International trade of global scarce water use in agriculture: Modeling on watershed level with monthly resolution

Journal Article

Author(s):
Weinzettel, Jan; Pfister, Stephan

Publication date:
2019-05

Permanent link:
https://doi.org/10.3929/ethz-b-000325571

Rights / license:
Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International

Originally published in:
Ecological Economics 159, https://doi.org/10.1016/j.ecolecon.2019.01.032

This is a reprint. The final publication is available at Ecological Economics

https://doi.org/10.1016/j.ecolecon.2019.01.032

International trade of global scarce water use in agriculture: Modeling on watershed level with monthly resolution.

Jan Weinzettel[a]
Stephan Pfister[b]

[a] Charles University, Environment Centre, José Martího 2, 161 00 Prague, Czech Republic
[b] ETH Zurich, Dep. of Civil, Env. and Geomatic Eng., Institut für Umweltingenieurwiss., John-von-Neumann-Weg 9, 8093 Zürich, Switzerland

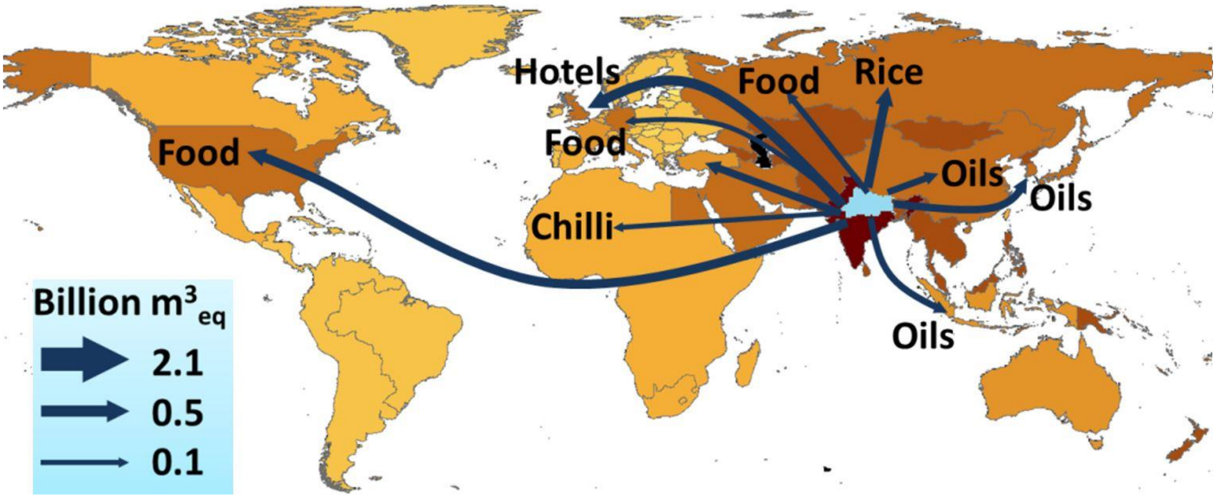
Abstract

Fresh water is a renewable yet limited natural resource. While abundant in some areas, fresh water is scarce in others where its consumption in agriculture leads to negative impacts on human society, ecosystems and biodiversity. International trade in water intensive products can help to reduce water stress or may increase water consumption in water stressed regions.

A number of previous studies have looked at the water footprint at the national level but in this study, we estimate the share of global scarce water use by the agricultural production for final demand of individual countries. We convert the volume of blue water use to cubic meters of scarce water equivalent by reflecting local and temporal water scarcity on a watershed and monthly level and allocate the scarce water use to final consumers, who pull the production chains. We further advance previous research by constructing product-by-product input-output table under product technology assumption avoiding negative numbers and we track the international trade of agricultural crops outside the input-output system on a high level of crop and country detail.

Our results indicate that international trade "helps" to limit water stress in arid regions, such as the Middle East region, Portugal and Mexico. However, the Middle East and Mexico still embody high scarce water use in exported products, which counter-acts stress mitigation. Most developed countries have a higher footprint than in a hypothetical no-trade scenario. From the global perspective, the role of international trade in water stress mitigation is ambiguous as it enables humanity to thrive in inhospitable areas of the Middle East region, which favors the role of international trade in water scarcity mitigation due to high food imports to the arid region; and consumption of products which are not available under domestic climatic conditions, e.g. cotton, sugar cane and rice, with high scarce water requirements abroad. If we divide the world according to GDP per capita at around 7000 USD, the richer part of the world is responsible for consumption of 61 billion cubic meters scarce water equivalents in the poorer part, representing about 12% of the global total. Local policies in water stressed regions should address exported products with high water requirements considering the full production chains, thus covering processed products as well.

Graphical abstract



Highlights

- International trade is driven by economic concerns rather than water scarcity
- Human settlement in inhospitable areas is supported by trade
- Consumption of crops unavailable domestically has a significant scarce water share
- Poorer regions suffer from water use resulting from consumption in richer regions

Introduction

With the increasing complexity of global supply chains, consumers are disconnected from the environmental consequences caused by the production of the commodities and services they consume. While water is perceived as an abundant renewable resource in many countries and regions, fresh water is a limited resource upon which overconsumption increases water stress and poses a threat to human society, ecosystems and biodiversity (McGlade et al., 2012; Millennium Ecosystem Assessment, 2005). Water availability and the environmental consequences of its consumption differ in terms of water basin levels and fresh water scarcity is a local problem with a global dimension (Ridoutt and Pfister, 2010; Steffen et al., 2015). The most important driver worldwide for human water consumption is irrigation, which is responsible for ~86% of annual global freshwater consumption (Shiklomanov and Rodda, 2003). Increasing human demand for food, fiber, energy crops and other agricultural products drives land use in arid locations, where irrigation substantially increases yields while limiting water availability for other purposes (Foley *et al.*, 2005). In a globalized economy, consumers of products are connected to water use based on the concept of virtual water trade (Allan, 1998). Based on this, the water footprint was defined as the total volume of water used throughout the whole production chain of products, mainly originating from the cultivation of agricultural products (Hoekstra and Hung, 2002). However, as pointed out by Pfister and Hellweg (2009), such a concept ignores water scarcity, i.e. the fact that environmental impacts of water use differ widely around the world depending on local water availability, and it varies over the year due to temporal dependence of water availability and scarcity. This is now considered in the ISO water scarcity footprint definition (ISO, 2013). Accordingly, Pfister and Bayer (2014) developed monthly water use characterization factors, which reflect water scarcity on a watershed level, and calculated crop specific water stress indexes with high spatial resolution and global coverage for assessing scarce water use. We use the term “scarce water” to describe the water consumption weighted by these characterization factors.

Global analysis concerning water footprints has been provided via process analysis (Hoekstra and Mekonnen, 2012) and multi-regional input-output analysis (Daniels et al., 2011; Dietzenbacher and Velázquez, 2007; Feng et al., 2011; Lenzen et al., 2013; Lutter et al., 2016; Steen-Olsen et al., 2012; Wang et al., 2016; Wang and Zimmerman, 2016). While the process analysis benefits from a detailed classification of international trade of the most relevant agricultural crops and derived products, multi-regional input-output analysis (MRIO) covers all internationally traded products and their full supply chains. Therefore, the two approaches may lead to substantial differences (Feng et al., 2011; Kastner et al., 2014). Weinzettel et al. (2014) showed that a standard MRIO is not suitable for the accounting of land footprints due to low product resolution in the available MRIO datasets, and the process analysis lacks an important part of the land footprint of international trade due to its limited scope. They recommend using hybrid MRIO proposed by Ewing et al. (2012) since it enables an increased level of detail regarding the international trade of primary agricultural crops to a level commonly reached in the process analysis. This level of detail is acquired from bilateral trade data and commodity balance sheets provided by the FAO (FAO, 2014). Since both water and land are closely related to agriculture, this insight is valid for water footprints, too. Additionally, previous studies, except for Wang and Zimmermann (2016), Lutter et al. (2016) and Lenzen et al. (2013) did not consider water scarcity. Lenzen and colleagues conclude that the global trade of volumetric virtual water has a different pattern from scarce water, highlighting the need to include water scarcity assessment in the analysis. Lutter et al. (2016) used detailed water consumption and scarcity data, but only based on MRIO results with a very rough resolution for Africa, South America and Asia. In contrast to their study in our approach we extend both, the product and the regional detail to FAOSTAT level for all primary crops even though we also use Exiobase MRIO dataset, see Table 1 for comparison of the studies which considered water scarcity. Wang and Zimmermann recently provided a hybrid MRIO analysis based on a GTAP 8 database for the year 2007, using national average annual water consumption data and watershed withdrawals to estimate the locations of water consumption and the related effects on water scarcity, but not specifically accounting for the actual location of specific crop cultivation and the temporal dimension of water scarcity, which is demanded by ISO 14046 for a water scarcity footprint. Furthermore, this simplification does not allow accounting for different trade patterns of crops grown in different regions of the country (e.g. rice from China has different origins than cotton or wheat from China).

Table 1 Overview of the main studies which considered water scarcity in water footprint accounting.

	Lenzen et al. (2013)	Wang and Zimmermann (2016)	Lutter (2016)	This study
MRIO dataset	EORA	GTAP 8	Exiobase 2.2	Exiobase 2.2
MRIO regional detail	187	134	48	48
MRIO product detail	25-500*	57	200	151
Physical use extension (products, regions)	No	Yes (FAO classification, 209 products, full list of FAO countries)	No	Yes (FAO classification, 169 products, full list of FAO countries)
Water scarcity modelled on the watershed level		Yes, but not crop-specific resolution	Yes	Yes
Time of water scarcity model		Annual resolution	Monthly resolution	Monthly resolution
Anything else?				

* total amount of sectors (by countries) is 15 909, many countries have only 26 sectors.

Our objective is to connect scarce water consumption in supply chains with final consumers of derived products and to analyze the role of international trade for global scarce water use by combining state-of-the-art data on crop water consumption, water scarcity, international trade in agricultural crops and MRIO. We aim to answer the question: How do individual countries contribute to global water scarcity from consumption responsibility perspective based on spatially and temporally explicit models? How is the scarce water use attributed to exports related to income level of the importing countries? Or in other words, how is the displacement (with no distinction of intentional and unintentional) of scarce water use related to income level?

We apply the most detailed MRIO dataset regarding consistent product classification based on Exiobase 2.2 (Wood *et al.*, 2015) and we advance previous research in this study: (a) water consumption for crop irrigation is modeled on high spatial resolution on a monthly level to account for temporal variation in water scarcity; (b) fresh water consumption in crop irrigation is accounted for in cubic meters of scarce water equivalent (m^3_{eq}) by applying characterization factors, which consider monthly water scarcity on a scale from 0.01-1 (Pfister and Bayer, 2014); (c) we construct the product-by-product MRIO table under the product technology assumption using the Almon algorithm (Almon, 2000); (d) we track the international trade of agricultural crops outside the MRIO system on a high level of crop and country detail consistent with FAOSTAT data and classification (e) we report the most important traded products and the crops behind the footprint. We discuss the results in a socio-economic and policy context.

Materials and Methods

Crop production: In order to perform the analysis we use country specific harvest data of primary agricultural crops from FAOSTAT for the year 2007 (FAO, 2015) to provide most detailed data in line with Exiobase 2.2.

The harvest of primary crops was converted into volume of scarce water equivalents using monthly crop irrigation results on 5 arc minutes spatial resolution and watershed-specific characterization factors developed by Pfister and Bayer (2014). Those factors are based on global climate data and hydrological models. They account for water use for crop irrigation and water scarcity during crop growth period. Each liter of water use is converted into its scarcity equivalents according to monthly local water scarcity. This enables to put together water used in regions and seasons with different water stress levels. While the factors were derived to represent the year 2000, it is assumed they reflect 2007 conditions as well, considering the relatively high uncertainties of the characterization factors. We use the monthly average water stress characterization factors which are recommended for assessing total production within watersheds.

Trade analysis: For the allocation of scarce water requirements to final consumers we employ the most advanced MRIO method up to date, the so-called hybrid environmentally-extended MRIO model. The monetary core of this model is derived from the Exiobase supply and use tables version 2.2 (Wood et al., 2015) under product technology assumption following Almon’s algorithm (Almon, 2000). We chose Exiobase over other MRIO dataset for its consistently high product detail.

The harvest of primary agricultural crops is allocated to the economic sectors of their first use (Figure 1) based on detailed trade matrices and commodity balance sheets (FAO, 2014), and monetary data of the core MRIO model. We track international trade and type of the first use according to FAOSTAT database for over 160 primary agricultural crops and over 200 individual countries. This adds a product detail and a substantial regional detail into the 5 rest of the world regions (RoW) of the MRIO dataset in comparison to Lutter et al. (2016) and thus counteract the main limitation of regional aggregations into these RoW regions. As a main novelty, we utilized country specific FAOSTAT commodity balance sheets for the allocation of agricultural crops to economic sectors (second step, third row of Figure 1).

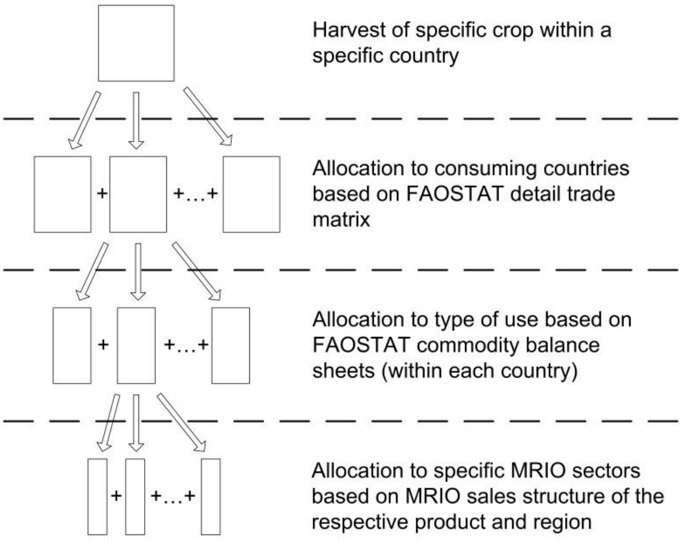


Figure 1 Allocation of primary crops to MRIO sectors.

In order to focus on a watershed level we utilized spatially specific data on crop harvests and assumed equal sales structure for each crop irrespective of its origin within a country. For example, if 30% of the wheat harvest in a specific country occurs in a specific watershed, we assumed 30% of wheat originating from this country and consumed by any economic sector comes from this watershed. This assumption is determined by current data availability.

We present bilateral trade exports (BTEXP) and final demand imports (FDIMP) in the analysis of the international trade in order to avoid double counting when reporting the footprint of internationally traded products which cross national boundaries multiple times within the production chains of final consumer products. BTEXP and FDIMP differ from each other as they show the international trade from different perspectives (Kanemoto et al., 2012). Bilateral trade exports show the footprint of exported products imposed on the environment of the country of origin (Peters *et al.*, 2012), while final demand imports include the foreign part of global footprint of imports which are directly or indirectly used for domestic final demand. For example, China imports soybean: part of this soybean ends up in the supply chains of products consumed by non-Chinese final consumers and is therefore excluded from final demand imports. Final demand imports include only the part of soybeans imported to China, which ends up in the products consumed by Chinese final consumers. In contrast, the footprint of Chinese bilateral trade exports exclude the footprint of all products imported to China, i.e. the footprint of imported soybeans embodied in Chinese exports is not included in bilateral trade exports. Both methods are important from a different perspective: bilateral trade exports are important for the exporting country, while final demand imports are important for the importing country.

No-trade scenario: In order to contribute to the discussion regarding the potential of international trade to reduce global water stress we calculated the alternative hypothetical national scarce water footprints by converting the weight of harvested crops embodied in the domestic final demand into scarce water use using the domestic characterization factors if the crop is produced locally, and we assumed zero for crops not harvested domestically and we report their footprint separately. We interpret the positive difference between the sum over all countries of this hypothetical footprint and the national footprints as a potential to save global scarce water use by international trade. This scenario is intended to indicate how local vs imported production differs.

Additional details are provided in the SI.

Results

Overall results: production versus consumption perspective

The scarce water footprint per capita in each region is presented in Figure 2. Mostly arid and semi-arid countries/regions, such as Spain, Greece and the Middle East, have the highest per-capita scarce water footprint from both a producer and consumer perspective. While in the Middle East water scarcity is mainly a local problem (the footprint occurs mainly in domestic territory), the footprint of Spain and Greece has an important share from abroad, mainly from non-European countries. Most European and other developed countries benefit from production that is nearly independent of scarce water use resulting in close to zero scarce water use in domestic production, but they are still recorded in the world average footprint due to imports. It reflects the high affluence in these countries that drives imports of products derived from agriculture (Weinzettel *et al.*, 2013), which often come from water-scarce regions. India, the Middle East and the US have well-above world-average production and consumption water scarcity impacts and together contribute >50% to total global scarce water use, while covering about one quarter of the global population. The agricultural sectors of these regions are known to be largely irrigated and therefore have a higher mitigation potential than e.g. China, which is another major contributing country to global scarce water use, but with a lower per-capita footprint.

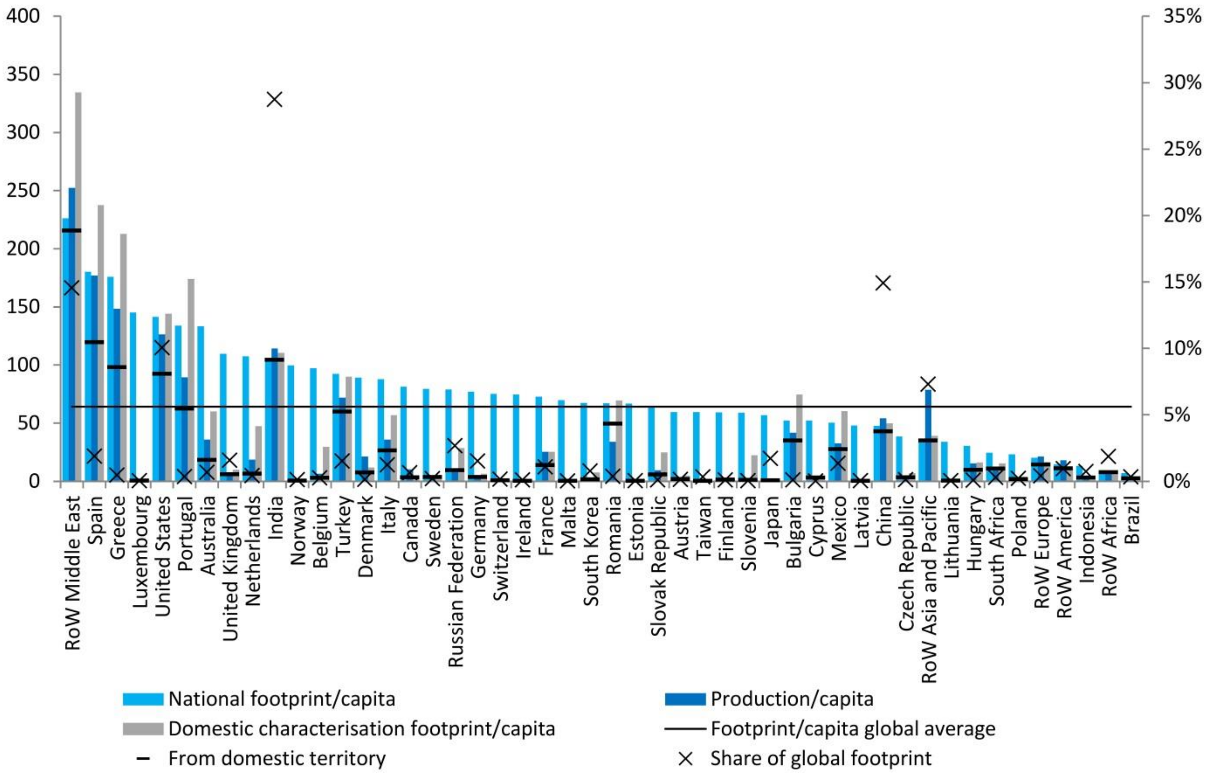


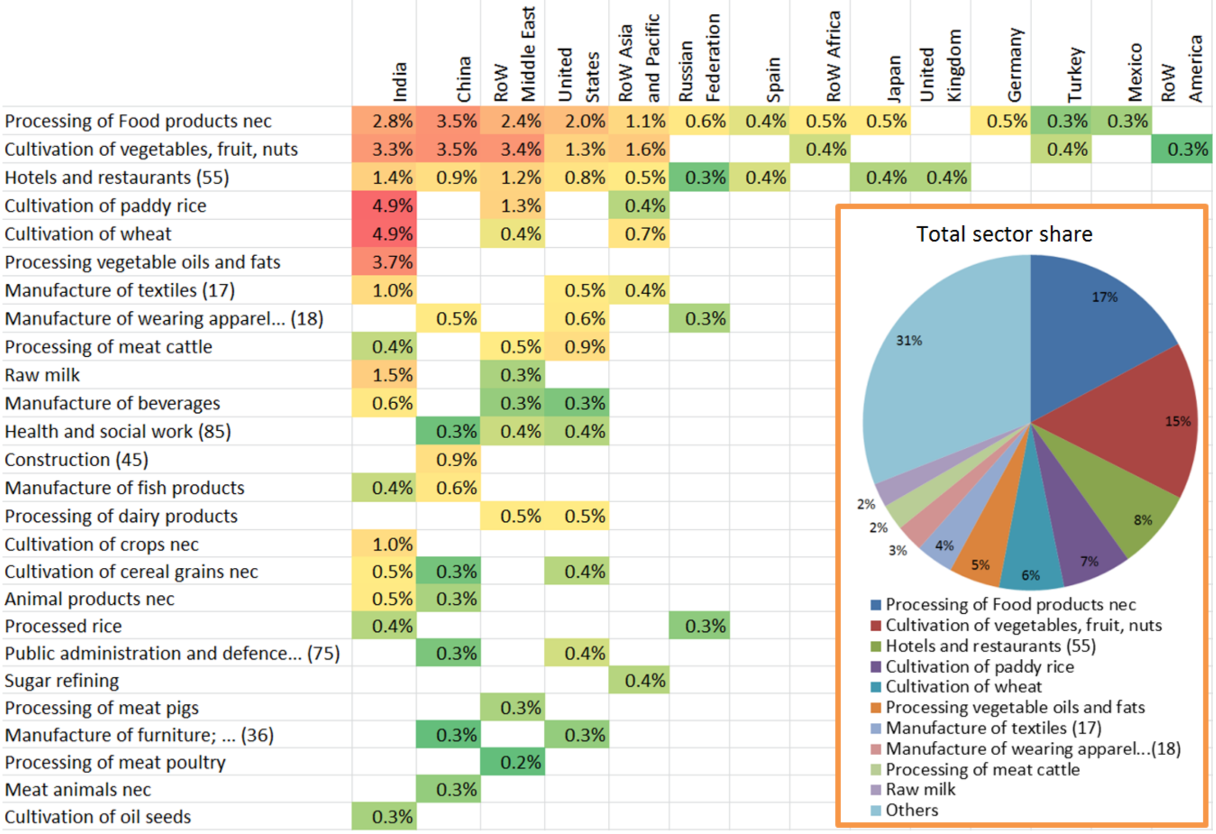
Figure 2: National scarce water footprints. The left axis represents the scarce water footprint of nations in 2007 in m^3_{eq} per capita (National footprint/capita), scarce water use per capita from a production perspective (Production/capita), the hypothetical footprint if domestic characterization factors were applied to the primary crops embodied in domestic final demand (Domestic characterization footprint/capita) and a mark which divides both the footprint and domestic use into a domestic part and an international trade part (hence, the part of the footprint above this mark is imported and the domestic use part above this mark is exported). The right axis shows the global importance of the respective country from the footprint perspective (Share of global footprint).

From the national footprint perspective most arid regions and countries benefit from international trade, which helps to decrease their overall scarce water requirements in agriculture and to reduce their domestic scarce water use. However, these countries also have substantial exports of water intensive products, which counteract virtual water savings. Most other countries yield higher footprints in the current situation than in the hypothetical no-trade situation due to imports from water scarce regions (see also Discussion).

Dominance of region-specific final demand product groups

Our underlying EE-MRIO includes 48 regions and 151 product groups (7248 region-specific product groups) but the final demand in the top five regions cover >75% of the impacts, while the top five product groups account for 53% of global final demand (Figure 3). Overall, most water scarcity is the result of the final demand of processed food, followed by the product group “Vegetables, fruit, nuts”, which are often consumed in raw form. The third most important product group for final demand concerning water scarcity is “Hotels and Restaurants”, which is more evenly distributed among the regions. The direct final demand of unprocessed wheat and rice, as well as processed vegetable oil is important mainly in Indian final demand. Most other product groups with a significant contribution are other food items, including dairy and meat production. Construction products contribute significantly to water scarcity mainly due to final demand in China. This may be well explained by food consumption on construction sites as emphasized by Hubacek and Feng (2016).

The concentration in a few regions is caused by large countries - India, China, US and the ROW regions - which aggregate a large share of the global population. However, it can be seen that especially rich EU countries, which are relatively small, such as Spain, the UK, Germany, Italy and France, have a high share of scarce water due to the final demand of processed food. This is also true for Australia.



	India	China	RoW Middle East	United States	RoW Asia and Pacific	Russian Federation	Spain	RoW Africa	Japan	United Kingdom	Germany	Turkey	Mexico	RoW America
Processing of Food products nec	2.8%	3.5%	2.4%	2.0%	1.1%	0.6%	0.4%	0.5%	0.5%		0.5%	0.3%	0.3%	
Cultivation of vegetables, fruit, nuts	3.3%	3.5%	3.4%	1.3%	1.6%			0.4%				0.4%		0.3%
Hotels and restaurants (55)	1.4%	0.9%	1.2%	0.8%	0.5%	0.3%	0.4%		0.4%	0.4%				
Cultivation of paddy rice	4.9%		1.3%		0.4%									
Cultivation of wheat	4.9%		0.4%		0.7%									
Processing vegetable oils and fats	3.7%													
Manufacture of textiles (17)	1.0%			0.5%	0.4%									
Manufacture of wearing apparel... (18)		0.5%		0.6%		0.3%								
Processing of meat cattle	0.4%		0.5%	0.9%										
Raw milk	1.5%		0.3%											
Manufacture of beverages	0.6%		0.3%	0.3%										
Health and social work (85)		0.3%	0.4%	0.4%										
Construction (45)		0.9%												
Manufacture of fish products	0.4%	0.6%												
Processing of dairy products			0.5%	0.5%										
Cultivation of crops nec	1.0%													
Cultivation of cereal grains nec	0.5%	0.3%		0.4%										
Animal products nec	0.5%	0.3%												
Processed rice	0.4%					0.3%								
Public administration and defence... (75)		0.3%		0.4%										
Sugar refining					0.4%									
Processing of meat pigs			0.3%											
Manufacture of furniture; ... (36)		0.3%		0.3%										
Processing of meat poultry			0.2%											
Meat animals nec		0.3%												
Cultivation of oil seeds	0.3%													

Figure 3: The table shows the global share of the top 75 FD product-country combinations (combining 70% of total scarce water use). Each product's contribution to global scarce water is presented in the pie chart (others combines all product groups with contributions <2%).

Aggregating product groups into broader categories reveals the overall importance of food and textiles. The importance of textiles in the EU, the US and Japan is around 12%, while the global average is about 7%; most countries reach approximately only 3%. The importance of textiles further increases for international trade, since cotton lint is cropped in only a few countries, where it requires substantial irrigation. This further helps people in rich countries to ignore the environmental consequences of textile consumption because for most people they occur far away. Even the US as a major producer has a positive footprint for net trade originating from cotton lint production of about 22% of their consumption (thus displacing the impacts to other countries).

Table 2 Contribution of broader product groups to the global footprint and for bilateral trade exports.

Aggregated product group*	Final demand	Bilateral trade exports
Food (excl. oils)	67%	46%
Hotels	8%	5%
Textiles, wearing apparel and leather	7%	24%
Oils	5%	12%
Other	13%	13%

* A detailed composition is included in SI, Table S5.

International trade

In Figure 4 we show the footprint of international trade for the top fifteen exporters and importers. It highlights the fact that developing economies dominate the exporters (except for the US), while economically developed regions dominate importers of scarce water. Also, the size of imports decreases rapidly for two reasons: (a) the underlying MRIO database distinguishes a higher number of developed countries, while it groups most of the developing countries into just a few regions, and (b) the import side is dominated by developed economies, while the countries with high exports are aggregated into broader regions with a high population. Therefore, many specific countries with high export footprints are not directly visible. Countries such as the US and China belong to both the top five most important exporters and importers, with a significantly high net trade footprint pointing in different directions. While China is shown as a net exporter, the US is net importer of scarce water use.

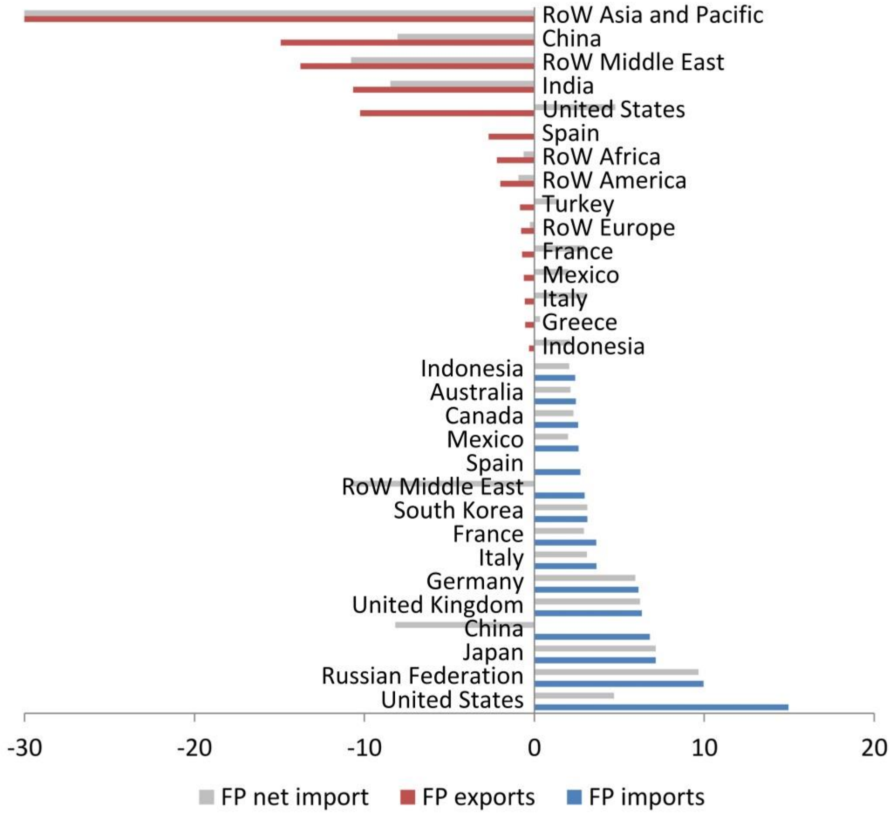


Figure 4 Exports and imports of scarce water use, including net imports (billion m^3_{eq}).

Trade among the studied regions and countries is dominated by food related products (Table 1). Textiles, clothing apparel and leather related products account for one quarter, followed by oil crops and oil related products (about 10%), and hotels and restaurants (about 5%). Primary crops are responsible for only one quarter of the footprint of international trade, leaving the majority for manufactured goods and services. Cotton lint is the most important primary crop, followed by wheat and maize. While bilateral trade exports yield about 10 billion m^3_{eq} for cotton lint, final demand imports yield only about 4 billion, indicating that most cotton lint is traded to be processed and re-exported, mainly in China and ROW Asia (Table 3). Table 3 and Table 4 show the most important bilateral trade exports and final demand imports for the top three exporting and importing regions, respectively.

Table 3 The five most important BTEXP (bilateral trade exports) for the top three exporting regions (billion m^3_{eq} of scarce water). The top three primary crops behind the footprint and the top three regions of destination are provided next to the product name.

ROW Asia and Pacific		ROW Middle East		China	
Food products n.e.c. (wheat 57%, rice 10%, maize 5%), (US 25%, Japan 16%, Russia 12%)	9.2	Food products n.e.c. (rice 32%, wheat 30%, maize 8%), (US 20%, Russia 16%, Germany 14%)	4.2	Textiles (cotton lint 66%, wheat 12%, maize 11%), (US 22%, Russia 7%, Germany 7%)	3.6
Vegetable oils and fats (cotton seed 58%, Coconuts 8%, sunflower seed 7%), (China 42%, Netherlands 10%, US 9%)	5.0	Hotels and restaurants (rice 21%, wheat 18%, forage and silage 15%), (Russia 48%, GB 14%, Germany 11%)	2.2	Meat animals n.e.c. (maize 69%, wheat 19%), (Spain 36%, GB 16%, Greece 13%)	1.9
Processed rice (rice 97%, wheat 1%, Forage crops 1%), (Russia 47%, China 15%, South Korea 12%)	3.3	PP_Pistachios* (pistachios 100%), (RoW Asia and Pacific 24%, China 14%, Germany 11%)	1.2	Wearing apparel; furs (cotton lint 47%, wheat 20%, maize 15%), (Russia 56%, Japan 22%, US 13%)	1.2
PP_cotton lint (cotton lint 100%), (China 33%, Russia 28%, Turkey 15%)	3.2	Furniture; other manufactured goods n.e.c. (forage and silage 46%, maize 14%, wheat 11%), (US 65%, India 18%, GB 3%)	1.0	Food products n.e.c. (wheat 60%, rice 9%, maize 5%), (US 29%, Japan 21%, Russia 12%)	1.1
Wearing apparel; furs (cotton lint 92%, forage and silage 2%, wheat 2%), (US 49%, GB 8%, Germany 6%)	3.1	Chemical and fertilizer minerals, salt, other mining and quarrying products n.e.c. (forage and silage 23%, maize 15%, rice 15%), (India 34%, Turkey 22%, Belgium 11%)	0.8	Furniture; other manufactured goods n.e.c. (wheat 39%, maize 18%, rice 8%), (US 30%, Germany 10%, Japan 10%)	0.8

* Product names starting with PP include only the direct footprint associated with harvesting of the primary crop.

Table 4 The five most important FDIMP (Final demand imports) for the top three importing regions (billion m^3_{eq} of scarce water). The top three primary crops behind the footprint and the top three regions of water use are provided next to the product name.

United States		Russian Federation		Japan	
Food products n.e.c. (wheat 45%, rice 13%, maize 6%), (RoW Asia and Pacific 52%, RoW Middle East 20%, China 8%)	4.4	Food products n.e.c. (wheat 43%, rice 14%, maize 6%), (RoW Asia and Pacific 48%, RoW Middle East 28%, China 7%)	2.3	Food products n.e.c. (wheat 51%, rice 11%, maize 5%), (RoW Asia and Pacific 70%, China 12%, RoW Middle East 7%)	2.1
Wearing apparel; furs (cotton lint 84%, wheat 4%, maize 3%), (RoW Asia and Pacific 75%, China 11%, India 8%)	2.2	Processed rice (rice 89%, groundnuts 2%, forage and silage 1%), (RoW Asia and Pacific 82%, India 17%, Italy 0.3%)	1.9	Hotels and restaurants (wheat 31%, rice 11%, maize 9%), (RoW Asia and Pacific 46%, China 34%, India 8%)	0.6
Textiles (cotton lint 81%, wheat 6%, maize 5%), (China 39%, RoW Asia and Pacific 33%, India 21%)	2.0	Wearing apparel; furs (cotton lint 66%, wheat 11%, maize 8%), (China	1.4	Wearing apparel; furs (cotton lint 70%, wheat 10%, maize 7%), (China 45%,	0.6

		49%, RoW Asia and Pacific 28%, India 10%)		RoW Asia and Pacific 38%, India 8%)	
Furniture; other manufactured goods n.e.c. (forage and silage 30%, wheat 18%, maize 13%), RoW Middle East 54%, China 22%, RoW Asia and Pacific 20%)	1.3	Hotels and restaurants (wheat 20%, rice 19%, forage and silage 13%), (RoW Middle East 82%, RoW Asia and Pacific 7%, China 5%)	1.3	PP_Maize* (maize 100%), US 88%, China 12%, RoW America 0.2%)	0.4
Chemicals n.e.c. (cotton lint 28%, wheat 14%, sugar cane 11%), (RoW Asia and Pacific 52%, India 22%, RoW Middle East 15%)	0.7	PP_cotton lint (cotton lint 100%), (RoW Asia and Pacific 99.5%, India 0.3%, US 0.1%)	0.6	Vegetable oils and fats (cotton seed 36%, groundnuts 9%, soybeans 8%), (RoW Asia and Pacific 53%, India 30%, US 9%)	0.4

Watershed level assessment

Irrigation is highly concentrated in a few watersheds and the top 11 global watersheds combine more than 50% of global scarce water use. Watersheds are defined in Watergap 2.1 (Alcamo *et al.*, 2003) and even divide the largest rivers such as the Mississippi, Nile and Indus into sub-watersheds. Figure 5 presents the top five (Ganges, Indus-Luni Basin, Upper Indus, Nile, Hai River) and a sub-watershed of the Mississippi (the Platte river), which account for 12%, 9%, 8%, 4%, 3% and 2% of global scarce water use respectively. Exports from the other watersheds of the top 11 are shown in the SI. The maps reflect the high share of India, but show significant differences as a function of the watersheds. The ten top flows per region on average cover only 6% of the total use, mainly due to the high share of domestic use in India, China and the US. Imports from Indian watersheds are mainly processed foods, rice, textiles and vegetable oils, while imports from the Hai River are dominated by meat, cloths, textile and processed food. From the Nile, imports are mainly processed foods followed by Hotels (and restaurants) and Furniture. Furniture is important mainly due to leather production and also observed in imports from the Hai River. Finally, imports from the Mississippi sub-watershed are mainly Maize and Soybean.

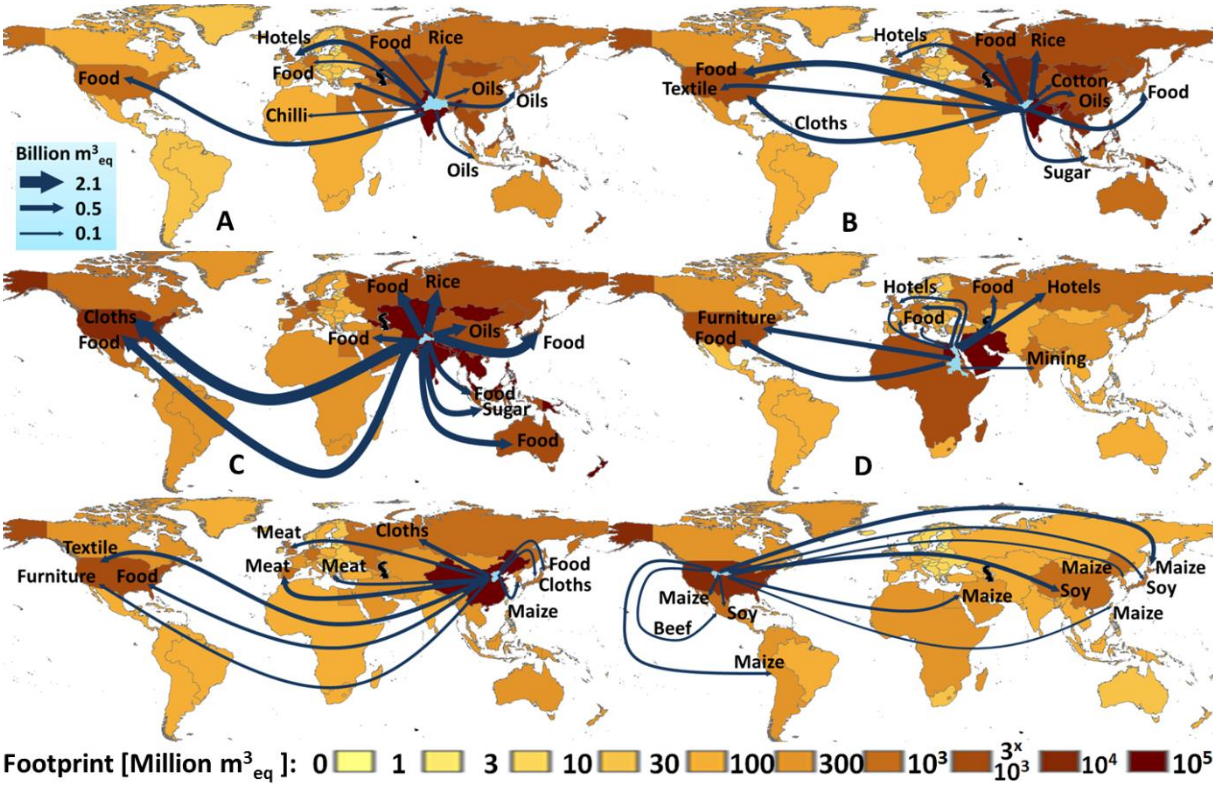


Figure 5 Top 10 region-product specific flows for the five top watersheds in terms of scarce water use plus the top watershed outside Asia and Africa (number 10 globally): Colors indicate the scarce water footprint of final demand in each region occurring in the specific watershed, and the arrows indicate the top ten final demand import flows (product-region combination). Product abbreviations are explained in Table S2.

Discussion

"Offshoring" from rich to poor countries

The clear distinction between more developed economies as net importers and low-income countries as exporters leads to the question whether the richer consumers pose an environmental burden related to scarce water use in poorer regions. We ranked the countries according to gross domestic product (GDP) per capita and displayed the cumulative net trade in Figure 6. The resulting curve rises almost monotonously until a tipping point after which it decreases almost monotonously. This means that with the exception of Indonesia and South Africa, all the countries or ROW regions with GDP below the threshold GDP of 7 000 USD per capita are net exporters, while all the countries above this threshold are net importers of virtual scarce water use, except Spain. We can conclude that there is a profound offshoring from richer to poorer countries, if the distinction between those two groups is between 6 400 – 9 000 USD per capita per year. In this range, the net offshoring from richer to poorer countries is about 60 billion $m^3_{eq}$of scarce water use, with the maximum of 61 m^3_{eq}, roughly equivalent to the impact of total Chinese consumption or ~12% of total world scarce water use. This is a significant amount, which is a burden shift from consumption of ~24% of the global population to the producer regions of the remaining ~76%.

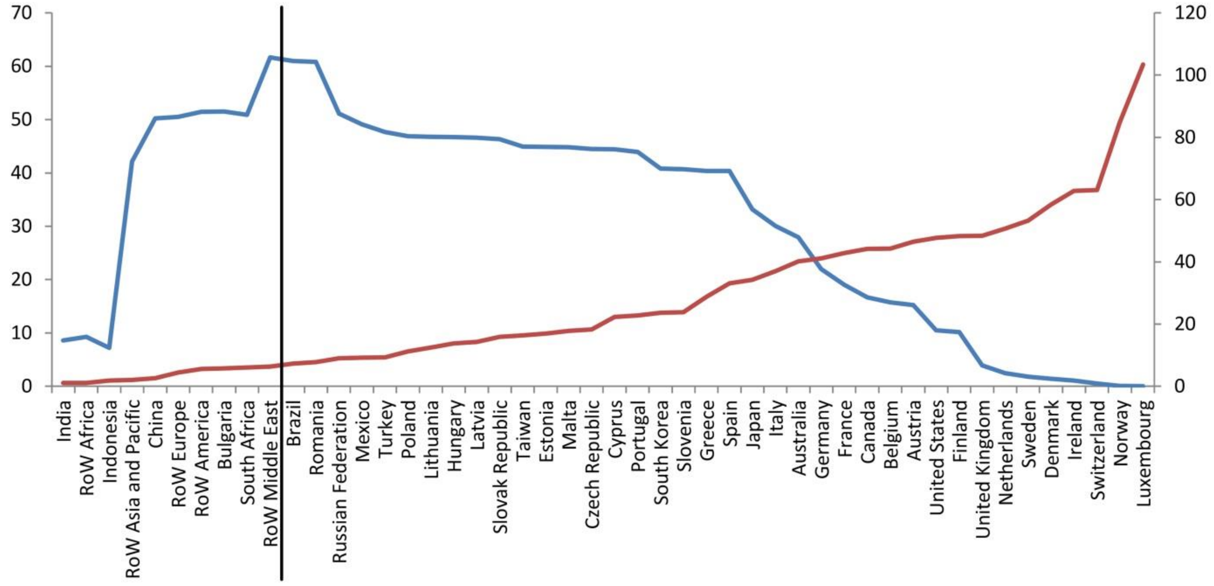


Figure 6 Cumulative net trade of scarce water use (blue line; billion m^3_{eq}, left-hand axis), countries sorted by GDP per capita (red line; 1000 USD per capita, right-hand axis). The vertical line separates the regions between 6.4 (Rest of World Middle East) and 7.3 (Brazil) thousands USD per capita.

The footprint results and actual offshoring values for the richer and poorer parts of the world are presented in Table 3. The poorer part of the world has a per-capita scarce water footprint of about two thirds of the rich countries. If we look at the gross displacements, we can see that rich countries offshore over ten times more to poorer countries than vice versa. Comparison of the share of the displaced part reveals that the rich countries displace almost half of their footprint to poor countries, while it is about 1 % in the opposite direction. From this analysis we can conclude that rich countries have (a) a significantly higher per capita footprint, and (b) displace a higher consumption of scarce water to poor countries. The production impacts per capita are almost twice as high in the poorer part of the world.

Since water scarcity is not evenly distributed around the world and not only in the poorer part, both perspectives (the footprint per capita and the absolute values of offshoring) are important when looking at the shift of environmental burden from richer countries to poorer regions. The high offshoring by the footprints of rich countries emphasizes the importance of the rich countries for water scarcity in poor countries as a driving force increasing that scarcity, even though most scarce water from poor regions is used for final demand in poor regions. Considering that a high share of the global population is living in poor regions, the shift is affecting a large share of the population and might continue to worsen, since by 2025, 1.8 billion people are projected to live under absolute water scarcity and two thirds of the global population could face water stress (FAO, 2016).

Table 5 Offshoring and absorption of the scarce water footprint (billion $m^3_{eq}$of scarce water), rows show source, columns destination, i.e. rich regions require 54 billion m^3_{eq}in poor regions

	Poor (5.1 billion people)	**Rich (1.6 billion people)**
Scarce water from poor regions (10^9 m^3_{eq})	294	66
Per capita **(m^3_{eq} /cap)**	58	42
Scarce water from rich regions (10^9 m^3_{eq})	4	64
Per capita **(m^3_{eq} /cap)**	1	41

Footprint per capita ($m^3{}_{eq}$ /cap)	59	82
Production per capita ($m^3{}_{eq}$ /cap)	70	43
Footprint from abroad (%)	1%	51%

Is the virtual water transfer beneficial for global water scarcity?

In Figure 2 we show the hypothetical scarce water footprint calculated by converting the harvested crops embodied in the final consumption to the scarce water footprint using the domestic characterization factors. International trade clearly helps the arid countries of the Middle East region, Spain, Portugal and Greece, which save a large portion of scarce water use on domestic territory through imports. However, at the same time all those countries export products which are responsible for scarce water use on their own territories. Scarce water use in poorer regions can be attributed to consumption in rich countries through international trade, even if the rich countries have abundant water resources. Summing the benefits and costs of international trade in water scarcity over all the studied countries and regions (Table 5) yields a negative number, indicating that from a global perspective international trade increases scarce water use. This results mainly from many internationally traded products without domestic production (and therefore also without the characterization factor) due to inconvenient domestic climatic conditions. Therefore, the no-trade situation would lead to lower product choice. Cotton is the crop with by far the highest share of such trade. Without it, people would have to use other products like linen, hemp or polyester to produce clothes. Replacing cotton with polyester has a high potential to save water and land resources (Pfister *et al.*, 2011). Rice and sugar cane are other crops with high shares. They increase consumer choices in developed countries. The displaced footprint through all such products is more than one quarter of the total displaced scarce water use, and in 18 European countries more than half. Subtracting the footprint of such products from the national footprint yields a positive effect for water scarcity from international trade, i.e. the trade of products that are also grown domestically is beneficial on a global level.

Table 6 Summary of the current global footprint and the no-trade scenario (10^9 $m^3{}_{eq}$.).

Current global water footprint	428
Hypothetical no-trade scenario global water footprint	422
Water footprint of products with no characterization factor*	29

* those products are not included in the hypothetical no-trade scenario footprint.

Focusing on the trade and population development of Middle Eastern countries reveals that the population of those eight countries for which data is available (out of 15) increased 3.7 times between 1960 and 2007, and imports of cereals increased nearly 14 times, increasing its share in domestic supply from one quarter to one half (FAO, 2015). Therefore, we conclude that international trade enables people to live in inhospitable areas and to consume (directly and indirectly) crops unavailable domestically, rather than reducing scarce water use.

Scarce water imports increase with income

In Figure 7 we show a scatter plot of GDP per capita and scarce water footprint increase by trade per capita. This graph shows that the Middle East region, Spain, Greece, Portugal and Bulgaria’s water scarcity footprint is reduced by international trade. However, for most countries the use of scarce water for agricultural products is higher under current patterns of international trade and it increases generally with income. For water abundant countries this is due to imports from water stressed regions which generally increase with GDP per capita, and for arid regions this is due to exports. However, this only includes the part of the footprint which is saved through imports and it ignores the fact that international trade enables countries to export water intensive products. Spain and Greece in particular export a lot, which compensates the benefits and also for Portugal, Bulgaria and the Middle East the water footprint savings are largely reduced. It might be recommended that these countries limit their export of water intensive agricultural and derived products from a water scarcity perspective. Income versus environmental footprints have also been analyzed by Moran et al. (2013): they concluded for eight environmental impacts that inter-regional balance of trade in biophysical terms is disproportional to the balance of trade in financial terms, but not strongly. They further reported that exports from developing nations are more ecologically intensive than those from developed nations and that high income nations are mostly exporters, not importers, of biophysical resources (which was against their hypothesis). Our analysis shows, that the results depend a lot on the climate of the country, since water scarcity is very variant among production regions. Thus their findings are not fully consistent with our results: exports from developing countries are not generally of higher water scaracity intensity (it depends on the climate) and as Figure 4 shows, the high income countries are mainly net importers.

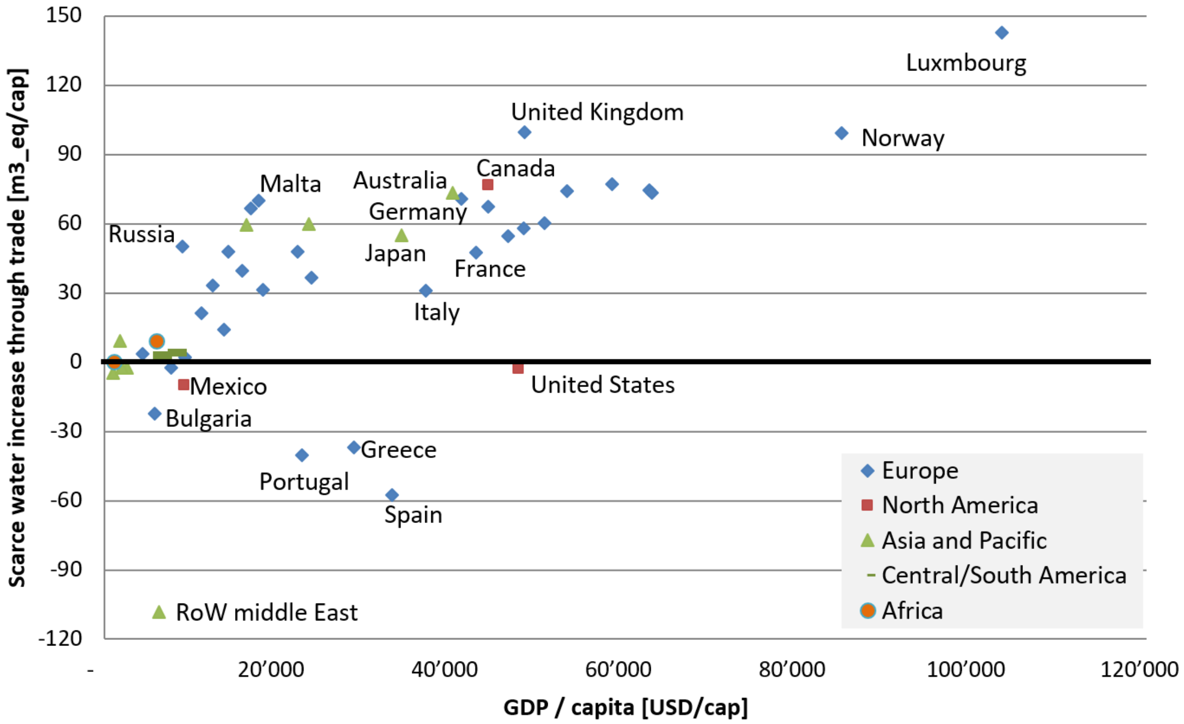


Figure 7 Scatter plot of GDP per capita and scarce water footprint increase through trade per capita [m3eq/cap].

Informing consumers

Many regions on our planet have no problems accessing fresh water while at the same time regions with limited fresh water resources experience impacts on human wellbeing and ecosystems. Consumers might therefore not be fully aware of the scarce water embodied in imports, and their consequences. While freshwater is one of the most important resources for ecosystems and humanity (Falkenmark and Rockstrom, 2004), it is unevenly distributed. In contrast to greenhouse gas emissions, whose impact is independent of the place of emission, for the impacts of water consumption the place of consumption and the specific conditions influence the size of impact. The external costs related to water scarcity affect the producer region and not the consumer regions. One option to mitigate or avoid water scarcity impact can be through internalizing these impacts in consumer costs and investing in better water management and water productivity measures while mutually guaranteeing income for the local population. However, responsibility lies not only with the consumer, since producers generate money and therefore should also contribute to mitigating environmental impact.

Policy implications

International trade in water intensive products can help to reduce water stress. However, since the trade is driven by different forces (Wang et al., 2016), consumption in a water rich region can result in water demand in water stressed regions, especially in a globalized economy, where consumers and producers are only tele-connected (Hubacek *et al.*, 2014). While we observe a clear pattern from scarce water trade from poor to rich countries, a major problem when saving water resources globally is the dependence of poor countries on the agricultural sector. Generally speaking, developing countries have a high share of agricultural gross domestic product (GDP), even India and China still generate ~18% and >9% of their GDP from agriculture, respectively, while Spain, a major exporter within the EU has <3% of GDP from this sector (WB, 2016). Without alternative income options, developing countries cannot reduce their exports and therefore a reduction of irrigation water in the scarce water areas of these countries is not achievable without external pressure or consumer action. We suggest the following policy actions: (1) producer regions should identify which share of water stress is attributed to exported products and consider if this makes sense from a comprehensive sustainability perspective addressing economic, social and environmental aspects, (2) supply chain transparency should be improved through supply chain management of retailers to better identify potential risks of water related impacts and inform consumers, (3) international action must be taken to counter-act uneven exchange between rich and poor countries and account for external environmental costs, which is in line with international goals, e.g. by UNEP (2011) and the OECD (2014), (4) voluntary payment schemes for consumer in rich countries might complement international efforts and should be incentivized by policy makers. Further research is required to determine social responsibility in markets and useful policy actions, since markets generally reduce social responsibility (Bartling et al., 2015). However, richer countries might be more willing to pay premiums for avoiding negative externalities in markets, such as shown for the case of Switzerland (Bartling et al., 2015).

Volumetric and water scarcity footprint

There is a continuous discussion in the scientific literature regarding an appropriate water consumption impact measure (Hoekstra, 2016; Chenoweth et al., 2014; Pfister et al., 2017). The original water footprint as proposed by (Hoekstra and Hung, 2002) aimed to account for volumetric fresh water consumption and pollution arguing that water is scarce on a global level. However, water scarcity is often a local problem and water consumption approaching global fresh water availability would imply catastrophic consequences because of damage to local ecosystems. Another important aspect is the temporal dimension, as water scarcity varies throughout the year, and we apply monthly weighted characterization factors to account for it, which is demanded by the ISO 14046 standard on water footprint.

Limitations and uncertainties

In this work, we do not account for water pollution for a full ISO water footprint or "green water" (soil moisture) consumption, as we aim to account for water consumption only. We acknowledge that there is another environmental dimension to account for when assessing environmentally friendly agriculture, especially land use impacts (which overlap with green water) as well as greenhouse gas, eutrophying and toxic emissions, which are their own research fields.

The water consumption estimates represent the situation in year 2000. Setting it equal to 2007 production is a simplification which adds uncertainty. However, considering the approximations in any global crop production model, these limitations do not dominate the results. Comparing two datasets with water consumption for the year 2000 differ on global level by a factor of two and much more on individual crop and country level (Hoekstra and Mekonnen, 2012; Pfister et al., 2011).

The characterization factors we used are standard in product LCA and ISO water footprint and reflect the local scarcity of water resources. It includes both ground and surface water scarcity in a combined way and does not simply classify stress / no stress situation but accounts for the level of scarcity. As it is based on global hydrological models and human water consumption estimates, the uncertainty of underlying data is relatively high. Processing into a water scarcity indicator ensures that extreme situations do not dominate the results and implicitly accounts for environmental water requirements, but it also adds uncertainty related to the choice of the water scarcity model. This involves high but unquantified uncertainties. Overall the uncertainty of water consumption and scarcity are high compared to e.g. carbon footprints (Pfister and Scherer, 2015). The concept of multi-regional input-output analysis suffers from product and regional aggregation. Products of different types and origins are aggregated into groups which are further assumed to be homogenous, i.e. having the same production recipes and sales structures. If both those characteristics are violated it results in an aggregation error (if at least one of those assumptions holds, the results for national footprints are accurate). The detail analysis of the uncertainties related to product and region aggregation as well as the underlying data uncertainty as done e.g. by Malik et al. (2018), are out of scope of this work. Generally, the coverage of the full global economy and all internationally traded products comes at the expense of precision. Previous research revealed that while the product level results are subject to considerable uncertainties, the national results are quite robust (Lenzen *et al.*, 2010).

Another source of uncertainty in input-output analysis stems from the necessity to model the production technology of by-products, i.e. the products supplied by an economic sector other than its characteristic product. We aim to utilize product-by-product MRIO model constructed under product technology assumption, as this assumption is argued to be "*theoretically superior*" to industry technology assumption by Lenzen and Rueda-Cantuche (2012). The Almon's algorithm is applied in order to avoid negative values in the resulting MRIO table. The necessity to choose the production technology in product-by-product model or sales structures in an industry-by-industry model is inherent also in the direct application of multi-regional supply and use framework (Lenzen and Rueda-Cantuche, 2012). Furthermore, an application of standard mathematical procedures to derive the Leontief inverse matrix through the matrix of input technological coefficients applied to supply and use framework results in product-by-product table under industry technology assumption and industry-by-industry table under fixed product sales structure, both of which should be less preferred for input-output analysis (Lenzen and Rueda-Cantuche, 2012).

Conclusions

The results indicate that the role of international trade in water stress mitigation is ambiguous on a global level as over one quarter of displaced scarce water use is induced by crops without appropriate climatic conditions in the country of destination, extending the consumption choice of the importing countries. Arid regions, such as Middle East, Mexico, Portugal, Greece and Spain benefit from the scarce water use perspective from the existence of international trade, even though their exports general embody a significant fraction of the domestic scarce water use. Through the utilization of resources abroad countries are able to increase domestic consumption beyond the limits of domestic resources. This also enables settlement in arid regions which do not provide enough water resources to produce food for human society. Our results further highlight the importance of scarce water use in poor countries attributed to the rich ones, which generally import scarce water (as shown also by (Wang et al., 2016)), although they often have no local water scarcity problems and could enhance local crop production. Over one quarter of displaced scarce water use is induced by crops without appropriate climatic conditions in the country of destination, extending the consumption choice of the importing countries. It has to be noted that our analysis reports on the status of trade and does not provide an analysis of causality. This is also discussed by Jakob and Marschinski (2013), as consumption versus production based footprints provide „a necessary but not a sufficient informational basis for guiding the design of effective and fair policies aimed at reducing greenhouse gas emissions“.

The major part of trade concerns processed products. Primary crops represent only about one quarter of international trade. Food products in a raw and processed form represent nearly one half of international trade, followed by textiles, clothing apparel and leather related products due to the high water scarcity footprint of cotton lint. Stable crops like wheat and rice have a high share of global scarce water trade, as do vegetables, fruits and oils. The share of actual crops varies greatly among countries and therefore the specific supply chain results provided in this work help to identify hotspots in countries’ scarce water use. As discussed above, uncertainties in global assessments are always important to consider and thus the results need to be interpreted with care. Although we applied monthly and spatially explicit crop and water scarcity models and coupled it with MRIO and FAOSTAT trade data to increase resolution compared to previous research, uncertainties of individual numbers remain high.

Water scarcity is only one big issue in agriculture, with land use, global warming and eutrophication being others. Land use offshoring and nitrogen pollution show a similar pattern (Oita et al., 2016; Weinzettel et al., 2013), but are also tradeoffs in some regions (Pfister *et al.*, 2011). The spatial disconnection of production impacts and consumption needs to be considered when aiming at reducing global environmental damage. While climate change cause impacts on a global level, scarce water use mainly affects local societies and ecosystems. The attempt to reduce global scarce water use might be difficult due to the economic dependence of poor countries on agriculture. It has to be explored in future research how wealthy nations can take responsibility for those problems and best contribute to mitigating them. We suggest to explore various policy options to reduce water scarcity problems caused by trade, integrating the local (integrated water resource management) and international level (transparency by retailers, international agreements and voluntary payment schemes).

Acknowledgement

This research was supported by the Czech Science Foundation under grant number 17-07140S, by the European Commission under grant number PCIG13-GA-2013-618520 and by H2020-MSCA-RISE project GEMCLIME-2020 under GA no. 681228.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2019.01.032

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S. (2003) Development and testing of the WaterGAP 2 global model of water use and availability. Hydrological Sciences Journal 48, 317-338.
Allan, J.A. (1998) Virtual water: A strategic resource global solutions to regional deficits. Ground Water 36, 545-546.
Almon, C. (2000) Product-to-product tables via product-technology with no negative flows. Economic Systems Research 12, 42-43.
Bartling, B., Weber, R.A., Yao, L. (2015) Do markets erode social responsibility? Quarterly Journal of Economics 130, 219-266.
Daniels, P.L., Lenzen, M., Kenway, S.J. (2011) The Ins and Outs of Water Use – A review of multi-region input–output analysis and water footprints for regional sustainability analysis and policy. Economic Systems Research 23, 353-370.
Dietzenbacher, E., Velázquez, E. (2007) Analysing Andalusian Virtual Water Trade in an Input-Output Framework. Regional Studies 41, 185-196.
Ewing, B.R., Hawkins, T.R., Wiedmann, T.O., Galli, A., Ertug Ercin, A., Weinzettel, J., Steen-Olsen, K. (2012) Integrating ecological and water footprint accounting in a multi-regional input-output framework. Ecological Indicators 23, 1-8.
Falkenmark, M., Rockstrom, J. (2004) Balancing Water for Humans and Nature: The New Approach in Ecohydrology. Earthscan, London.
FAO, (2014) FAOSTAT. Food and Agriculture Organization of the United Nations.
FAO, (2015) FAOSTAT Database. Food and Agriculture Organization of the United Nations, Rome, Italy.
FAO, (2016) Hot issues: water scarcity. Food and Agricutural Organisation Land and Water Division [http://www.fao.org/nr/water/issues/scarcity.html].
Feng, K., Chapagain, A., Suh, S., Pfister, S., Hubacek, K. (2011) Comparison of Bottom-up and Top-down Approaches to Calculating the Water Footprints of Nations. Economic Systems Research 23, 371-385.
Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz,

J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K. (2005) Global consequences of land use. Science 309, 570-574.

Hoekstra, A.Y. (2016) A critique on the water-scarcity weighted water footprint in LCA. Ecological Indicators 66, 564-573.

Hoekstra, A.Y., Hung, P.Q., (2002) Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade, Value of Water Research Report Series No. 11. UNESCO-IHE Institute for Water Education, Delft, the Netherlands.

Hoekstra, A.Y., Mekonnen, M.M. (2012) The water footprint of humanity. Proceedings of the National Academy of Sciences of the United States of America 109, 3232-3237.

Hubacek, K., Feng, K. (2016) Comparing apples and oranges: Some confusion about using and interpreting physical trade matrices versus multi-regional input-output analysis. Land Use Policy 50, 194-201.

Hubacek, K., Feng, K., Minx, J.C., Pfister, S., Zhou, N. (2014) Teleconnecting Consumption to Environmental Impacts at Multiple Spatial Scales. Journal of Industrial Ecology 18, 7-9.

Chenoweth, J., Hadjikakou, M., Zoumides, C. (2014) Quantifying the human impact on water resources: A critical review of the water footprint concept. Hydrology and Earth System Sciences 18, 2325-2342.

ISO, I. (2013) DIS 14046 Water footprint–principles, requirements and guidelines. The International Organization for Standardization.

Jakob, M., Marschinski, R. (2013) Interpreting trade-related CO2 emission transfers. Nature Climate Change 3, 19-23.

Kanemoto, K., Lenzen, M., Peters, G.P., Moran, D.D., Geschke, A. (2012) Frameworks for comparing emissions associated with production, consumption, and international trade. Environmental Science and Technology 46, 172-179.

Kastner, T., Schaffartzik, A., Eisenmenger, N., Erb, K.H., Haberl, H., Krausmann, F. (2014) Cropland area embodied in international trade: Contradictory results from different approaches. Ecological Economics 104, 140-144.

Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., Foran, B. (2013) International trade of scarce water. Ecological Economics 94, 78-85.

Lenzen, M., Rueda-Cantuche, J.M. (2012) A note on the use of supply-use tables in impact analyses. SORT 36, 139-152.

Lenzen, M., Wood, R., Wiedmann, T. (2010) Uncertainty analysis for multi-region input - output models - a case study of the UK'S carbon footprint. Economic Systems Research 22, 43-63.

Lutter, S., Pfister, S., Giljum, S., Wieland, H., Mutel, C. (2016) Spatially explicit assessment of water embodied in European trade: A product-level multi-regional input-output analysis. Global Environmental Change 38, 171-182.

Malik, A., Lenzen, M., McAlister, S., McGain, F. (2018) The carbon footprint of Australian health care. The Lancet Planetary Health 2, e2-e3.

McGlade, J., Werner, B., Young, M., Matlock, M., Jefferies, D., Sonneman, G., Aldaya, M., Pfister, S., Berger, M., Farell, C. (2012) Measuring water use in a green economy, a report of the working group on water efficiency to the International Resource Panel. UNEP.

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC.

Moran, D.D., Lenzen, M., Kanemoto, K., Geschke, A. (2013) Does Ecologically Unequal Exchange Occur? Ecological Economics 89, 177-186.

OECD (2014) Green Growth Indicators 2014. OECD Publishing.

Oita, A., Malik, A., Kanemoto, K., Geschke, A., Nishijima, S., Lenzen, M. (2016) Substantial nitrogen pollution embedded in international trade. Nature Geoscience 9, 111-115.

Peters, G.P., Davis, S.J., Andrew, R. (2012) A synthesis of carbon in international trade. Biogeosciences 9, 3247-3276.

Pfister, S., Bayer, P. (2014) Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production. Journal of Cleaner Production 73, 52-62.

Pfister, S., Bayer, P., Koehler, A., Hellweg, S. (2011) Environmental impacts of water use in global crop production: Hotspots and trade-offs with land use. Environmental Science and Technology 45, 5761-5768.

Pfister, S., Boulay, A.M., Berger, M., Hadjikakou, M., Motoshita, M., Hess, T., Ridoutt, B., Weinzettel, J., Scherer, L., Döll, P., Manzardo, A., Núñez, M., Verones, F., Humbert, S., Buxmann, K., Harding, K., Benini, L., Oki, T., Finkbeiner, M., Henderson, A. (2017) Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA". Ecological Indicators 72, 352-359.

Pfister, S., Hellweg, S. (2009) The water "shoesize" vs. footprint of bioenergy. Proceedings of the National Academy of Sciences of the United States of America 106.

Pfister, S., Scherer, L. (2015) Uncertainty analysis of the environmental sustainability of biofuels. Energy, Sustainability and Society 5.

Ridoutt, B.G., Pfister, S. (2010) Reducing humanity's water footprint. Environmental Science and Technology 44, 6019-6021.

Shiklomanov, I.A., Rodda, J.C. (2003) World water resources at the beginning of the twenty-first century. Cambridge University Press, Cambridge, UK ; New York.

Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A.E., Hertwich, E.G. (2012) Carbon, Land, and Water Footprint Accounts for the European Union: Consumption, Production, and Displacements through International Trade. Environmental Science & Technology 46, 10883-10891.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S. (2015) Planetary boundaries: Guiding human development on a changing planet. Science.

UNEP (2011) Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication.

Wang, R., Hertwich, E., Zimmerman, J.B. (2016) (Virtual) Water Flows Uphill toward Money. Environmental Science & Technology 50, 12320-12330.

Wang, R., Zimmerman, J. (2016) Hybrid Analysis of Blue Water Consumption and Water Scarcity Implications at the Global, National, and Basin Levels in an Increasingly Globalized World. Environmental Science & Technology 50, 5143-5153.

WB, (2016) World Bank Open Data. The World Bank.

Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A. (2013) Affluence drives the global displacement of land use. Global Environmental Change 23, 433-438.

Weinzettel, J., Steen-Olsen, K., Hertwich, E.G., Borucke, M., Galli, A. (2014) Ecological footprint of nations: Comparison of process analysis, and standard and hybrid multiregional input-output analysis. Ecological Economics 101, 115-126.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J.H., Merciai, S., Tukker, A. (2015) Global sustainability accounting-developing EXIOBASE for multi-regional footprint analysis. Sustainability (Switzerland) 7, 138-163.