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7 International trade of global scarce water  
8 use in agriculture: Modeling on watershed  
9 level with monthly resolution.  
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16  
17 **Abstract**

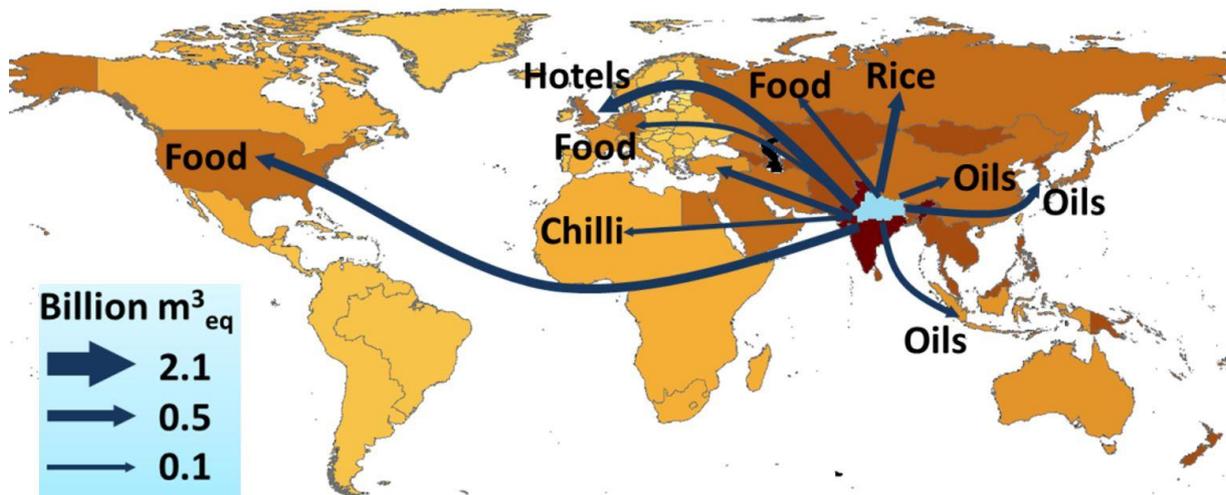
18 Fresh water is a renewable yet limited natural resource. While abundant in some areas, fresh water  
19 is scarce in others where its consumption in agriculture leads to negative impacts on human society,  
20 ecosystems and biodiversity. International trade in water intensive products can help to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

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

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

43

#### 44 Graphical abstract



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46

#### 47 Highlights

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

52

53

## 54 Introduction

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

79 Global analysis concerning water footprints has been provided via process analysis (Hoekstra and  
80 Mekonnen, 2012) and multi-regional input-output analysis (Daniels et al., 2011; Dietzenbacher and  
81 Velázquez, 2007; Feng et al., 2011; Lenzen et al., 2013; Lutter et al., 2016; Steen-Olsen et al., 2012;  
82 Wang et al., 2016; Wang and Zimmerman, 2016). While the process analysis benefits from a detailed  
83 classification of international trade of the most relevant agricultural crops and derived products,  
84 multi-regional input-output analysis (MRIO) covers all internationally traded products and their full  
85 supply chains. Therefore, the two approaches may lead to substantial differences (Feng et al., 2011;  
86 Kastner et al., 2014). Weinzettel et al. (2014) showed that a standard MRIO is not suitable for the  
87 accounting of land footprints due to low product resolution in the available MRIO datasets, and the  
88 process analysis lacks an important part of the land footprint of international trade due to its limited  
89 scope. They recommend using hybrid MRIO proposed by Ewing et al. (2012) since it enables an  
90 increased level of detail regarding the international trade of primary agricultural crops to a level  
91 commonly reached in the process analysis. This level of detail is acquired from bilateral trade data  
92 and commodity balance sheets provided by the FAO (FAO, 2014). Since both water and land are  
93 closely related to agriculture, this insight is valid for water footprints, too. Additionally, previous  
94 studies, except for Wang and Zimmermann (2016), Lutter et al. (2016) and Lenzen et al. (2013) did  
95 not consider water scarcity. Lenzen and colleagues conclude that the global trade of volumetric  
96 virtual water has a different pattern from scarce water, highlighting the need to include water  
97 scarcity assessment in the analysis. Lutter et al. (2016) used detailed water consumption and scarcity

108 data, but only based on MRIO results with a very rough resolution for Africa, South America and Asia.  
 109 In contrast to their study in our approach we extend both, the product and the regional detail to  
 110 FAOSTAT level for all primary crops even though we also use Exiobase MRIO dataset, see Table 1 for  
 111 comparison of the studies which considered water scarcity. Wang and Zimmermann recently  
 112 provided a hybrid MRIO analysis based on a GTAP 8 database for the year 2007, using national  
 113 average annual water consumption data and watershed withdrawals to estimate the locations of  
 114 water consumption and the related effects on water scarcity, but not specifically accounting for the  
 115 actual location of specific crop cultivation and the temporal dimension of water scarcity, which is  
 116 demanded by ISO 14046 for a water scarcity footprint. Furthermore, this simplification does not  
 117 allow accounting for different trade patterns of crops grown in different regions of the country (e.g.  
 118 rice from China has different origins than cotton or wheat from China).

109 **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?				

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

111

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

120 We apply the most detailed MRIO dataset regarding consistent product classification based on  
 121 Exiobase 2.2 (Wood *et al.*, 2015) and we advance previous research in this study: (a) water

122 consumption for crop irrigation is modeled on high spatial resolution on a monthly level to account  
123 for temporal variation in water scarcity; (b) fresh water consumption in crop irrigation is accounted  
124 for in cubic meters of scarce water equivalent ( $m^3_{eq}$ ) by applying characterization factors, which  
125 consider monthly water scarcity on a scale from 0.01-1 (Pfister and Bayer, 2014); (c) we construct the  
126 product-by-product MRIO table under the product technology assumption using the Almon algorithm  
127 (Almon, 2000); (d) we track the international trade of agricultural crops outside the MRIO system on  
128 a high level of crop and country detail consistent with FAOSTAT data and classification (e) we report  
129 the most important traded products and the crops behind the footprint. We discuss the results in a  
130 socio-economic and policy context.

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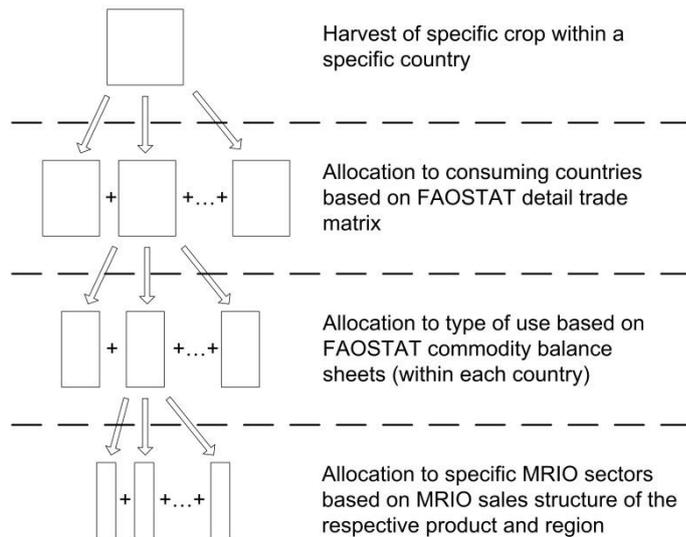
## 132 **Materials and Methods**

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

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

146 **Trade analysis:** For the allocation of scarce water requirements to final consumers we employ the  
147 most advanced MRIO method up to date, the so-called hybrid environmentally-extended MRIO  
148 model. The monetary core of this model is derived from the Exiobase supply and use tables version  
149 2.2 (Wood et al., 2015) under product technology assumption following Almon's algorithm (Almon,  
150 2000). We chose Exiobase over other MRIO dataset for its consistently high product detail.

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



160

161 **Figure 1 Allocation of primary crops to MRIO sectors.**

162 In order to focus on a watershed level we utilized spatially specific data on crop harvests and  
 163 assumed equal sales structure for each crop irrespective of its origin within a country. For example, if  
 164 30% of the wheat harvest in a specific country occurs in a specific watershed, we assumed 30% of  
 165 wheat originating from this country and consumed by any economic sector comes from this  
 166 watershed. This assumption is determined by current data availability.

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

183 **No-trade scenario:** In order to contribute to the discussion regarding the potential of international  
 184 trade to reduce global water stress we calculated the alternative hypothetical national scarce water  
 185 footprints by converting the weight of harvested crops embodied in the domestic final demand into  
 186 scarce water use using the domestic characterization factors if the crop is produced locally, and we  
 187 assumed zero for crops not harvested domestically and we report their footprint separately. We  
 188 interpret the positive difference between the sum over all countries of this hypothetical footprint

189 and the national footprints as a potential to save global scarce water use by international trade. This  
 190 scenario is intended to indicate how local vs imported production differs.

191 Additional details are provided in the SI.

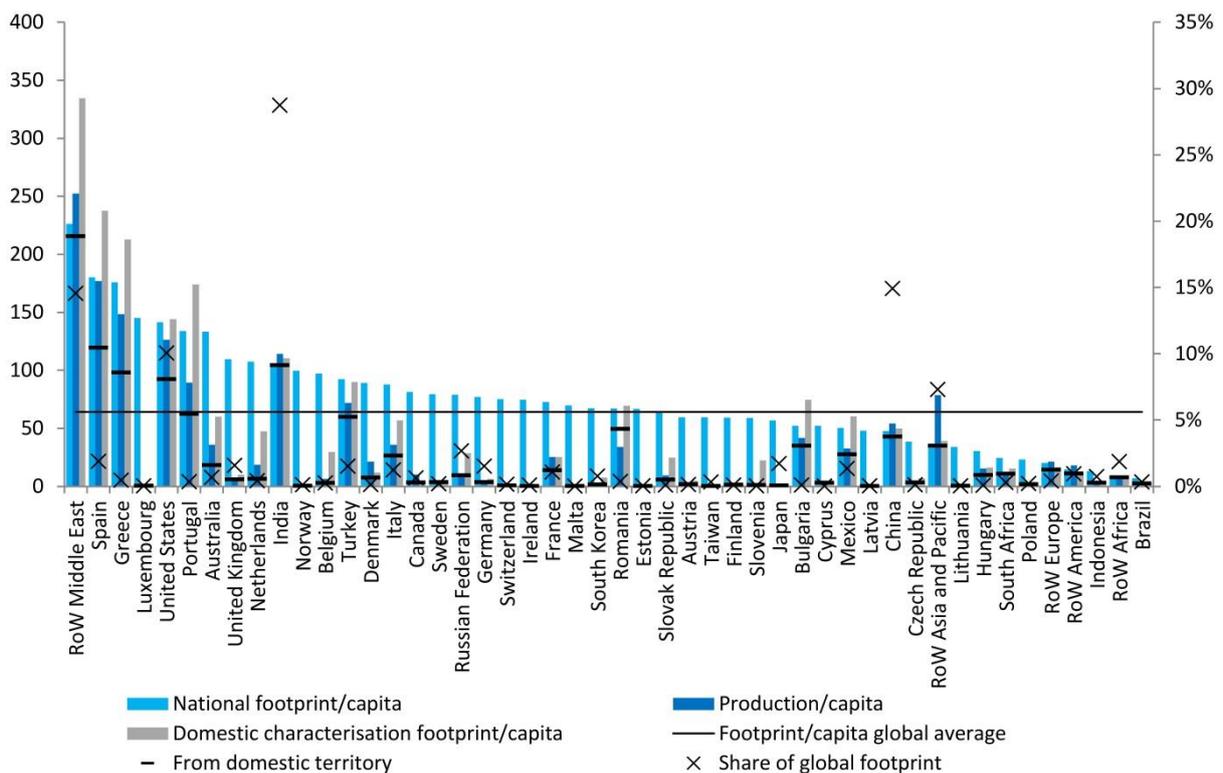
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193 **Results**

194 **Overall results: production versus consumption perspective**

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

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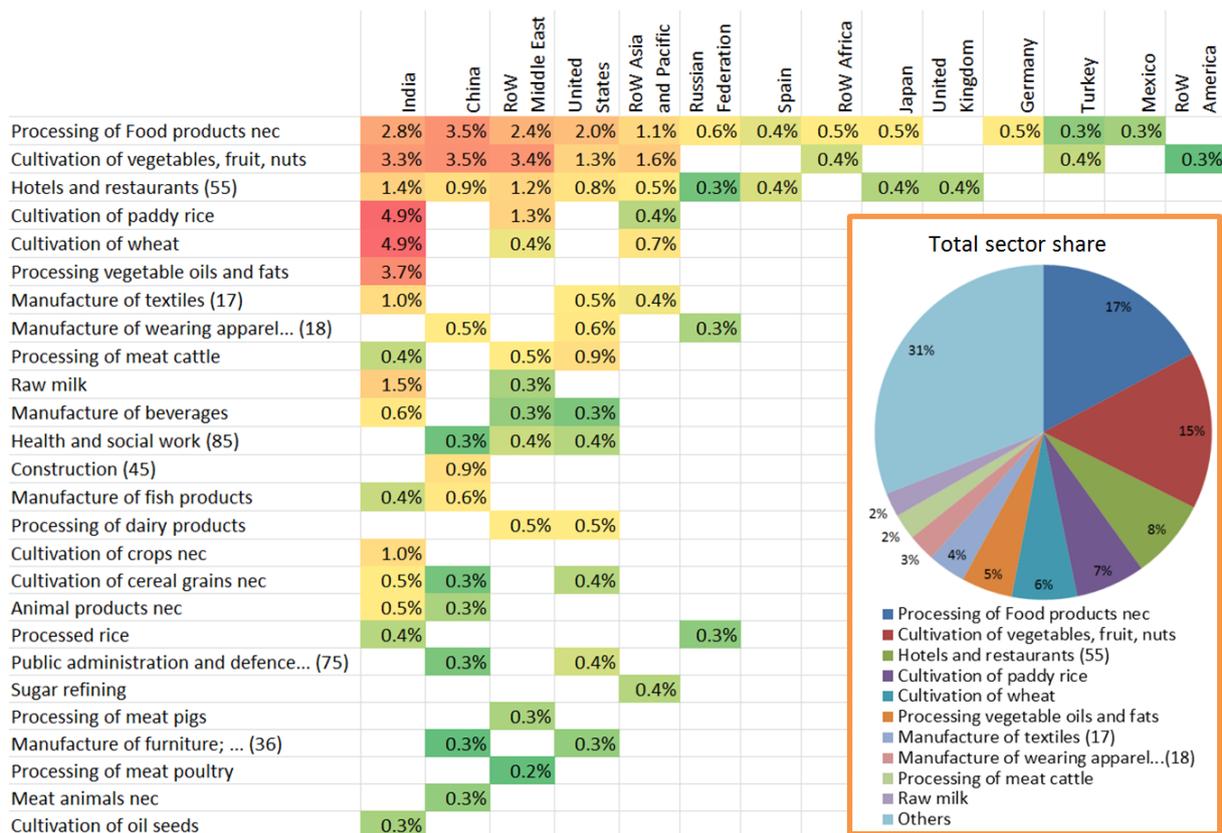
212 **Figure 2: National scarce water footprints.** The left axis represents the scarce water footprint of nations in 2007 in  $m^3_{eq}$   
213 per capita (National footprint/capita), scarce water use per capita from a production perspective (Production/capita),  
214 the hypothetical footprint if domestic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

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

### 225 **Dominance of region-specific final demand product groups**

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

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



242

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

246

247 Aggregating product groups into broader categories reveals the overall importance of food and  
 248 textiles. The importance of textiles in the EU, the US and Japan is around 12%, while the global  
 249 average is about 7%; most countries reach approximately only 3%. The importance of textiles further  
 250 increases for international trade, since cotton lint is cropped in only a few countries, where it  
 251 requires substantial irrigation. This further helps people in rich countries to ignore the environmental  
 252 consequences of textile consumption because for most people they occur far away. Even the US as a  
 253 major producer has a positive footprint for net trade originating from cotton lint production of about  
 254 22% of their consumption (thus displacing the impacts to other countries).

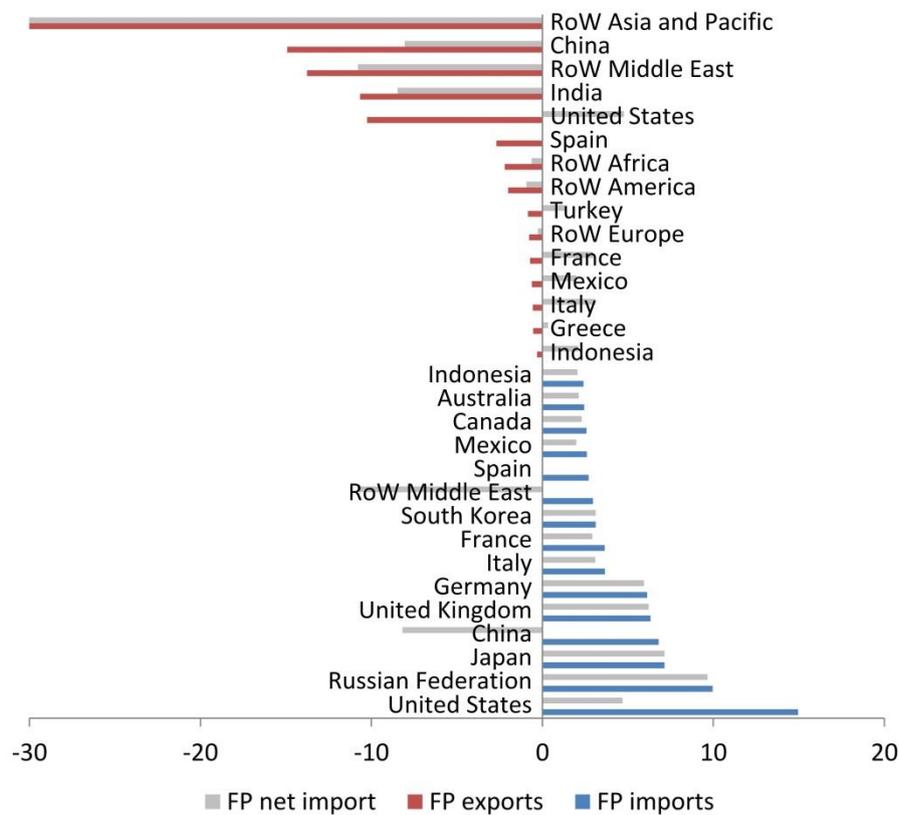
255 **Table 2 Contribution of broader product groups to the global footprint and for bilateral trade exports.**

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%

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

257 **International trade**

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



269

270 Figure 4 Exports and imports of scarce water use, including net imports (billion m³<sub>eq</sub>).

271

272 Trade among the studied regions and countries is dominated by food related products (Table 1).  
 273 Textiles, clothing apparel and leather related products account for one quarter, followed by oil crops  
 274 and oil related products (about 10%), and hotels and restaurants (about 5%). Primary crops are  
 275 responsible for only one quarter of the footprint of international trade, leaving the majority for  
 276 manufactured goods and services. Cotton lint is the most important primary crop, followed by wheat  
 277 and maize. While bilateral trade exports yield about 10 billion m³<sub>eq</sub> for cotton lint, final demand  
 278 imports yield only about 4 billion, indicating that most cotton lint is traded to be processed and re-  
 279 exported, mainly in China and ROW Asia (Table 3). Table 3 and Table 4 show the most important

280 bilateral trade exports and final demand imports for the top three exporting and importing regions,  
 281 respectively.

282 **Table 3 The five most important BTEXP (bilateral trade exports) for the top three exporting regions (billion m<sup>3</sup><sub>eq</sub> of scarce**  
 283 **water). The top three primary crops behind the footprint and the top three regions of destination are provided next to**  
 284 **the product name.**

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

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

287

288 **Table 4 The five most important FDIMP (Final demand imports) for the top three importing regions (billion m<sup>3</sup><sub>eq</sub> of scarce**  
 289 **water). The top three primary crops behind the footprint and the top three regions of water use are provided next to the**  
 290 **product name.**

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

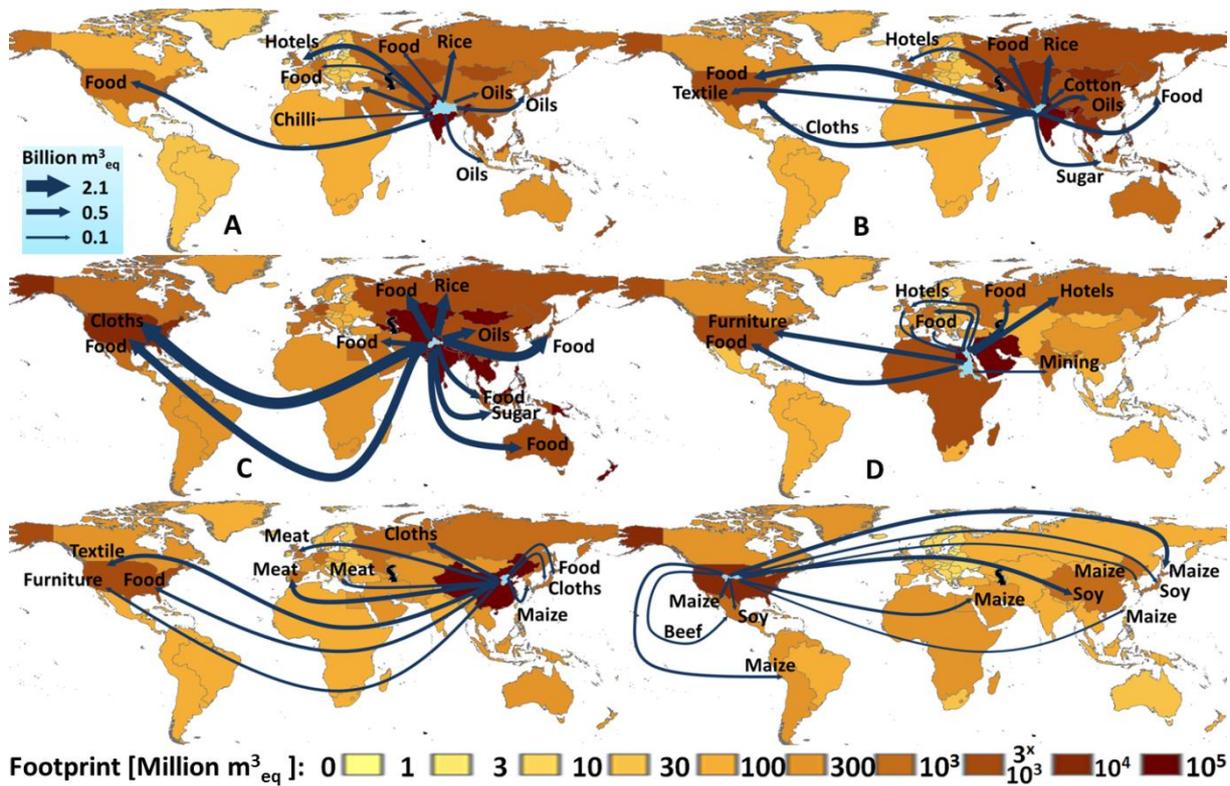
	49%, RoW Asia and Pacific 28%, India 10%)	RoW Asia and Pacific 38%, India 8%)
Furniture; other manufactured goods n.e.c. (forage and silage 30%, wheat 18%, maize 13%), RoW Middle East 54%, China 22%, RoW Asia and Pacific 20%)	Hotels and restaurants (wheat 20%, rice 19%, forage and silage 13%), (RoW Middle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

291

## 292 Watershed level assessment

293 Irrigation is highly concentrated in a few watersheds and the top 11 global watersheds combine  
294 more than 50% of global scarce water use. Watersheds are defined in Watergap 2.1 (Alcamo *et al.*,  
295 2003) and even divide the largest rivers such as the Mississippi, Nile and Indus into sub-watersheds.  
296 Figure 5 presents the top five (Ganges, Indus-Luni Basin, Upper Indus, Nile, Hai River) and a sub-  
297 watershed of the Mississippi (the Platte river), which account for 12%, 9%, 8%, 4%, 3% and 2% of  
298 global scarce water use respectively. Exports from the other watersheds of the top 11 are shown in  
299 the SI. The maps reflect the high share of India, but show significant differences as a function of the  
300 watersheds. The ten top flows per region on average cover only 6% of the total use, mainly due to  
301 the high share of domestic use in India, China and the US. Imports from Indian watersheds are mainly  
302 processed foods, rice, textiles and vegetable oils, while imports from the Hai River are dominated by  
303 meat, cloths, textile and processed food. From the Nile, imports are mainly processed foods followed  
304 by Hotels (and restaurants) and Furniture. Furniture is important mainly due to leather production  
305 and also observed in imports from the Hai River. Finally, imports from the Mississippi sub-watershed  
306 are mainly Maize and Soybean.

307



308 **Footprint [Million m<sup>3</sup><sub>eq</sub>]:** 0 1 3 10 30 100 300 10<sup>3</sup> 3<sup>x</sup>10<sup>3</sup> 10<sup>4</sup> 10<sup>5</sup>

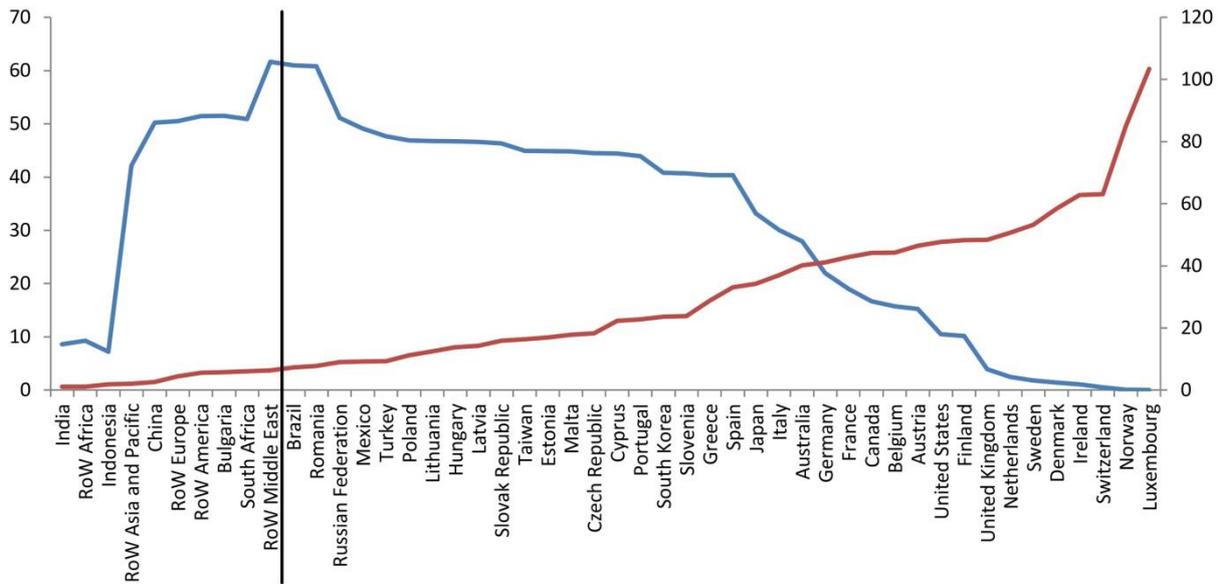
309 **Figure 5** Top 10 region-product specific flows for the five top watersheds in terms of scarce water use plus the top  
 310 watershed outside Asia and Africa (number 10 globally): Colors indicate the scarce water footprint of final demand in  
 311 each region occurring in the specific watershed,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

313 **Discussion**

314 **“Offshoring” from rich to poor countries**

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

329



330

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

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

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

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

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

<b>Footprint per capita (m<sup>3</sup><sub>eq</sub>/cap)</b>	59	82
<b>Production per capita (m<sup>3</sup><sub>eq</sub>/cap)</b>	70	43
<b>Footprint from abroad (%)</b>	1%	51%

354

355 **Is the virtual water transfer beneficial for global water scarcity?**

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

377 **Table 6 Summary of the current global footprint and the no-trade scenario (10<sup>9</sup> m<sup>3</sup><sub>eq</sub>).**

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

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

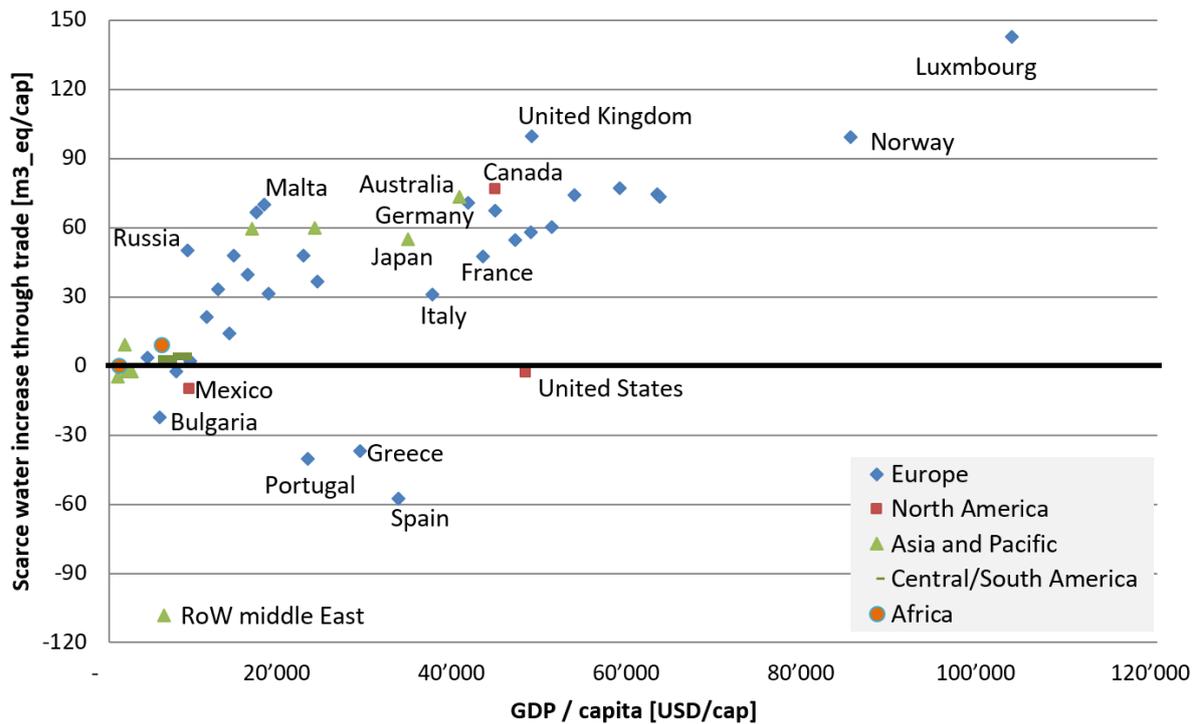
379 Focusing on the trade and population development of Middle Eastern countries reveals that the  
380 population of those eight countries for which data is available (out of 15) increased 3.7 times  
381 between 1960 and 2007, and imports of cereals increased nearly 14 times, increasing its share in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

385 **Scarce water imports increase with income**

386 In Figure 7 we show a scatter plot of GDP per capita and scarce water footprint increase by trade per  
387 capita. This graph shows that the Middle East region, Spain, Greece, Portugal and Bulgaria's water

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

407



408

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

410

411 **Informing consumers**

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

425

### 426 **Policy implications**

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

### 451 **Volumetric and water scarcity footprint**

452 There is a continuous discussion in the scientific literature regarding an appropriate water  
453 consumption impact measure (Hoekstra, 2016; Chenoweth et al., 2014; Pfister et al., 2017). The

454 original water footprint as proposed by (Hoekstra and Hung, 2002) aimed to account for volumetric  
455 fresh water consumption and pollution arguing that water is scarce on a global level. However, water  
456 scarcity is often a local problem and water consumption approaching global fresh water availability  
457 would imply catastrophic consequences because of damage to local ecosystems. Another important  
458 aspect is the temporal dimension, as water scarcity varies throughout the year, and we apply  
459 monthly weighted characterization factors to account for it, which is demanded by the ISO 14046  
460 standard on water footprint.

#### 461 **Limitations and uncertainties**

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

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

472 The characterization factors we used are standard in product LCA and ISO water footprint and reflect  
473 the local scarcity of water resources. It includes both ground and surface water scarcity in a  
474 combined way and does not simply classify stress / no stress situation but accounts for the level of  
475 scarcity. As it is based on global hydrological models and human water consumption estimates, the  
476 uncertainty of underlying data is relatively high. Processing into a water scarcity indicator ensures  
477 that extreme situations do not dominate the results and implicitly accounts for environmental water  
478 requirements, but it also adds uncertainty related to the choice of the water scarcity model. This  
479 involves high but unquantified uncertainties. Overall the uncertainty of water consumption and  
480 scarcity are high compared to e.g. carbon footprints (Pfister and Scherer, 2015). The concept of  
481 multi-regional input-output analysis suffers from product and regional aggregation. Products of  
482 different types and origins are aggregated into groups which are further assumed to be homogenous,  
483 i.e. having the same production recipes and sales structures. If both those characteristics are violated  
484 it results in an aggregation error (if at least one of those assumptions holds, the results for national  
485 footprints are accurate). The detail analysis of the uncertainties related to product and region  
486 aggregation as well as the underlying data uncertainty as done e.g. by Malik et al. (2018), are out of  
487 scope of this work. Generally, the coverage of the full global economy and all internationally traded  
488 products comes at the expense of precision. Previous research revealed that while the product level  
489 results are subject to considerable uncertainties, the national results are quite robust (Lenzen *et al.*,  
490 2010).

491 Another source of uncertainty in input-output analysis stems from the necessity to model the  
492 production technology of by-products, i.e. the products supplied by an economic sector other than  
493 its characteristic product. We aim to utilize product-by-product MRIO model constructed under  
494 product technology assumption, as this assumption is argued to be “*theoretically superior*” to  
495 industry technology assumption by Lenzen and Rueda-Cantuche (2012). The Almon’s algorithm is

496 applied in order to avoid negative values in the resulting MRIO table. The necessity to choose the  
497 production technology in product-by-product model or sales structures in an industry-by-industry  
498 model is inherent also in the direct application of multi-regional supply and use framework (Lenzen  
499 and Rueda-Cantuche, 2012). Furthermore, an application of standard mathematical procedures to  
500 derive the Leontief inverse matrix through the matrix of input technological coefficients applied to  
501 supply and use framework results in product-by-product table under industry technology assumption  
502 and industry-by-industry table under fixed product sales structure, both of which should be less  
503 preferred for input-output analysis (Lenzen and Rueda-Cantuche, 2012).

## 504 **Conclusions**

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

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

534 Water scarcity is only one big issue in agriculture, with land use, global warming and eutrophication  
535 being others. Land use offshoring and nitrogen pollution show a similar pattern (Oita et al., 2016;  
536 Weinzettel et al., 2013), but are also tradeoffs in some regions (Pfister *et al.*, 2011). The spatial  
537 disconnection of production impacts and consumption needs to be considered when aiming at

538 reducing global environmental damage. While climate change cause impacts on a global level, scarce  
539 water use mainly affects local societies and ecosystems. The attempt to reduce global scarce water  
540 use might be difficult due to the economic dependence of poor countries on agriculture. It has to be  
541 explored in future research how wealthy nations can take responsibility for those problems and best  
542 contribute to mitigating them. We suggest to explore various policy options to reduce water scarcity  
543 problems caused by trade, integrating the local (integrated water resource management) and  
544 international level (transparency by retailers, international agreements and voluntary payment  
545 schemes).

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#### 550 **Supplementary data**

551 Supplementary data to this article can be found online at  
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