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LETTER

Global unsustainable virtual water flows in agricultural trade

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**Abstract**

Recent studies have highlighted the reliance of global food production on unsustainable irrigation practices, which deplete freshwater stocks and environmental flows, and consequently impair aquatic ecosystems. Unsustainable irrigation is driven by domestic and international demand for agricultural products. Research on the environmental consequences of trade has often concentrated on the global displacement of pollution and land use, while the effect of trade on water sustainability and the drying of over-depleted watercourses has seldom been recognized and quantified. Here we evaluate unsustainable irrigation water consumption (UWC) associated with global crop production and determine the share of UWC embedded in international trade. We find that, while about 52% of global irrigation is unsustainable, 15% of it is virtually exported, with an average 18% increase between year 2000 and 2015. About 60% of global virtual transfers of UWC are driven by exports of cotton, sugar cane, fruits, and vegetables. One third of UWC in Mexico, Spain, Turkmenistan, South Africa, Morocco, and Australia is associated with demand from the export markets. The globalization of water through trade contributes to running rivers dry, an environmental externality commonly overlooked by trade policies. By identifying the producing and consuming countries that are responsible for unsustainable irrigation embedded in virtual water trade, this study highlights trade links in which policies are needed to achieve sustainable water and food security goals in the coming decades.

Introduction

In the last decade, many studies have shown that some of the world's major agricultural baskets rely on unsustainable water use for irrigation (Gleick and Palaniappan 2010, Konikow 2011, Gleeson *et al* 2012, Scanlon *et al* 2012, Kummur *et al* 2016, Mekonnen and Hoekstra 2016). Irrigation practices are classified as unsustainable when their water consumption exceeds local renewable water availability. In these conditions, irrigation uses water that should be allocated to environmental flows and therefore contributes to environmental degradation and groundwater depletion (Rosa *et al* 2018a). About 40% of global irrigation water use is at the expenses of environmental flow requirements (Jägermeyr *et al* 2017) with detrimental effects on aquatic habitats, riparian biodiversity, and

ecosystem services (Dudgeon *et al* 2006, Richter *et al* 2012, Palmer and Ruhli 2019). Moreover, about 20% of irrigation water use worldwide is from non-renewable groundwater abstractions (Wada *et al* 2012). Indeed, irrigation water withdrawals may also deplete freshwater stocks (both surface water bodies and aquifers) when their abstraction rates exceed those of natural recharge (Wada *et al* 2010, Famiglietti 2014, AghaKouchak *et al* 2015, Richey *et al* 2015, Rodell *et al* 2018, Wang *et al* 2018).

The reliance of food production on unsustainable irrigation threatens local and global water and food security (Aeschbach-Hertig and Gleeson 2012, Turner *et al* 2019). The problem is worsened when the nexus between irrigation-dependent agricultural production and food consumption occurs through distant interconnections resulting from the globalization of food

and water resources through trade or international investments (Hoekstra and Chapagain 2008, D'Odorico *et al* 2018). About 20%–24% of water resources embedded in food production—or ‘virtual water’—are internationally traded (D'Odorico *et al* 2014). While the virtual water trade associated with agricultural commodities (Konar *et al* 2011, Hoekstra and Mekonnen 2012), and the regions of unsustainable irrigation have been extensively investigated and mapped (Rosa *et al* 2018a), the globalized dimension of unsustainable irrigation, the loss of environmental flows, and the associated unsustainable virtual water trade are poorly studied (D'Odorico *et al* 2019).

Research on virtual water has often focused on quantitative analyses of water flows, with no consideration of the environmental impacts of virtual water transfers and of how trade affects the sustainability of irrigation practices (Gawel and Bernsen 2013). Virtual water transfers have been related to groundwater depletion in the United States (Marston *et al* 2015) and globally (Dalin *et al* 2017). As important as these studies are, the extent to which virtual water trade contributes to the loss of environmental flows, remains poorly understood. It is not clear to what extent unsustainable surface water consumption for irrigation contributes to the desiccation of rivers and the loss of environmental flows to sustain agricultural production for the export market. Because surface water accounts for about 60% of total consumptive irrigation water use (Siebert *et al* 2010), there is a direct association between agricultural production and patterns of streamflow depletion (Richter 2014) that was not considered in previous analyses of unsustainable irrigation and virtual water trade (Marston *et al* 2015, Dalin *et al* 2017). Indeed, many rivers around the world are so strongly depleted that minimum flow requirements to sustain aquatic habitat are not met and in some cases the flow does not even reach the ocean anymore (Richter 2014, Jägermeyr *et al* 2017).

Here, we provide a comprehensive global analysis of unsustainable irrigation water consumption for crop production, accounting for the depletion of both freshwater stocks (including surface and ground water bodies) and environmental flows. We quantify the associated virtual water flows through trade (or ‘unsustainable virtual water trade’) in year 2000 and 2015 through a global spatially-distributed biophysical analysis of irrigation water consumption considering 130 primary crops or 26 crop classes (Portman *et al* 2010). We quantify the amount of irrigation water that is unsustainably consumed by comparing irrigation water consumption to local renewable freshwater availability, calculated through a process-based water balance model accounting for environmental flows. We then determine the unsustainable water footprint of crop production and trade (FAOSTAT; <http://faostat.org/faostat/en/#data>) to quantify the unsustainable

irrigation water consumption embodied in the international trade of agricultural commodities.

This analysis sheds light on the water unsustainability of crop trade. It identifies the ‘culprits’ of unsustainable irrigation water consumption in terms of both production regions and consumer countries, and determines the associated virtual water flows. These results can assist in the development of consumption based decision-making tools aiming at meeting Sustainable Development Goals by ensuring sustainable use of water resources to reduce the number of people suffering from water scarcity (Vanham *et al* 2018).

Methods

Assessment of unsustainable irrigation water consumption

We quantified unsustainable water consumption from irrigation worldwide (at 5×5 arcminute resolution) in years 2000 and 2015 for 26 crop classes, based on the MIRCA2000 dataset (Portmann *et al* 2010). For year 2000 (the reference year for the MIRCA2000 global agricultural datasets), we used a global process-based crop water model to assess irrigation water requirements. This model has been extensively used to assess irrigation water requirements (Rosa *et al* 2018a, 2018b). The model calculates spatially explicit crop-specific irrigation water requirements (mm yr^{-1}) using a daily soil water balance during each crop's growing season. To assess irrigation water consumption, we then multiplied crop-specific irrigation water requirements by the irrigated harvested area of that crop in the year 2000 (Portmann *et al* 2010).

Because there are no up-to-date global datasets of crop-specific irrigated harvested area, we estimated the change in irrigation water consumption between year 2000 and 2015 as proportional to the change in country-specific irrigation water withdrawals (from FAO's AQUASTAT) and crop-specific change in production (from FAO's FAOSTAT). Specifically, national crop-specific estimates of volumes of irrigation water consumption for year 2000 were scaled to year 2015 based on national agricultural water withdrawal and crop-specific production data (see supplementary materials is available online at stacks.iop.org/ERL/14/114001/mmedia). To quantify the sustainability of irrigation water consumption in year 2015, we assumed that the variation in irrigation water consumption between years 2000 and 2015 is proportional to country-specific sustainable and unsustainable irrigation expansion potentials. For example, if a country increases irrigation water consumption but has no potential to do so sustainably, all the additional irrigation volumes are assumed to be consumed unsustainably (at the expenses of environmental flows and surface- and ground-water stocks). Country specific values of the sustainability and unsustainability of irrigation expansion were taken from Rosa *et al* (2018a). Crop-specific production in years

2000 and 2015 were taken from FAO's FAOSTAT database (see section: Assessment of unsustainable virtual water trade). Agricultural water withdrawals in years 2000 and 2015 were taken from FAO's AQUASTAT database.

To determine total blue water consumption (WC) in each grid cell, crop-specific irrigation water consumption values were summed with municipal and industrial water consumption estimates (for the 1996–2005 period) (Hoekstra and Mekonnen 2012). By combining total blue water consumption and renewable blue water availability (WA) we assessed unsustainable irrigation practices. We identified areas of unsustainable irrigation water consumption as those where local renewable blue water resources are less than local total water blue consumption ($WC > WA$). This methodology to evaluate water sustainability has been extensively validated in studies aiming at analyzing the influence of energy and agricultural production on water resources (Rosa *et al* 2018a, 2018b, Rosa and D'Odorico 2019). Renewable blue water availability (30×30 arcminute resolution, or ~ 50 km at the Equator) was assessed following Mekonnen and Hoekstra (2016) and was calculated as the difference between blue water flows generated in that grid cell and environmental flow requirements. Renewable blue water availability accounts for surface- and ground-water volumes that are replenished through the annual hydrological cycle (Rosa *et al* 2018a, 2018b). This methodology explicitly links irrigation water consumption to unsustainable irrigation practices. Long term (circa year 2000) blue water flows were assessed from local runoff estimates (Fekete *et al* 2002) and were calculated using the upstream-downstream routing 'flow accumulation' function in ArcGIS[®]. Total blue water consumption (WC) at a 5×5 arcminute resolution was aggregated to the 30×30 arcminute resolution of the global available water (WA) dataset. Following previous global analyses we assumed that 80% of annual blue water flows should be allocated for environmental flows preservation (i.e. remain unavailable to human consumption) (Richter *et al* 2012, Mekonnen and Hoekstra 2016, Flörke *et al* 2018).

We considered 26 crop classes or 130 primary crops (or nearly 100% of global crop production) (wheat, maize, rice, barley, rye, millet, sorghum, soybeans, sunflower, potatoes, cassava, sugar cane, sugar beets, oil palm, rapeseed, groundnut, cassava, groundnuts, pulses, citrus, date palm, grapes, cotton, cocoa, coffee, other perennials, fodder grasses, other annual) based on the MIRCA2000 dataset (Portmann *et al* 2010) (supplementary materials). Crop classes 'other annual' and 'other perennials' are labeled as 'Fruits & Vegetables' in figures 2 and 3. 'Sugar Crops' include 'sugar beet' and 'sugar cane'; 'Other Grains' considers aggregated values of 'barley', 'rye', 'millet', and 'sorghum'. Water consumption from industrial and domestic sectors were taken from

Hoekstra and Mekonnen (2012) and were assumed to be constant between year 2000 and 2015. Possible inaccuracies in water consumption estimates for domestic and industrial uses are difficult to evaluate with the available data, however, they are expected to have limited impacts on our results. In fact, water consumption from industrial and domestic sectors accounts for just $\sim 7\%$ of total water consumption. Moreover, previous global studies of irrigation water consumption provided estimates that range from 847 to 1180 km³ (Siebert *et al* 2010, Hoekstra and Mekonnen 2012). This range of uncertainty, by far, exceeds total water consumption from the domestic and industrial sectors (80 km³; Hoekstra and Mekonnen 2012).

Assessment of unsustainable virtual water trade

We used international trade matrices and national production data (FAOSTAT) (<http://fao.org/faostat/en/#data>) for 302 food commodities to assess the trade T of a food commodity x from a country y to z in year n (2000 and 2015) noted as $T(y, z, x, n)$. Because international trade and national crop production are dynamic and vary year by year, for international trade and national production data we used a five-year average around years 2000 and 2015 to smooth out this variability. For trade matrix data we used FAO's import data, because import reporting is more reliable than export reporting owing to custom reports at the port of entry. Import data are expected to be more accurate, because customs have an incentive to collect data for tax purposes. Exports data are generally poorer, as very few countries tax exports. Moreover, the variation between import and export data of the FAO's dataset has a relatively small effect on the quantification of virtual water flows. Because FAOSTAT's trade data are at the country and annual scales, our analysis is performed at annual and country levels.

We aggregated international trade matrices and national production data for 302 food commodities x into their 130 primary crops c dividing the quantity of produced or traded commodity $R(x)$ by its primary product extraction rate E_x :

$$\sum_{x \in c} \frac{R(x)}{E_x}.$$

E_x was taken from FAO's technical conversion factors for agricultural commodities (<http://fao.org/fileadmin/templates/ess/documents/methodology/tcf.pdf>) (supplementary materials), and $R(x)$ is the quantity of produced or traded commodity x , and c is the set of commodities based on the same primary crop. Primary product extraction rate (E_x) is the fraction of the processed product obtained from the processing of the primary product. For example, FAOSTAT's commodities 'sunflower seed', 'sunflower oil', and 'sunflower cake' are based on the primary crop 'sunflower' and they have an extraction rate E equal to 1, 0.47, 0.49, respectively. To assess

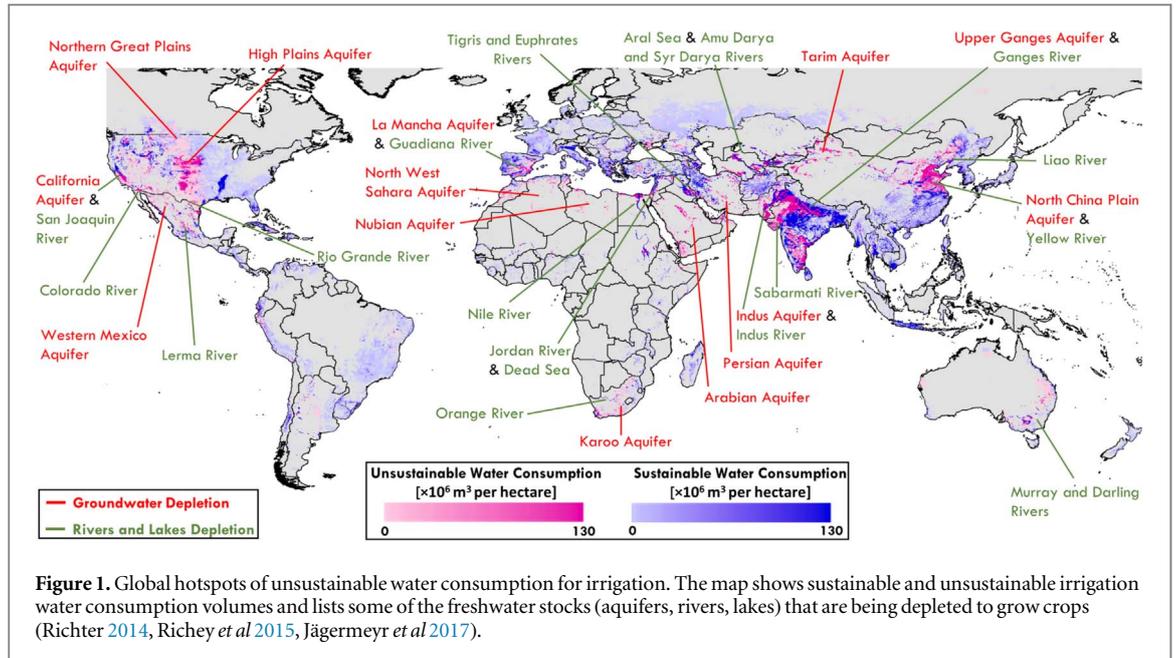


Figure 1. Global hotspots of unsustainable water consumption for irrigation. The map shows sustainable and unsustainable irrigation water consumption volumes and lists some of the freshwater stocks (aquifers, rivers, lakes) that are being depleted to grow crops (Richter 2014, Richey *et al* 2015, Jägermeyr *et al* 2017).

production and trade of the primary crop ‘sunflower’ we divided each commodity by its extraction rate and summed the results to obtain aggregated international trade matrices and national production data for sunflower in year n . The international trade matrices of the 130 primary crops were then aggregated into the 26 MIRCA2000 crop classes (M) to obtain trade fluxes T from a country y to z in year n of crop class M , $T(y, z, M, n)$. The same procedure was followed for FAO-STAT’s production data to obtain production data P of country y in year n of crop class M , $P(y, M, n)$. Crop-specific primary product extraction rates are kept constant among countries.

We then assessed unsustainable irrigation water consumption intensity ($UWCI$) of each MIRCA2000 crop class (M) in each country (y) and year (n), as follows:

$$UWCI_{(y,M,n)} = \frac{UWC_{(y,M,n)}}{P_{(y,M,n)}}$$

where UWC is the unsustainable irrigation water consumption of crops in class M , country y , and year n (expressed in m^3 of water). UWC has been assessed by aggregating irrigation blue water consumption (WC) at the country level. P is the aggregated production (expressed in tons) of crops belonging to class M in country y and year n .

We then used $UWCI$ to convert the trade fluxes T (expressed in tons) into unsustainable virtual water flows (expressed in m^3):

$$UWCT_{(y,z,M,n)} = UWCI_{(y,M,n)} \times T_{(y,z,M,n)}$$

where the trade T of a food commodity x from a country y to z in year n (2000 or 2015) is noted as $T(y, z, x, n)$.

Results

The unsustainability of irrigation

We find that 52% (569 km^3) of global irrigation practices are unsustainable because they deplete freshwater stocks and/or environmental flows (figure 1). About 70% of the global unsustainable water consumption for irrigation (hereunder UWC) is contributed by India (28%), China (16%), Pakistan (13%), and the United States (12%) alone (figure 2(a)). In many countries a big share of irrigation water consumption is unsustainable (supplementary figure 1) as in the case of India (54% of national irrigation water consumption or 157 $km^3 yr^{-1}$), China (66% or 91 $km^3 yr^{-1}$), Pakistan (61% or 71 $km^3 yr^{-1}$), and the United States (62% or 69 $km^3 yr^{-1}$).

The impact of agriculture on UWC strongly varies with crop type and geographic location with wheat, maize, rice, cotton, and fruits and vegetables collectively contributing to 73% (or 417 $km^3 yr^{-1}$) of global UWC (figure 3). While in India and Pakistan, wheat is the major contributor to UWC (32% and 38%, respectively), in China most of the UWC is from rice (33%) and in the United States from maize (29%) (figure 2(b)).

UWC increased by 8% in fifteen years, from 525 km^3 in year 2000, to 569 km^3 in 2015 (figure 2(a)), mostly because of irrigation expansion in India (+32 km^3), Pakistan (+6 km^3), Mexico (+2.5 km^3), China (+1.9 km^3), South Africa (+1.7 km^3), and Spain (+1.1 km^3). At the same time, UWC decreased in the United States (−7.2 km^3), Uzbekistan (−1.9 km^3), and Australia (−1.8 km^3). In this period, most of the increase in global UWC was contributed by irrigation expansion for maize (+23 km^3), wheat (+10 km^3), and cotton (+7 km^3) production, while most of the decrease in global UWC practices was from fodder

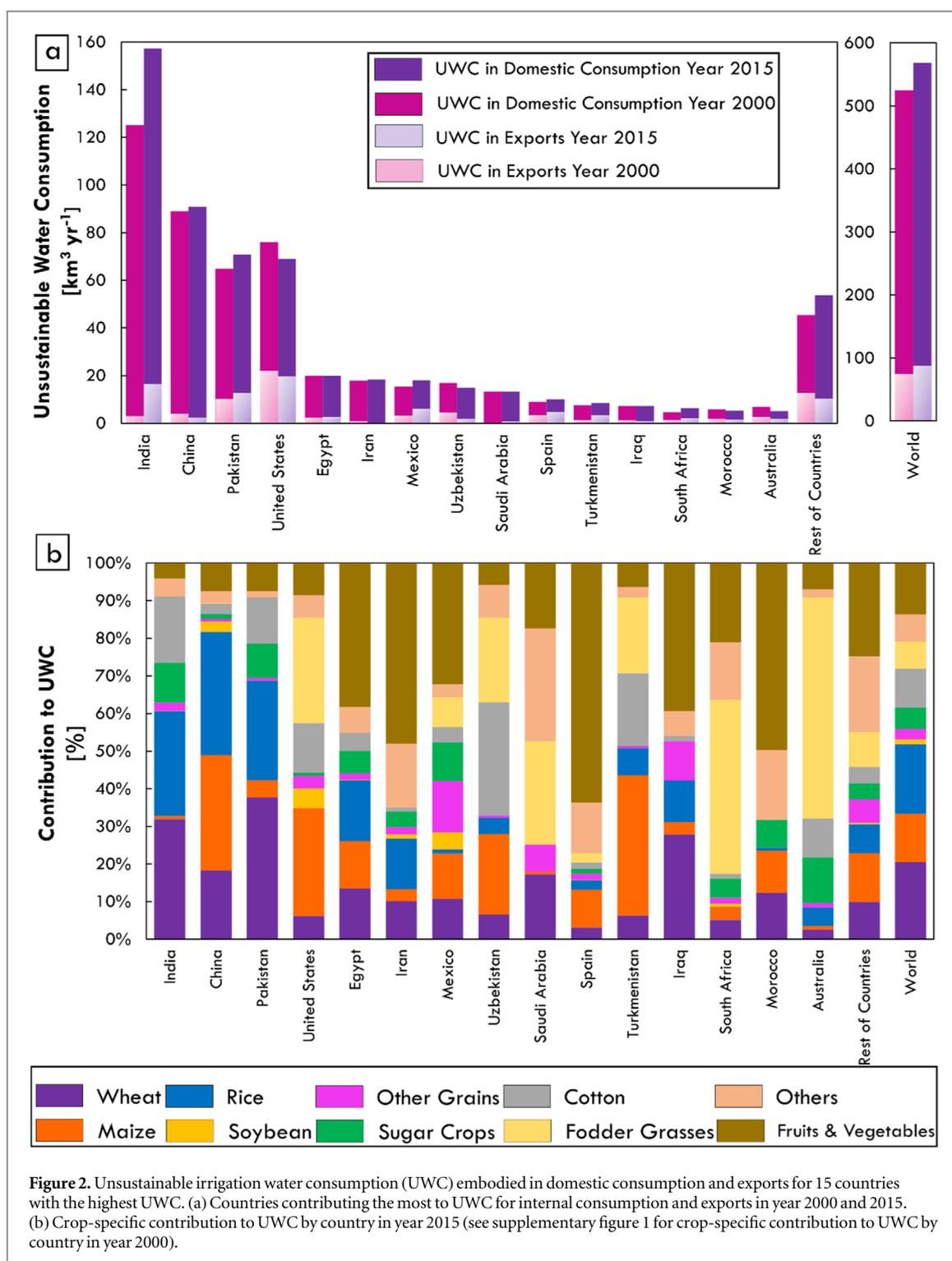


Figure 2. Unustainable irrigation water consumption (UWC) embodied in domestic consumption and exports for 15 countries with the highest UWC. (a) Countries contributing the most to UWC for internal consumption and exports in year 2000 and 2015. (b) Crop-specific contribution to UWC by country in year 2015 (see supplementary figure 1 for crop-specific contribution to UWC by country in year 2000).

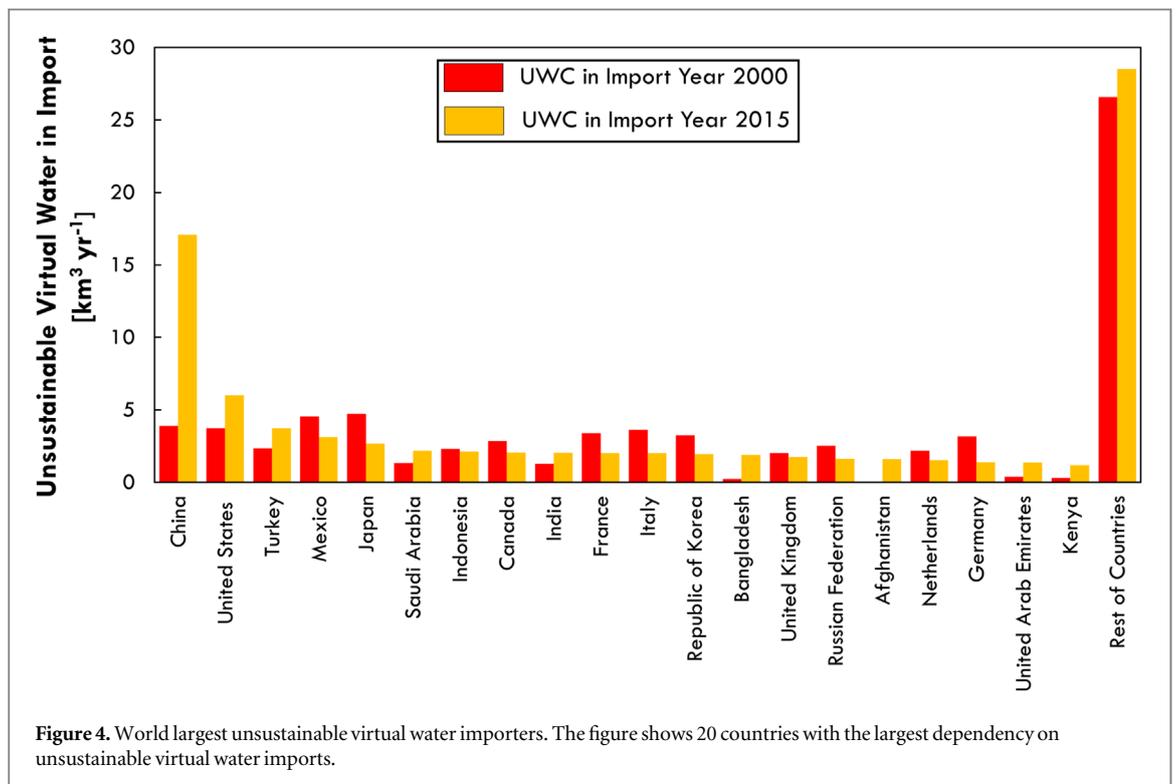
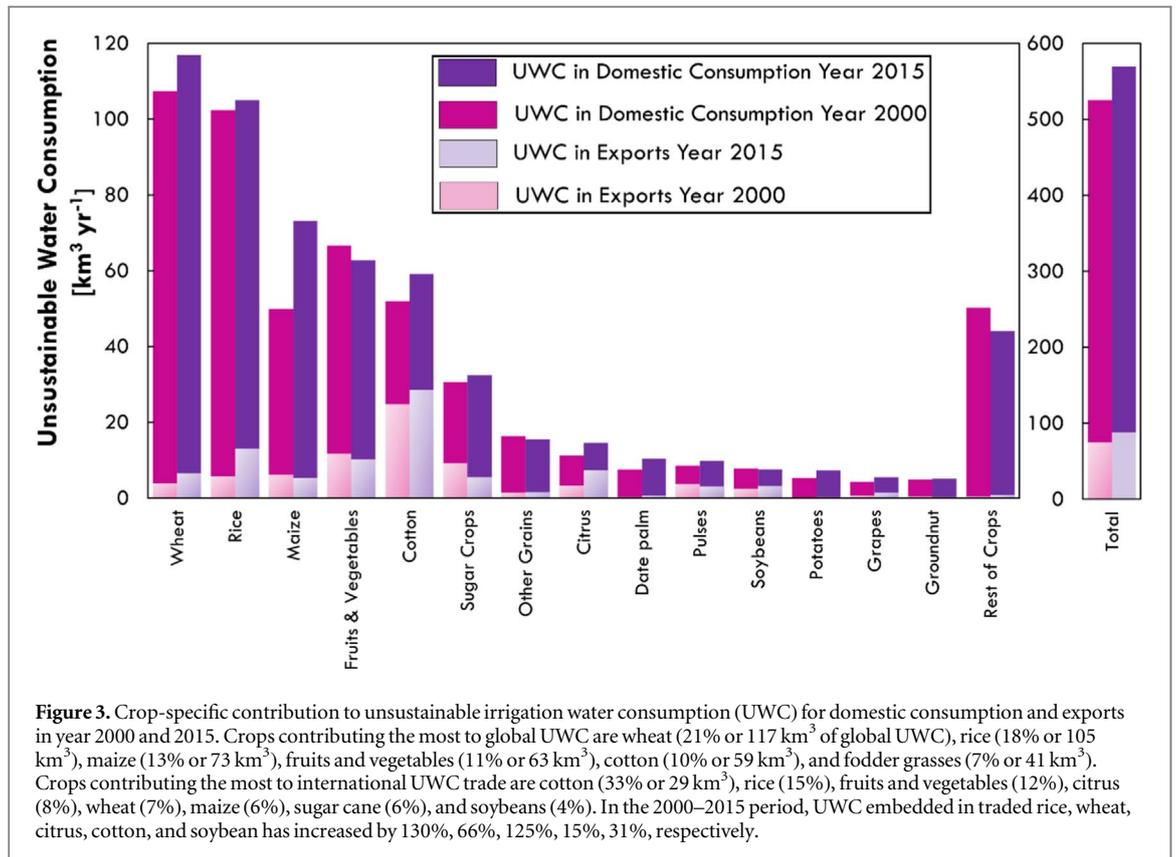
grasses (-7.1 km^3), fruits and vegetables (-3.84 km^3), and sorghum (-1.24 km^3) (figure 3).

Unsustainability embodied in international food trade

We find that 15% of global UWC (88 km^3) is embedded in international crop trade. In the 2000–2015 period, global unsustainable virtual water trade increased by 18%, from 75 to 88 km^3 (figure 2(a)), while the amount of food traded increased by 65%. Over this period, UWC in

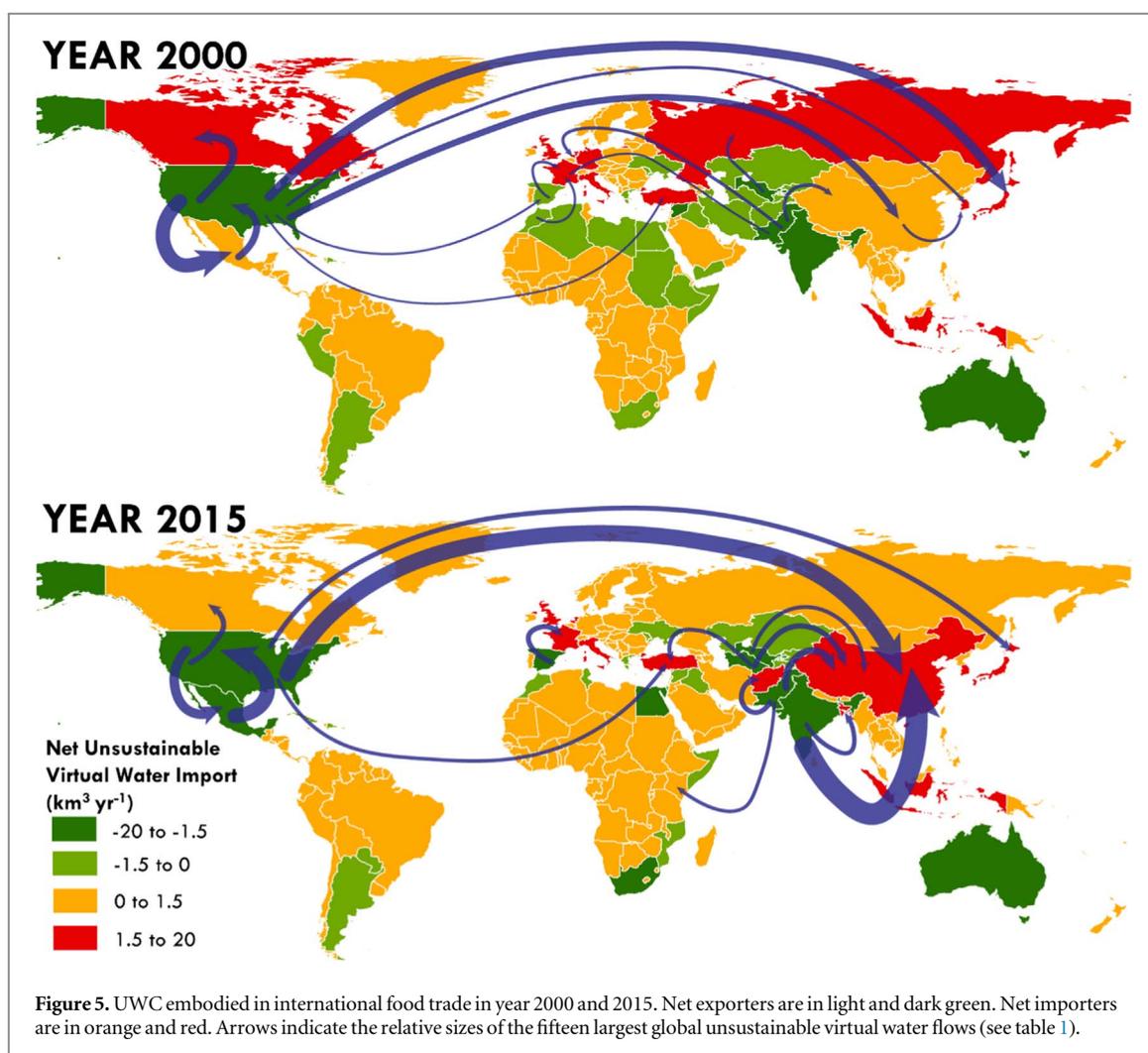
agricultural exports increased fourfold ($+13.4 \text{ km}^3$) for India, followed by a 25% increase for Pakistan, Egypt ($+9\%$), Mexico ($+89\%$), and Spain ($+42\%$). At the same time, the United States decreased their unsustainable exports of virtual water trade by 11% (-2.3 km^3), followed by China (-38%), Iran (-65%), and Uzbekistan (-61%).

In year 2015, the United States, India, Pakistan, Mexico, and Spain account for two thirds of UWC embodied in food trade. The United States is the largest exporter, with 22% (19.7 km^3) of global



unsustainable virtual water transfers, followed by India (19%), Pakistan (14%), Mexico (7%), and Spain (5%). China is the largest importer of UWC-based crops, followed by the United States, Turkey, Mexico and Japan (figure 4).

India, the United States, Pakistan, Spain, Turkmenistan, Egypt, Uzbekistan, and Australia consistently act as net exporters of UWC-based crops (figure 5), while Canada, United Kingdom, France, Germany, Italy, China, Turkey, Russia, and Indonesia act as net



importers of UWC-based crops. In the 2000–2015 period, Iran, Peru, Libya, Algeria, and Ethiopia have switched from being net exporters to net importers of unsustainable virtual water. Other countries such as Mexico, Tunisia, and Mozambique have become net exporters. Figure 5 also shows recent history of international food trade with the increasing presence of China as major importer, while it also shows the rise of India and Pakistan as major exporters of non-sustainable agricultural commodities.

In the United States 29% of the UWC is due to crops for export markets (figure 2(a)). India and Pakistan are the second and third largest exporters of UWC-based crop production, even though they keep 90% and 82% of UWC for domestic consumption, respectively. China is the world largest net importer of UWC-based crops (19% of the global virtual trade of UWC). Moreover, China keeps 97% (89 km³) of its UWC-based crops for domestic consumption.

In year 2015, 42% (8.2 km³) of the United States' unsustainable virtual water trade was embedded in cotton export mainly to China, Mexico, Canada, Japan, and Turkey (table 1 and figure 5). Maize and

soybeans accounted for 17% and 11% of the United States' unsustainable virtual water exports to China, Mexico, and Japan (table 1). India exported unsustainably produced cotton and rice to China and Bangladesh. Mexico is a major exporter of unsustainably produced citrus and fruits and vegetables to the United States. UWC embedded in rice production accounts for 70% of Pakistan's unsustainable virtual water exports, mainly to China, Afghanistan, and Kenya. Uzbekistan and Turkmenistan export unsustainably produced cotton to China and Turkey. Spain and Morocco are major exporters of fruits and vegetables to European countries.

Discussion

Virtual water trade is fundamental to achieve food security in water scarce regions of the world, however, it establishes a disconnection between consumers and the water resources they rely on. This ultimately leads to a loss of ecosystem stewardship (D'Odorico *et al* 2019) and the enhancement of environmental degradation associated with the drying of rivers and loss of

Table 1. Global largest unsustainable trade relationships in year 2000 and 2015. The table shows importers, exporters, volume of unsustainable virtual water traded (UWT) per trade link, and the main crops contributing to each unsustainable virtual water trade link.

YEAR 2000				
Rank	Importer	Exporter	UWT (km ³)	Crops mainly traded
1	Mexico	United States	4.5	Cotton (53%); Sorghum (16%); Maize (12%)
2	Japan	USA	2.9	Maize (38%); Cotton (16%); Wheat (10%)
3	Canada	USA	2.5	Cotton (36%); Other Annual (34%)
4	USA	Mexico	2.2	Cotton (62%); Sugar Cane (12%)
5	China	USA	2.0	Cotton (37%)
6	China	Pakistan	1.1	Cotton (47%); Sugar Cane (29%)
7	Netherlands	Pakistan	1.0	Sugar Cane (91%)
8	South Korea	USA	0.9	Maize (32%); Cotton (42%)
9	Russia	Uzbekistan	0.9	Cotton (96%)
10	South Korea	China	0.9	Maize (70%)
11	France	Spain	0.8	Fruits & Vegetables (40%); Citrus (42%)
12	France	Morocco	0.8	Fruits & Vegetables (80%)
13	France	Pakistan	0.7	Sugar Cane (67%); Cotton (30%)
14	Spain	USA	0.7	Cotton (27%); Maize (16%)
15	Turkey	USA	0.7	Cotton (66%); Maize (30%)
YEAR 2015				
1	China	India	6.9	Cotton (90%)
2	China	USA	5.2	Cotton (50%); Soybeans (20%)
3	USA	Mexico	4.6	Citrus (50%); Fruits and Vegetables (20%); Sugar Cane (13%)
4	Mexico	USA	3.0	Cotton (47%); Maize (20%)
5	China	Pakistan	2.1	Rice (68%); Cotton (17%)
6	China	Turkmenistan	1.7	Cotton (98%)
7	Canada	USA	1.7	Fruits & Vegetables (44%); Cotton (19%)
8	France	Spain	1.6	Citrus (26%); Fruits & Vegetables (20%)
9	Afghanistan	Pakistan	1.6	Wheat (36%); Rice (31%); Sugar Cane (26%)
10	Japan	USA	1.5	Maize (41%); Cotton (16%)
11	Bangladesh	India	1.4	Cotton (70%); Wheat (15%); Rice (12%)
12	Turkey	Turkmenistan	1.3	Cotton (100%)
13	China	Uzbekistan	1.3	Cotton (96%)
14	Turkey	USA	1.1	Cotton (94%)
15	Kenya	Pakistan	1.1	Rice (100%)

aquatic habitat (Soligno *et al* 2017, 2018). Research on the environmental impacts of trade and trade policies (Peters *et al* 2011, Zhang *et al* 2017) suggests that production is expected to shift to regions of the world with weaker environmental regulations (Dean *et al* 2009). In the case of agricultural production and trade, however, the focus has often been on environmental pollution, land use change, and labor rights, while the environmental impacts of unsustainable irrigation and their displacement through trade have remained poorly understood and have just started to be recognized and quantified.

Our results shed light on crops, country, and trade relationships that rely on unsustainable irrigation practices in production and consumption. More than 30% of unsustainable irrigation practices of Mexico, Spain, Turkmenistan, South Africa, Morocco, and Australia are embedded in food exports, while, in India, China, Iran, and Saudi Arabia 90% of unsustainable irrigation volumes are embodied in domestic food consumption. We also find that 60% (53 km³) of global unsustainable virtual water trade is driven by cash crops (cotton, sugar cane, fruits and vegetables).

In particular, cotton alone is responsible for 33% of UWC embedded in international crop trade. These findings show important trade-offs between the economic benefits and the environmental consequences of unsustainable irrigation practices.

Not surprisingly, the fact that only 30% of the increase in virtual water trade (in the 2000–2015 period) is contributed by unsustainable irrigation, confirms previous studies that quantified the increasing reliance of international markets on cropland expansion and rain-fed agriculture, including soybean production in Brazil and Argentina, and oil palm production in Indonesia and Malaysia (Aldaya *et al* 2010, D’Odorico *et al* 2019).

This study improves our previous assessment of unsustainable irrigation water consumption (Rosa *et al* 2018a), where we found that in year 2000 about 40% (336 km³) of global irrigation was unsustainable, based on 16 major crops that account for 70% of global crop production. Here, we considered 130 primary crops (or nearly 100% of global crop production) and found that 51% (525 km³) of global irrigation volumes are unsustainable. Moreover, here we also provide

crop-specific and country-specific analyses of unsustainable irrigation and evaluate extent to which it is contributed by international trade.

Uncertainty, limitations, and assumptions

The complexity of a global analysis often requires the adoption of suitable assumptions. We used a well-established methodology to assess irrigation water consumption based on existing maps of irrigated areas for the year 2000 (Siebert *et al* 2010). However, it is important to note that the estimation of irrigated areas would change significantly using different input data and statistics (Meier *et al* 2018). Because, to our knowledge, there are not global datasets providing crop-specific irrigated harvested areas after year 2000, we used country-scale statistics to assess irrigation water consumption in year 2015. While this is a limit of global studies aiming at an assessment of irrigation water consumption, our results are in good agreement with recent country-specific changes in irrigation water consumption as available for Australia (-1.3 km^3 from 2000 to 2015) (Australian Bureau of Statistic 2018), and India ($+26 \text{ km}^3$ from 2000 to 2009) (Davis *et al* 2018).

Our assessment is based on temporal averages and does not account for inter-annual variability in river discharge and crop water requirements. We performed a sensitivity analysis of irrigation water consumption with respect to changes in climate conditions between 2000 and 2015. We run our crop water model with year 2015 climate forcing, while keeping the same spatial extent of irrigated area as in the MIRCA2000 dataset. We find that there is little sensitivity of irrigation water consumption between the two years (1025 km^3 for year 2000 versus 1035 km^3 for year 2015) (see supplementary table 4 for crop-specific values).

Because fodder grasses (Alfalfa, clover, and grasses) are not present in FAOSTAT's trade data, we excluded them from our unsustainable virtual water trade analysis. It is important to notice that fodder grasses are mainly used for domestic consumption as feed to livestock and therefore they are not commonly traded among countries. Nevertheless, we find that fodder grasses account for 7% of global unsustainable irrigation water consumption (figure 2(b)).

Our results show little sensitivity to different environmental flow thresholds, as previously highlighted also by Mekonnen and Hoekstra (2016). With the current assumption that 80% of blue water flows should be allocated to environmental flows preservation, we find that, in year 2000, 51% (525 km^3) of global irrigation water consumption is unsustainable. When we assume that environmental flows account for 90% and 60% of blue water flows, unsustainable irrigation water consumption in the same year becomes 536 km^3 and 523 km^3 , respectively (see supplementary table 5 for crop-specific results).

As already stressed by Mekonnen and Hoekstra (2016), this low sensitivity to the threshold used to define environmental flows is due to the huge spatio-temporal mismatch between water consumption and availability.

Conclusions

Policymakers and major corporations are broadening the scope of their actions to meet the increasing consumer demand for sustainable commodities and improve corporate social responsibility. For example, there has been a recent commitment to purchase or produce deforestation-free products (Carlson *et al* 2018, Curtis *et al* 2018). In an increasingly water scarce world, governments could take specific actions targeting unsustainable irrigation practices by penalizing the associated imports. By identifying the producing and consuming countries that are responsible for unsustainable virtual water trade, this study highlights trade links in which policies are needed to achieve sustainable water and food security goals in the coming decades. Future studies should examine socio-economic implications, such as the feasibility to reduce unsustainable virtual water trade through the adoption of adequate policies.

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Data availability

The data that support the findings of this study are openly available at <https://doi.org/10.5281/zenodo.2593800>. The Mathematica code to process trade and production data, crop- and country-specific unsustainable virtual water flows for year 2000 and year 2015, and crop- and country-specific sustainable and unsustainable irrigation water consumption are available online at: <https://doi.org/10.5281/zenodo.2593800>.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

L R and P D conceived the study; L R and P D designed the research; L R performed the research, and analyzed

the data; D D C and M C R carried out the simulation to assess irrigation water requirements; C T processed crop trade and production data; and L R wrote the paper with inputs from all authors.

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