

Figure 3 Overview of the methodology

Data Sources

Four types of data are needed to perform the study: global MRIO data, water use of households and sectors in each country, hydrological water availability of each country in the country model, and hydrological water availability of each basin in the basin model.

Different forms of MRIO databases have been developed for uses in different scale, e.g. the World Input-Output Database (WIOD)[58, 59], Eora database[60, 61], and GTAP database[62]. The GTAP database does not include water use data on the sectoral level, while the other two databases provide such information. The WIOD database covers 27 European countries and 13 other major economies, each with 35 sectors including water use and other environmental satellite information. The Eora database divides the world into 190 nations characterized by 14,839 sectors in total, which has the highest resolution among the publicly available MRIO databases. One major drawback about the Eora database was that it only updated water use information until the year 2000. For the purpose of demonstrating the framework, Eora dataset was chosen mainly given its fine resolution on the global economy. Annual quantities of water use for each industrial sector including agriculture and domestic use were adopted from the corresponding Eora sector as its satellite indicators. In particular, the blue water use was calculated as the sum of *blue water uses* (used for animals, industrial production, and domestic supply) and 25% of *crop water uses* in the Eora database[38].

For the country model, the total actual renewable water resource was used to describe each country's hydrological blue water availability. This metric is defined as the sum of internal renewable water resources and external actual renewable water resources, which equals to the sum of total renewable surface water and total renewable groundwater minus the overlap between surface water and groundwater, taking into account flow reserved to upstream countries and downstream countries and possible upstream abstraction. Related data for the Year 2000 are from the AQUASTAT database of the Food and Agriculture Organization (FAO) of the United Nations[53].

For the basin model, the blue water availability of each basin accounts for environmental flow requirement by subtracting a certain percent from the total runoff for the presumed purpose of sustaining ecological health. The total runoff of each basin is the sum of observed actual runoff and the blue water footprint that represents the use of surface water and ground water associated with human activities in the specific region. The data used are from Water Footprint Network[55].

Results

Case I: Country Model

The world map in Figure 4 shows each country's virtual water scarcity risk export in 2000. Those are the risks originally impacting the primary input sectors in each country that are able to transfer to downstream sectors with indirect impacts. Three features could make a country a large virtual water scarcity risk exporter: (1) the country does not have many water resources; (2) the country uses a lot of water in its economic activities; and (3) the country exports a lot of goods, especially the ones that require much water to produce. The top exporting countries are the United States (34%), Colombia (21%), Italy (6%), France (5%), Spain (4%), UAE (3%), and Saudi Arabia (3%). These seven countries in total contribute to about three quarters of the global virtual water scarcity risk export. Some of them are large export economies, and some of them face stronger water stress domestically.

Figure 5 shows each country's virtual water scarcity risk import in 2000. Those are the risks impacting the final output sector in each country that are received from upstream sectors facing direct risks. Those top countries are featured as producing final products with water-scarce materials as input. The top importing countries include the United States (33%), Colombia (19%), Italy (6%), France (5%), Spain (4%), UAE (2%), UK (2%), Saudi Arabia (2%), and India (2%). These nine countries in total account for about three quarters of the global virtual water scarcity risk exports.

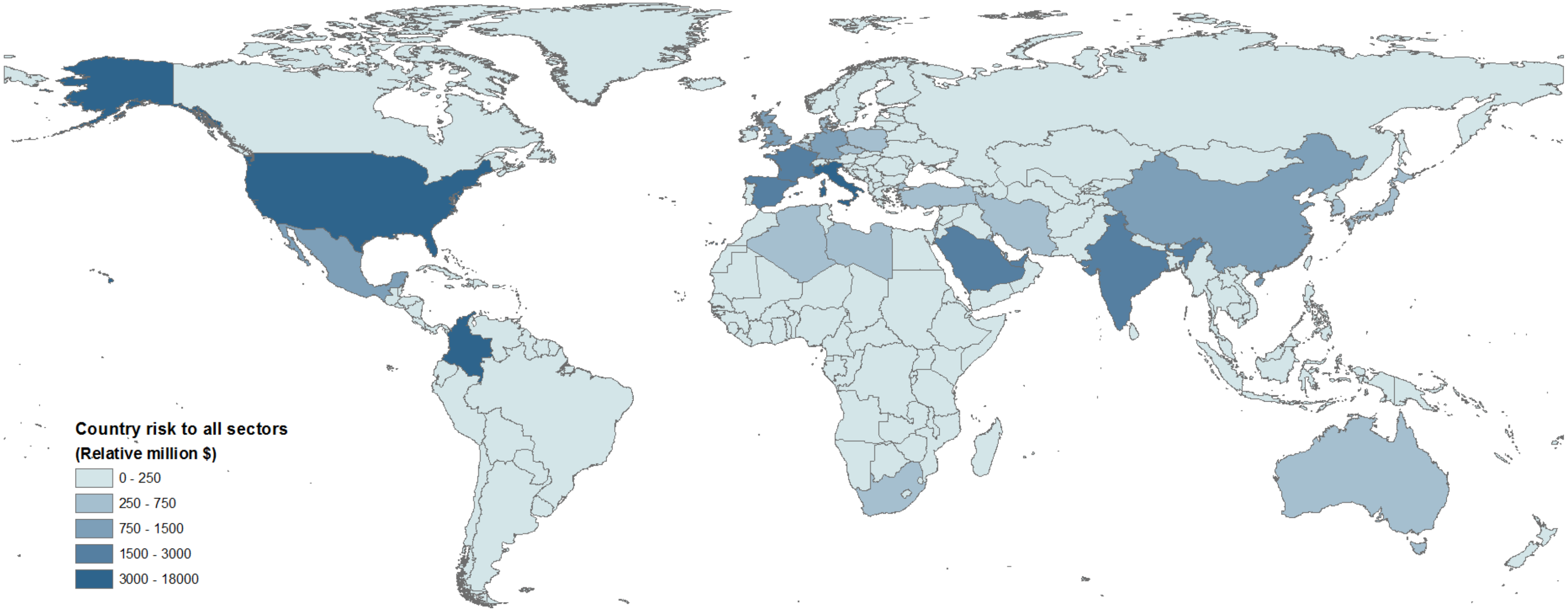

Figure 4 Each country's virtual water scarcity risk export in 2000 (unit: relative million US$)

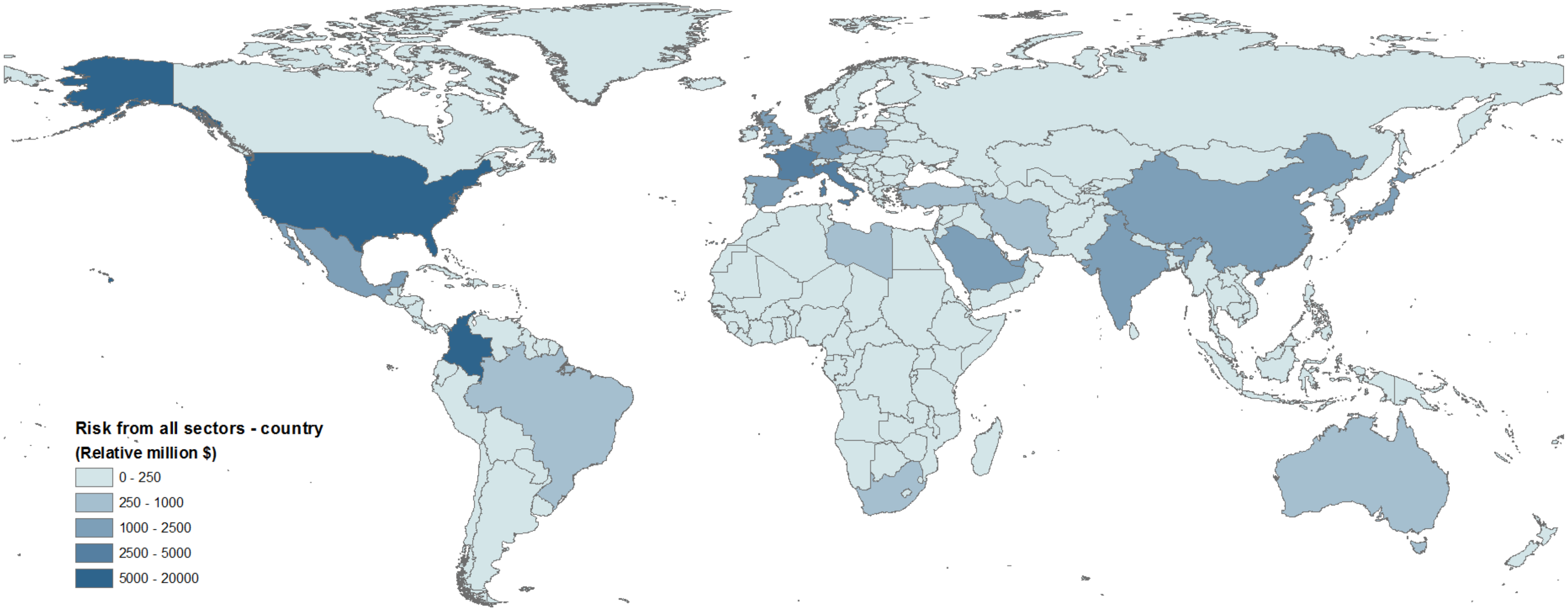

Figure 5 Each country virtual water scarcity risk import in 2000 (unit: relative million US$)

Table A1 shows the top 30 sectors experiencing local water scarcity risk, ranked by the direct impact on the sector itself. Those are typically agricultural sectors because agriculture directly uses lots of water among other sectors. Whenever a sector uses water heavily in a water-scarce place, the local water scarcity risk is high. For example, agriculture in Colombia, UAE, USA, Saudi Arabia, France, and Italy face larger local water scarcity risk. Table A2 shows the top 30 sectors that are able to export the local water scarcity risk to downstream sectors. Those upstream sectors include *Other agricultural products* in Colombia, *Grain farming* and *Oilseed farming* in USA, *Agriculture, hunting and related service activities* in Italy and France, and others. Table 1 in next page shows the top 30 sectors with largest water scarcity risk in their final output as a balanced result. Many of the final output sectors that import largest water scarcity risk are related to food production, including food processing sectors and hotel and restaurant sectors. Those sectors typically use the primary agricultural output as their materials in production, thus facing indirect risks from the upstream agricultural sectors.

Table 1 Top 30 sectors with largest water scarcity risk import in 2000 – country model

Rank	**Country**	**Sector**	**Water Scarcity Induced Risk (million US$)**
1	Colombia	Other agricultural products	3308
2	USA	Grain farming	850
3	USA	Soybean and other oilseed processing	674
4	Italy	Products of agriculture, hunting and related services	650
5	Colombia	Grain mill products, starch and related products	638
6	France	Products of agriculture, hunting and related services	635
7	USA	Oilseed farming	599
8	Colombia	Grain mill products, starch and related products	585
9	UAE	Food & Beverages	574
10	France	Food products and beverages	487
11	Italy	Food products and beverages	466
12	Italy	Manufacture of food products and beverages	398
13	Saudi Arabia	Food & Beverages	391
14	Colombia	Sugar and brown sugar	380
15	France	Manufacture of food products and beverages	373
16	USA	Other animal food manufacturing	372
17	Germany	Food products	353
18	USA	Poultry and egg production	337
19	Spain	Products of agriculture	299
20	USA	Animal (except poultry) slaughtering, rendering, and processing	294
21	Statistical Discrepancies	Total	292
22	USA	Fats and oils refining and blending	266
23	Colombia	Coffee and threshing products	259
24	Colombia	Food products n.e.c.	255
25	USA	Poultry processing	248

26	Mexico	Agriculture	245
27	USA	Cattle ranching and farming	244
28	Colombia	Hotel and restaurant	237
29	USA	Food services and drinking places	236
30	Colombia	Hotel and restaurant	232

The country model identifies critical sectoral links within the global trade network. Table A3 shows the top 30 domestic origin-destination pairs for virtual water scarcity risk at sector level in 2000, and Table 2 shows the top 30 international origin-destination pairs. Not surprisingly, many of the risk origin sectors are related to agriculture, and many of the risk destination sectors are related to food products in both domestic and international results. Among the top domestic pairs, *Agriculture, Hunting and related service activities* in Italy and France, *Grain farming* and *Oilseed Farming* in USA, *Other agricultural products* in Colombia, and *Agriculture* in Saudi Arabia are the top risk origin sectors. Among the top international pairs, *Grain farming* and *Oilseed Farming* in USA, *Mining and Quarrying* in Qatar, *Other agricultural products* in Colombia, and *Agriculture and hunting* in Germany and France are the top risk origin sectors. Food producing sectors in Canada, China, Germany, Netherlands, and Mexico are among the top risk destination sectors. In addition, it is also interesting that the second largest international pair is not related to agriculture – virtual WSR from *Mining and Quarrying* in Qatar to *Petroleum refineries* in USA.

The scales of risk in international links are significantly smaller than the ones in domestic links. The virtual water scarcity risks of top 30 international links range from 7 million relative US$ to 15 million relative US$, while the risks of top 30 domestic links range from 139 million relative US$ to 640 million relative US$. The reason might be that much more of the raw agricultural products are used within the country than being exported to another country to process, especially for the places with severe water stress.

Table 2 Top 30 international origin-destination pairs for virtual water scarcity risk at sector level in 2000 – country model

Rank	Risk Origin		Risk Destination		Virtual Water Scarcity Risk (million US$)
	Country	**Sector**	**Country**	**Sector**	
1	USA	Oilseed farming	Canada	Food products, beverages and tobacco	14.1
2	Qatar	Mining and Quarrying	USA	Petroleum refineries	12.0
3	USA	Grain farming	China	Animal Feeds	11.8
4	Colombia	Other agricultural products	Germany	Food products	11.6
5	Germany	Agriculture and hunting	Netherlands	Food products and beverages	11.5
6	Germany	Agriculture and hunting	Netherlands	Manufacture of food products and beverages	11.4
7	USA	Grain farming	Mexico	Food industry	11.3
8	France	Agriculture, hunting and related service activities	Italy	Food products and beverages	10.6
9	France	Agriculture, hunting and related service activities	Italy	Manufacture of food products and beverages	10.5
10	USA	Cotton farming	Mexico	Apparel Manufacturing	10.5
11	USA	Oilseed farming	Mexico	Food industry	10.4
12	France	Agriculture, hunting and related service activities	Germany	Food products	10.2
13	Spain	Agriculture, livestock and hunting	France	Food products and beverages	10.2
14	USA	Oilseed farming	Japan	Feeds	10.1
15	USA	Grain farming	Canada	Food products, beverages and tobacco	10.0
16	Italy	Agriculture, hunting and related service activities	Germany	Food products	9.9
17	Germany	Agriculture and hunting	Netherlands	Re-export	9.9
18	Spain	Agriculture, livestock and hunting	Germany	Food products	9.4

19	Spain	Agriculture, livestock and hunting	France	Manufacture of food products and beverages	9.4
20	Belgium	Agriculture, hunting and related service activities	Netherlands	Food products and beverages	9.3
21	Belgium	Agriculture, hunting and related service activities	Netherlands	Manufacture of food products and beverages	9.3
22	USA	Grain farming	China	Hogs	9.0
23	Germany	Agriculture and hunting	Netherlands	Re-export	9.0
24	Colombia	Other agricultural products	Spain	Manufacture of other food products	8.6
25	USA	Grain farming	China	Edible Oil & Fat By-Products	8.4
26	USA	Grain farming	China	Slaughtering & By-Products	8.2
27	USA	Grain farming	Japan	Flour and other grain milled products	8.1
28	Belgium	Agriculture, hunting and related service activities	Netherlands	Re-export	8.0
29	France	Agriculture, hunting and related service activities	Spain	Manufacture of other food products	7.8
30	Spain	Agriculture, livestock and hunting	Italy	Food products and beverages	7.6

Case II: Basin Model

The world map in Figure 6 shows the virtual water scarcity risk export of each basin in 2000. Table 3 in the next page lists the top 15 basins that export largest virtual water scarcity risk in 2000. The top 15 basins contribute about 70% of the total virtual water scarcity risks; the top 10 basins account for about 60% of the total virtual water scarcity risks; and the top 5 basins are responsible for about 40% of the total virtual water scarcity risks: Mississippi River (12%) in North America, Danube River (9%), Thames River (8%), and Rhine River (7%) in Europe, and Tigris & Euphrates (5%) in the Middle East.

It is worth noting that among the top 15 basins that export largest virtual water scarcity risk in 2000, 10 of them (accounting for 55% of the global risk) are international basins that cross country borders. In North America, Mississippi River (USA and Canada), Columbia River (USA and Canada), Colorado River (USA and Mexico), and Bravo (USA and Mexico) together contribute about 20% of the total global virtual water scarcity risk exports. Danube River, Rhine River and Po River in Europe account for another 20% of the total global virtual water scarcity risk exports. Tigris & Euphrates and the Dead Sea in the Middle East make up about 8%. Lake Chas in Africa is responsible for about 2% of the global virtual water scarcity risk exports.

Table 3 Top 15 basins that export largest virtual water scarcity risk in 2000

Rank	**Basin**	**Countries**	**Virtual Water Scarcity Risk (million US$)**
1	Mississippi River	USA, Canada	2727
2	Danube	Romania, Hungary, Serbia, Austria, Germany, Bulgaria, Czech, Slovakia, Croatia, Ukraine, Poland, Moldova	2020
3	Thames	UK	1679
4	Rhine	Switzerland, Liechtenstein, Austria, Germany, France, Luxembourg, Belgium, Netherlands	1502
5	Tigris & Euphrates	Turkey, Iran, Iraq, Syria, Jordan, Saudi Arabia	1137
6	Po	France, Switzerland, Italy	1013
7	Trent	UK	1013
8	Columbia River	USA, Canada	819
9	Dead Sea	Syria, Lebanon, Jordan, Israel, Egypt	580
10	Colorado River	USA, Mexico	550
11	Murray	Australia	436
12	Lake Chad	Algeria, Libya, Niger, Chad, Sudan, Nigeria, Cameroon, CAR	435
13	Sacramento	USA	414
14	Bravo	USA, Mexico	411
15	San Joaquin	USA	400

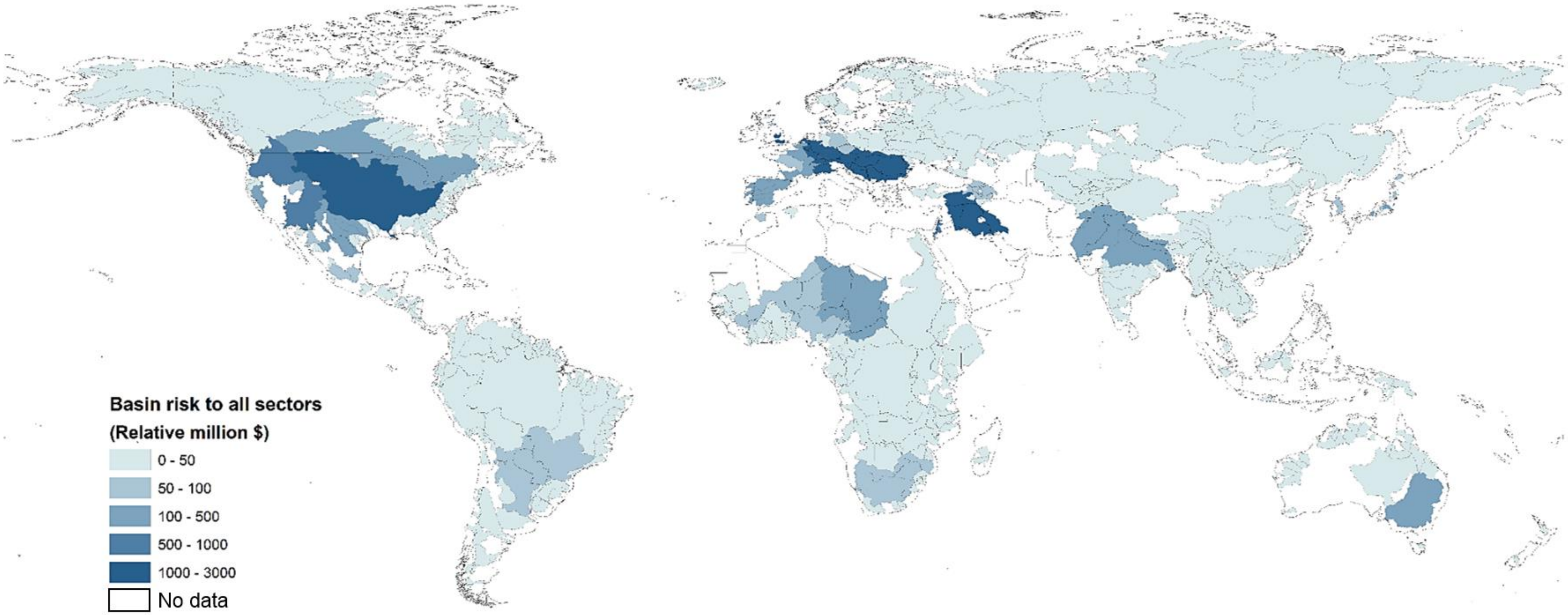

Figure 6 Each basin's virtual water scarcity risk export in 2000 (unit: relative million US$)

The basin virtual water risk results can also showcase the amount of risks that a specific country receives from each basin. For example, Figure 7 shows the basin virtual water scarcity risk impacting the United States in 2000, including risks from both domestic basins and international basins. Overall, about 91% of the total risks originate in the United States, including the basins within the U.S. border and the basins that cross borders with Mexico and Canada. Specifically, top five U.S. basins account for about 70% of the total virtual water scarcity risks: Mississippi River (41%), Columbia River (12%), Sacramento River (6%), San Joaquin River (6%), and Colorado River (Pacific Ocean) (5%).

In 2000, the United States imported about 9% of the total virtual water scarcity risk it faced from overseas. Some of the biggest virtual water scarcity risk origin international basins include Rhine River (0.5%), Danube River (0.5%) and Thames River (0.3%) in Europe, Tone River (0.3%) and Yodo River (0.3%) in Japan, Amazonas River (0.3%) in South America, and the Dead Sea (0.2%) in the Middle East.

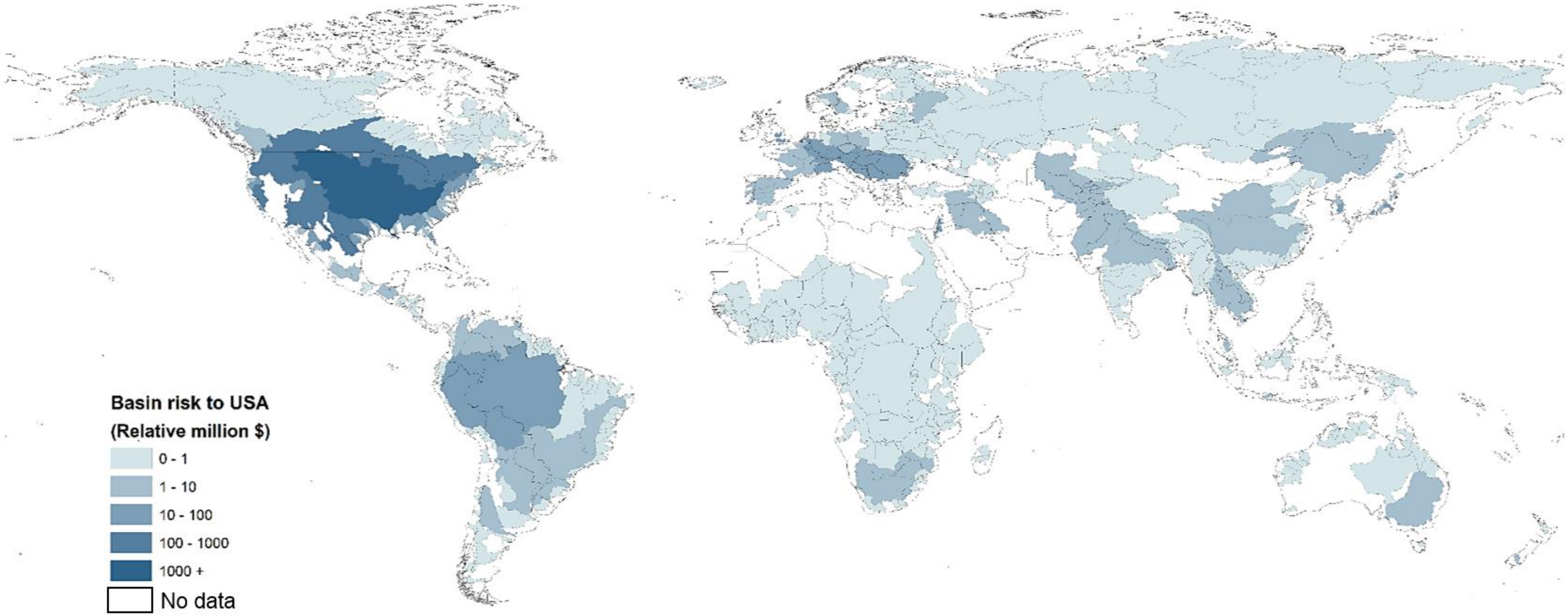

Figure 7 Each basin's virtual water scarcity risk export to the United States in 2000

The basin model is also able to identify critical sectoral links within the global trade network. Table A4 shows the top 30 domestic origin-destination pairs for virtual water scarcity risk at sector level in 2000, and Table 4 shows the top 30 international origin-destination pairs. An interesting common theme found in both domestic pairs and international pairs is that the risk origin sectors are often agriculture and related sectors, and the risk destination sectors are often food processing industries. Among the top domestic pairs, *Agriculture, Hunting and related service activities* in Italy, France, Macedonia and Turkey, *Grain farming* and *Oilseed Farming* in USA are the top risk origin sectors. Among the top international pairs, *Agriculture, Hunting and related service activities* in Italy, Netherlands, Belgium and France, *Agriculture in* Lebanon*, Agriculture and hunting* in Germany, *Grain farming* and *Oilseed farming* in USA are the top risk origin sectors. Food producing sectors in Germany, Brazil, France, Canada, and Japan are the top risk destination sectors.

The scales of risk in international links are again significantly smaller than the ones in domestic links. The virtual water scarcity risks of top 30 international links range from 3 million relative US$ to 10 million US$, while those of top 30 domestic links range from 58 million relative US$ to 625 million US$.

Table 4 Top 30 international origin-destination pairs for virtual water scarcity risk at sector level in 2000 – basin model

Rank	Risk Origin		Risk Destination		Virtual Water Scarcity Risk (million US$)
	Country	Sector	Country	Sector	
1	Italy	Agriculture, hunting and related service activities	Germany	Food products	9.7
2	Lebanon	Agriculture	Brazil	Food and beverages	9.6
3	Italy	Agriculture, hunting and related service activities	France	Food products and beverages	5.6
4	Italy	Agriculture, hunting and related service activities	France	Manufacture of food products and beverages	5.2
5	USA	Oilseed farming	Canada	Food products, beverages and tobacco	5.2
6	Netherlands	Agriculture, hunting and related service activities	Germany	Food products	5.2
7	Italy	Agriculture, hunting and related service activities	Germany	Reexport	5
8	Australia	Barley	Japan	Flour and other grain milled products	4.6
9	USA	Grain farming	China	Animal Feeds	4.4
10	USA	Grain farming	Mexico	Food industry	4.2
11	USA	Grain farming	Mexico	Food industry	4
12	Germany	Agriculture and hunting	Netherlands	Food products and beverages	3.9
13	Belgium	Agriculture, hunting and related service activities	Netherlands	Food products and beverages	3.9
14	USA	Cotton farming	Mexico	Apparel Manufacturing	3.9
15	USA	Oilseed farming	Mexico	Food industry	3.8
16	Germany	Agriculture and hunting	Netherlands	Manufacture of food products and beverages	3.8
17	Belgium	Agriculture, hunting and related service activities	Netherlands	Manufacture of food products and beverages	3.8
18	USA	Cotton farming	Mexico	Apparel Manufacturing	3.8
19	USA	Oilseed farming	Mexico	Food industry	3.8
20	USA	Oilseed farming	Japan	Feeds	3.7

21	France	Agriculture, hunting and related service activities	Italy	Food products and beverages	3.7
22	USA	Grain farming	Canada	Food products, beverages and tobacco	3.7
23	France	Agriculture, hunting and related service activities	Italy	Manufacture of food products and beverages	3.7
24	France	Agriculture, hunting and related service activities	Germany	Food products	3.6
25	USA	Grain farming	China	Hogs	3.4
26	Spain	Agriculture, livestock and hunting	France	Food products and beverages	3.3
27	Germany	Agriculture and hunting	Netherlands	Re-export	3.3
28	Italy	Agriculture, hunting and related service activities	Netherlands	Food products and beverages	3.3
29	Belgium	Agriculture, hunting and related service activities	Netherlands	Re-export	3.3
30	Italy	Agriculture, hunting and related service activities	Netherlands	Manufacture of food products and beverages	3.3

Discussion

Policy and Business Implications

This study identifies critical countries and sectors water scarcity risk of which has significant impacts on the global trade network. These countries and sectors are therefore important to the resilience of the global trade network against water scarcity risks. In this way, the findings direct hotspots for water conservation technology and policy support to mitigate water scarcity risks threatening the trade-connected global economy. Thus, international development agencies and programs, such as the World Bank and United Nations Environment Programme (UNEP), could focus more on reducing water scarcity risks of critical countries and sectors that have large impacts on the global economy. Such hotspot sectors are typically agriculture sectors in water-stressed countries.

International trade policy also plays an important role in mitigating potential water scarcity risks. For example, if a developing country's food industry relies heavily on importing agricultural products from the United States, it is likely that a potential deficiency of agricultural output due to water scarcity in the US would cause tremendous damage to the developing country, in the form of job loss, supply shortage, or price inflation. Therefore, all countries should establish flexible trade policies that can enable diversified international sourcing of certain critical products.

In addition, the basin model shows that many critical basins are international basins that cross country borders, which calls for a need in peaceful cross-border basin cooperation.

Corporate executives should also consider virtual water scarcity risks in their business value chain. Since the water scarcity risks are not evenly distributed across the globe, corporates need to seriously consider the potential water scarcity risks when sourcing from upstream suppliers, as a means to strengthening the resilience of their supply chains in the face of environmental risks. In addition, international corporates should also realize the virtual water scarcity risks when choosing a new country to enter.

Future Study

This study has developed a probabilistic network analysis framework to measure impacts of local resource scarcity risk to the global trade network. While water scarcity was selected as a case study to represent a common local environmental challenge, the framework can be easily adopted to assess the risks posed by other form of scarcity such as energy security and biodiversity losses. However, some improvements of the framework could be incorporated to better represent the rationales in decision-making and better inform the decision makers. As mentioned in previous sectors, once a new data source or method is available for any part of the framework, the rest parts can remain the same with only changes in the model inputs and outputs.

Two global cases at different scales were developed to showcase the implications using publicly available data. One concern regarding the publicly available data would center on the quality of the data. For example, Colombia becomes very critical in the country model while not as significant in the basin model. The biggest reason exists in the discrepancy of water availability between the two databases. It could be that FAO underestimates Colombia's water resources, or Water Footprint overestimates it. Though it might not be difficult verify which one is more unbiased, the same database should be used in one case study to keep up the consistency. On the other hand, state-of-art analytical tools, yet publicly available, have been developed to measure water scarcity on the basis of grid cell. Future development of the proposed framework could be based on grid model for water use and availability.

The proposed water scarcity probability (WSP) may serve as a simple indicator to evaluate sectoral water risk, taking into account both water use intensity and water availability. The consideration of distributing a region's water resources into sectors according to their economic output allows for reasonable comparison between different regions. While the proposed linear transformation of WTAs into WSPs may be questionable in terms of distorting the relative relations between different sectors, other non-linear transformation such as WSI[23] and WDI[24] are also subjective to some extent. Future development should also consider the variety of water resources across time and the societal factors that include infrastructures and governance.

By constructing the global trade network with multi-regional input-output model, some basic assumptions were also adopted from the original Leontief input-output model. The equilibrium assumption implies that all industry inputs and outputs are balanced with the final consumption and primary input. In the long term, the global economy may find its balance. However, perturbations usually lead to short-run non-equilibrium. This semi-static input-output model following the equilibrium assumption hence cannot illustrate the recovery process. The dynamic inoperability input-output model can be a useful tool to analyze the economic losses during the recovery process. On the other hand, the technological and allocation coefficients are assumed constant and linear for the global economy. In this way, no technological improvement in water use efficiency and substitutes between products from different water-scarce regions were taken into account in the model. However, the study well meets its main purpose, which is to identify key sectors and sectoral trade links that are most vulnerable to water scarcity in the global trade network.

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Appendix

Table A1 Top 30 sectors facing local water scarcity risk in 2000 – country model

Rank	**Country**	**Sector**	**Water Scarcity Risk (million US$)**
1	Colombia	Other agricultural products	3493
2	UAE	Agriculture	1294
3	USA	Grain farming	884
4	Saudi Arabia	Agriculture	787
5	France	Agriculture, hunting and related service activities	677
6	Italy	Agriculture, hunting and related service activities	631
7	USA	Oilseed farming	621
8	Germany	Agriculture and hunting	475
9	China	Crop cultivation	472
10	Spain	Agriculture, livestock and hunting	466
11	Mexico	Agriculture	246
12	Libya	Agriculture	221
13	Kuwait	Agriculture & livestock	213
14	Colombia	Food products n.e.c.	210
15	Turkey	Agriculture, hunting and related service activities	191
16	India	Paddy	188
17	Japan	Rice	176
18	South Korea	Crops	143
19	Colombia	Coffee and threshing products	139
20	Denmark	Agriculture	130
21	South Africa	Agriculture	125
22	Colombia	Coffee products	125
23	Belgium	Agriculture, hunting and related service activities	125
24	India	Other crops	116
25	Czech Republic	Agriculture, hunting and related service activities	106
26	Iran	Farming	105
27	Poland	Agriculture, hunting and related service activities	101

28	USA	Cotton farming	100
29	Qatar	Food & Beverages	96
30	Qatar	Agriculture	86

Table A2 Top 30 sectors with the largest virtual water scarcity risk export in 2000 – country model

Rank	Country	Sector	Virtual Water Scarcity Risk (million US$)
1	Colombia	Other agricultural products	7661
2	USA	Grain farming	7281
3	USA	Oilseed farming	4764
4	Italy	Agriculture, hunting and related service activities	2296
5	France	Agriculture, hunting and related service activities	2075
6	Spain	Agriculture and livestock	1518
7	UAE	Agriculture	1508
8	USA	Cotton farming	1484
9	Saudi Arabia	Agriculture	1135
10	Germany	Agriculture and hunting	675
11	Colombia	Coffee products	599
12	Mexico	Agriculture	591
13	China	Crop cultivation	571
14	Belgium	Agriculture, hunting and related service activities	477
15	South Africa	Agriculture	415
16	Colombia	Food products n.e.c.	371
17	Turkey	Agriculture	356
18	USA	All other crop farming	345
19	India	Paddy	344
20	Czech Republic	Agriculture, hunting and related service activities	333
21	India	Other crops	318
22	Colombia	Coffee and threshing products	304
23	Japan	Rice	285
24	Libya	Agriculture	282
25	Denmark	Agriculture	245
26	Iran	Farming	235
27	UK	Growing of wheat	230
28	Poland	Agriculture, hunting and related service activities	229
29	USA	Other animal food	195
30	Spain	Manufacture of other food	168

Table A3 Top 30 domestic origin-destination pairs for virtual water scarcity risk at sector level in 2000 – country model

Rank	Country	Risk Origin Sector	Risk Destination Sector	Virtual Water Scarcity Risk (million US$)
1	Italy	Agriculture, hunting and related service activities	Products of agriculture, hunting and related services	640
2	France	Agriculture, hunting and related service activities	Products of agriculture, hunting and related services	620
3	USA	Oilseed farming	Soybean and other oilseed processing	613
4	Colombia	Other agricultural products	Grain mill products, starch and related products	576
5	UAE	Agriculture	Food & Beverages	570
6	USA	Oilseed farming	Soybean and other oilseed processing	514
7	France	Agriculture, hunting and related service activities	Food products and beverages	421
8	Colombia	Other agricultural products	Sugar and brown sugar	379
9	Saudi Arabia	Agriculture	Food & Beverages	376
10	Italy	Agriculture, hunting and related service activities	Food products and beverages	355
11	Italy	Agriculture, hunting and related service activities	Manufacture of food products and beverages	344
12	France	Agriculture, hunting and related service activities	Manufacture of food products and beverages	322
13	Spain	Agriculture, livestock and hunting	Products of agriculture	286
14	Germany	Agriculture and hunting	Food products	259
15	USA	Oilseed farming	Fats and oils refining and blending	230
16	USA	Grain farming	Other animal food manufacturing	220
17	USA	Grain farming	Animal (except poultry) slaughtering, rendering, and processing	216
18	USA	Grain farming	Poultry and egg production	211

19	USA	Grain farming	Cattle ranching and farming	196
20	USA	Grain farming	Wet corn milling	179
21	Turkey	Agriculture, hunting and related service activities	Products of agriculture, hunting and related services	177
22	USA	Grain farming	Flour milling and malt manufacturing	172
23	Colombia	Other agricultural products	Hotel and restaurant	163
24	Colombia	Other agricultural products	Animal and vegetable oils/fat	163
25	USA	Oilseed farming	Fats and oils refining and blending	162
26	Colombia	Other agricultural products	Sugar and brown sugar	158
27	Japan	Rice	Grain milling	158
28	USA	Grain farming	Poultry processing	152
29	Spain	Agriculture, livestock and hunting	Live animals and animal products	147
30	Colombia	Coffee products	Coffee and threshing products	139

Table A4 Top 30 domestic origin-destination pairs for virtual water scarcity risk at sector level in 2000 – basin model

Rank	Country	Risk Origin Sector	Risk Destination Sector	Virtual Water Scarcity Risk (million US$)
1	Italy	Agriculture, hunting and related service activities	Products of agriculture, hunting and related services	625
2	Italy	Agriculture, hunting and related service activities	Food products and beverages	347
3	Italy	Agriculture, hunting and related service activities	Manufacture of food products and beverages	335
4	USA	Grain farming	Grain farming	311
5	USA	Oilseed farming	Soybean and other oilseed processing	226
6	France	Agriculture, hunting and related service activities	Products of agriculture, hunting and related services	216
7	USA	Oilseed farming	Oilseed farming	207
8	USA	Oilseed farming	Soybean and other oilseed processing	189
9	TFYR Macedonia	Agriculture, hunting and related service activities	Products of agriculture, hunting and related services	186
10	Mexico	Agriculture	Agriculture	172
11	Japan	Rice	Grain milling	164
12	Turkey	Agriculture, hunting and related service activities	Products of agriculture, hunting and related services	156
13	France	Agriculture, hunting and related service activities	Food products and beverages	147
14	France	Agriculture, hunting and related service activities	Manufacture of food products and beverages	112
15	Spain	Agriculture, livestock and hunting	Products of agriculture	93
16	Germany	Agriculture and hunting	Food products	87
17	Italy	Agriculture, hunting and related service activities	Hotel and restaurant services	86
18	USA	Oilseed farming	Fats and oils refining and blending	85
19	Saudi Arabia	Agriculture	Food & Beverages	83

20	Italy	Agriculture, hunting and related service activities	Hotels and restaurants	82
21	USA	Grain farming	Other animal food manufacturing	81
22	Netherlands	Agriculture, hunting and related service activities	Products of agriculture, hunting and related services	80
23	USA	Grain farming	Animal (except poultry) slaughtering, rendering, and processing	80
24	USA	Grain farming	Poultry and egg production	78
25	Libya	Agriculture	Food & Beverages	75
26	USA	Grain farming	Cattle ranching and farming	72
27	USA	Grain farming	Flour milling and malt manufacturing	63
28	South Africa	Agriculture	Agricultural products	60
29	Iran	Farming	Meat and meat products	60
30	India	Paddy	Paddy	58