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LETTER

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Groundwater depletion embedded in international food trade

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Recent hydrological modelling[1] and Earth observations[2,3] have located and quantified alarming rates of groundwater depletion worldwide. This depletion is primarily due to water withdrawals for irrigation[1,2,4], but its connection with the main driver of irrigation, global food consumption, has not yet been explored. Here we show that approximately eleven per cent of non-renewable groundwater use for irrigation is embedded in international food trade, of which two-thirds are exported by Pakistan, the USA and India alone. Our quantification of groundwater depletion embedded in the world's food trade is based on a combination of global, crop-specific estimates of non-renewable groundwater abstraction and international food trade data. A vast majority of the world's population lives in countries sourcing nearly all their staple crop imports from partners who deplete groundwater to produce these crops, highlighting risks for global food and water security. Some countries, such as the USA, Mexico, Iran and China, are particularly exposed to these risks because they both produce and import food irrigated from rapidly depleting aquifers. Our results could help to improve the sustainability of global food production and groundwater resource management by identifying priority regions and agricultural products at risk as well as the end consumers of these products.

Excessive abstraction of groundwater for irrigation is leading to rapid depletion of aquifers in key food-producing regions around the world (such as north-western India, the North China Plain, the central USA and California[3,5]). This depletion of the largest liquid freshwater stock on Earth threatens the sustainability of food production, and water and food security, not only locally[3,5], but also globally via international food trade. Aquifer depletion can also induce significant environmental degradation, such as land subsidence and seawater intrusion[6,7]. The globalized dimension of groundwater depletion is poorly understood because of the lack of research integrating crop water use, groundwater depletion and international food trade.

Studies of water resources embedded in food trade[8–11]— virtual water trade—have sometimes distinguished between blue water (surface water and groundwater) and green water (soil moisture) sources[12,13], which can provide additional information on the potential environmental impact of their use. More recently, indicators of water scarcity have been introduced[14], which help to evaluate the sustainability of global food supply. However, although the need to integrate recent evaluations of groundwater abstraction with virtual water trade and water footprint (embedded water) techniques has been highlighted[15], groundwater use, and in particular groundwater depletion for irrigation (GWD), has not been accounted for in global virtual water trade analyses.

Here, we aim to fill this crucial gap in the quantification of the water sustainability of global agriculture and food trade. To do so, we estimate the amount of GWD embedded in the world's food production and international food trade. GWD is defined as the volume of

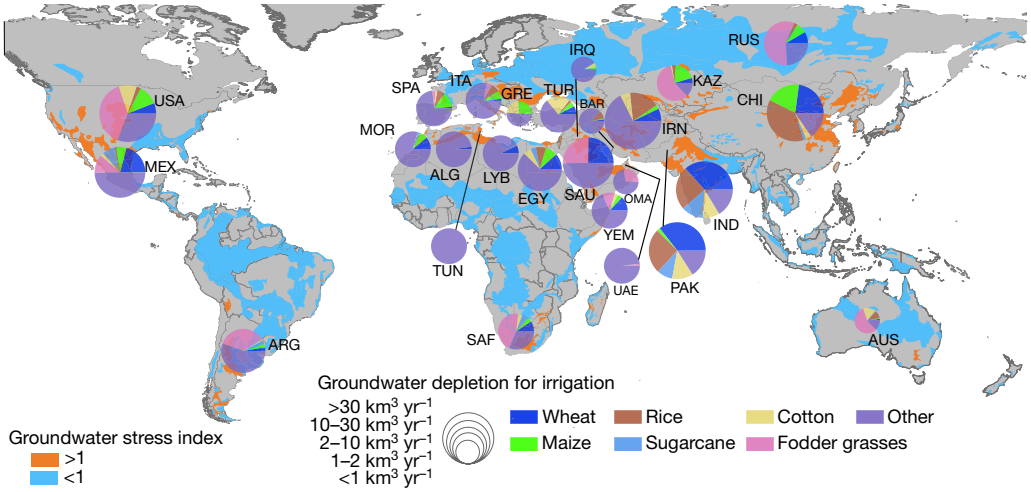

Figure 1 | Crop-specific contribution to groundwater depletion worldwide in 2010. The pie charts show fractions of groundwater depletion for irrigation (GWD) of major crops by country, and their sizes indicate total GWD volume. The background map shows groundwater stress index (corresponding to overexploitation when larger than one) of major aquifers[15]. Some countries have overexploited aquifers but no pie chart is shown because groundwater use is not primarily related to irrigation.

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Table 1 | Groundwater depletion embedded in food production and trade for the ten countries with the most domestic GWD

Year	Rank	Name	GWD in production ($km^3\ yr^{-1}$)	Fraction of global GWD (%)	GWD in imports ($km^3\ yr^{-1}$)	Fraction of GWD in national consumption (%)	GWD in exports ($km^3\ yr^{-1}$)	Fraction of GWD in national production (%)
2010								
	1	India	73.5	33.9	0.2	0.3	3.0	4.0
	2	Iran	33.3	15.4	1.4	4.2	1.2	3.5
	3	Pakistan	27.5	12.7	0.2	1.2	7.3	26.4
	4	China	24.0	11.1	2.2	8.5	0.3	1.1
	5	USA	16.2	7.5	1.7	15.3	6.9	42.4
	6	Saudi Arabia	12.5	5.7	0.8	6.0	0.4	3.5
	7	Mexico	11.1	5.1	1.0	10.6	2.5	22.6
	8	Libya	2.5	1.1	0.1	2.4	0	0.1
	9	Turkey	2.0	0.9	0.5	22.6	0.4	18.0
	10	Italy	2.0	0.9	0.5	27.9	0.8	39.2
		Total top ten	204.6	84.8	8.6	4.5	22.8	11.1
		Total world	241.4	100	25.6	NA	25.6	NA
2000								
	1	India	58.9	33.0	0.8	1.4	1.5	2.6
	2	Iran	28.4	15.9	0.3	1.1	2.2	7.7
	3	Pakistan	23.9	13.4	0.3	1.4	4.3	18.1
	4	Saudi Arabia	13.6	7.6	0.5	3.3	0.3	2.1
	5	USA	12.9	7.2	0.9	9.8	4.4	33.9
	6	China	11.8	6.6	0.8	6.7	0.3	2.6
	7	Mexico	11.4	6.4	0.9	8.2	1.6	14.2
	8	Libya	2.7	1.5	0	1.3	0.1	2.5
	9	Turkey	1.6	0.9	0.3	16.1	0.3	15.7
	10	Bulgaria	1.5	0.8	0	1.1	0.3	18.7
		Total top ten	166.7	85.6	4.8	3.1	15.3	9.2
		Total world	194.7	100	17.7	NA	17.7	NA

Groundwater depletion (GWD) for irrigation embedded in national food production, imported and exported GWD, and corresponding fractions of GWD in global food production, national food consumption and national food production, respectively, in the years 2000 and 2010. We also show totals for these ten countries and for the world. NA, not applicable.

groundwater that is abstracted for irrigation use in excess of the natural recharge rate and irrigation return flow[5], accounting for environmental flow requirements, and thus corresponds to an unsustainable use of groundwater for crop production. We combine global crop production data (FAOSTAT; http://www.fao.org/faostat/en/#data/QC) with crop-specific estimates of GWD (using the PCR-GLOBWB model[1,5]) for 26 crop classes in the years 2000 and 2010 to obtain GWD intensities for each commodity–country pair (see equation (1) in the Methods). We then multiply the bilateral trade flows (FAOSTAT; http://www.fao.org/faostat/en/#data/TM) of 360 crop commodities by the GWD intensity of each commodity in the country of export to obtain the GWD volume embedded in trade (see equation (2) in the Methods). Importantly, we apply an origin-tracing algorithm[16] to identify export flows from intermediary countries and assign them to the original country of production (see Methods). We identify the countries and crops contributing to global GWD, highlight key exporters and end-consumers of these crops irrigated from overexploited aquifers, and point out associated risks for local and global food and water security.

Global GWD has increased by 22% in ten years, from 240 km^3 in 2000, when it sustained 20% of the world's irrigation[5], to 292 km^3 in 2010. Over this period, global GWD has increased mostly owing to rises in India (23%), China (102%) and the USA (31%, Figs 1 and 2). The commodities analysed here (excluding non-traded ones) account for 241 km^3 of GWD (83% of the total) in 2010. Most GWD is concentrated in a few regions that rely significantly on overexploited aquifers to grow crops, mainly the USA, Mexico, the Middle East and North Africa, India, Pakistan and China (Figs 1 and 2 and Table 1), including almost all the major breadbaskets and population centres of the planet. The crops leading to the most depletion globally in 2010, both because of their large production and high GWD intensity, are wheat (22% of global GWD, or 65 $km^3\ yr^{-1}$), rice (17%), sugar crops (7%), cotton (7%) and maize (5%). India and Pakistan use the largest volumes of GWD (30% and 11% of global GWD, respectively, Fig. 1, Table 1). India has the largest GWD for wheat and rice (31.3 $km^3\ yr^{-1}$ and 21.3 $km^3\ yr^{-1}$, respectively), and China and the USA dominate GWD for maize (4.7 $km^3\ yr^{-1}$ and 3.0 $km^3\ yr^{-1}$, respectively).

We observe important differences in GWD intensity across regions and crop classes (Supplementary Table 1). On average (in countries with GWD), wheat, rice and maize are produced using 812, 199 and 72 litres of GWD per kilogram of crop, respectively. High extremes are found in Kuwait (21,900 litres per kilogram of wheat), Iran (2,100 litres per kilogram of rice) and Saudi Arabia (790 litres per kilogram of maize).

The countries irrigating crops from overexploited aquifers export them in various proportions (Table 1). India keeps most of its large GWD-based crop production for domestic use (only 4% of GWD exported), while the USA, Pakistan and Mexico export significant portions of their GWD-based crop production (42%, 26% and 23%, respectively; Table 1). The exports of Pakistan, the USA and India alone account for more than two-thirds of all GWD embedded in food trade (Extended Data Table 3). Pakistan is the largest exporter, with 29% of the global GWD trade volume, followed by the USA (27%) and India (12%; Fig. 3 and Table 1).

Globally, about 11% of GWD (25 $km^3\ yr^{-1}$) is embedded in international crop trade, while 18% of global crop production is traded internationally. This difference could be due to either crops with relatively smaller GWD intensity being more traded than others, or countries with relatively less GWD exporting more than other countries.

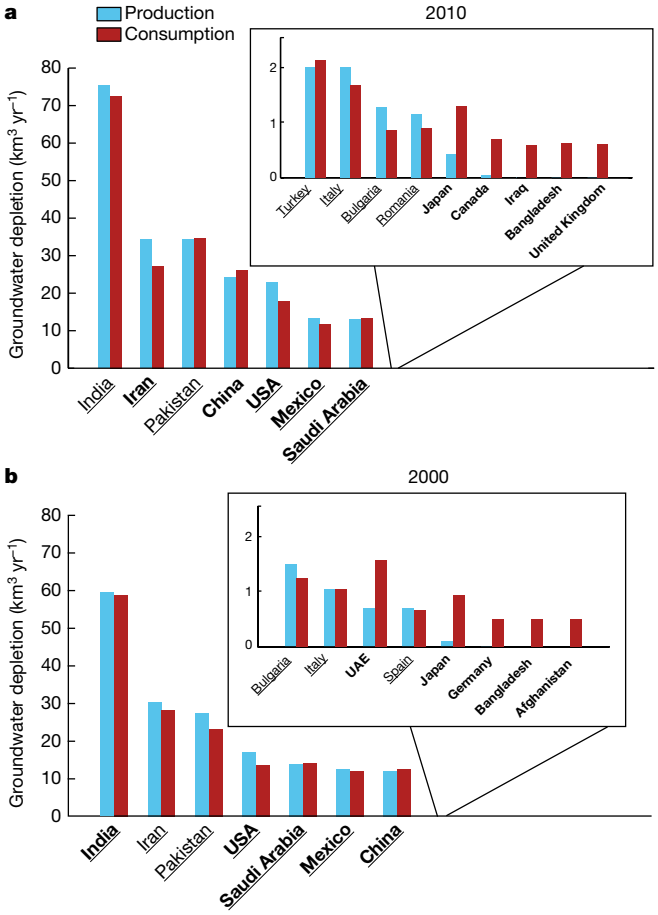

Figure 2 | Groundwater depletion associated with national crop production and consumption of major traders. a, 2010. **b**, 2000. The top ten importers of GWD are shown in bold font and the top ten exporters of GWD are underlined.

Individual crops contributing most to global GWD transfers are rice (29%), followed by wheat (12%), cotton (11%), maize (4%) and soybeans (3%). Citrus crops and sugar crops account for 5% of GWD transfers each. The majority of Pakistan's GWD exports are embedded in rice (82%), mostly to Iran (about 14%), Saudi Arabia, Bangladesh and Kenya. The USA's exports to its three main partners (China, Mexico and Japan) are much more diverse than Pakistan's, with the dominant commodity being cotton (24% of GWD exports), followed by wheat (16%), maize (10%) and soybeans (9%). Even though most of India's GWD is for domestic consumption, India is still the third-largest GWD exporter (Table 1), primarily via rice (25%) and cotton (24%), mainly to China. Although soybean exports from the USA to China, which have grown quickly owing to feed demand in China, have been highlighted as water-efficient[11,17], we find that they nevertheless induce 65% of GWD for soybean in the USA. This highlights the importance of including water sustainability and not just water productivity in virtual water trade analysis.

The major importers of GWD via crops include China (9% of global GWD trade), the USA, Iran, Mexico, Japan, Saudi Arabia, Canada, Bangladesh, the UK and Iraq (Fig. 3, Extended Data Table 3). The vast majority of China's GWD imports (about 47% cotton and 14% soybeans) originate from the USA and India. Japan also imports significant GWD from the USA (about 23% maize and 17% wheat).

When considering exports per capita, Israel and Moldova replace India and Turkey among the ten largest GWD exporters (Extended Data Fig. 2 and Extended Data Table 4). Five countries in the Middle East are among the top ten importers of GWD per capita (40–150 m^3 per capita per year, Extended Data Fig. 3 and Extended Data Table 5), highlighting the important dependence of this region on non-renewable groundwater for food imports.

Countries exporting GWD-based food (such as the USA, Pakistan, Italy and Mexico) may benefit in terms of trade, but this may not be viable in the long term owing to the unsustainable use of the aquifers currently supporting these exports. Importers, while saving domestic water, may be exposed to sustainability risk in their food supply, and could share some of the responsibility for the environmental damage and reduced water availability occurring in their trade partners. Importantly, some importers are also water scarce themselves, and may not be able to substitute imports with locally irrigated food. Along with supply-side adaptation, consumers of GWD-based products could also consider demand-side changes, such as reducing meat consumption or food waste[18,19].

Five of the ten countries with the most GWD—the USA, Mexico, Iran, Saudi Arabia and China—are also top importers of GWD via food trade (Fig. 2, Table 1 and Extended Data Table 3). These key countries import or export crops irrigated from the world's most stressed aquifer systems. The food production relying on these aquifers is particularly unsustainable as the extraction rates are 20 to 50 times higher than required for sustainable groundwater use[15]. For example, Iran mainly imports rice from Pakistan irrigated from the Upper Ganges and Lower Indus aquifers (overexploited by factors of 54.2 and 18.4, respectively) and exports perennial crops irrigated from the Persian aquifer (overexploitation factor 19.7) to neighbouring Iraq. Similarly, the USA imports about 1.5 times as much GWD from Mexico (mainly via citrus and sugar crops) as it exports there (mainly via cotton and maize, Fig. 3).

These regions are hotspots of water and food security risks related to GWD, as an exhaustion of these threatened aquifers would impact food supply both domestically and in their water-stressed trade partners. Furthermore, these risks are shared with many other countries via trade links. Indeed, we find that large parts of the world's population live in countries that source 90% or more of their staple crops imports from partners depleting groundwater to produce these crops: 89% of the population for sunflower seed, three quarters for maize, and a third for wheat and rice (Extended Data Table 6). Even though some countries with GWD use it for only a small part of their agricultural production, an exhaustion of currently overexploited aquifers represents a considerable risk for the global food supply, as it could also affect the imports of most of the world's population.

Projections of food demand (OECD-FAO; http://www.agri-outlook.org/) and water availability[20] suggest that GWD will continue to increase in the absence of targeted measures. Pakistan's rice exports have more than quadrupled from 1990 to 2010 and draw about a quarter of the country's GWD in 2010. Increasing rice demand abroad has probably played a considerable part in depleting Pakistan's aquifers, and accelerated depletion seems probable given projected population growth in both Pakistan (by 82% from 2010 to 2050) and its importing partner countries (such as Kenya, Bangladesh and Iran, by 137%, 33% and 25%, respectively; World Bank Databank, http://databank.worldbank.org/data/home.aspx).

GWD exports of top exporters have significantly increased from 2000 to 2010 (doubling in India, by 70% in Pakistan and 57% in the USA), and the largest increase in GWD imports occurred in China (tripling), mainly originating from the USA and India (Table 1, Figs 2 and 3 and Extended Data Fig. 1). Projected population growth in China until 2030, and changing diets requiring soybeans for animal feed[11], will probably further increase GWD for soybeans in the USA in the next decades. Surface water availability is expected to become more variable with climate change and the depletion of groundwater reserves will make it more difficult for agricultural regions to buffer these variations. Moreover, water availability is predicted to decline, particularly in northern Pakistan and Iran[20], regions which already rely on non-renewable groundwater for irrigation.

We note that although we have used state-of-the-art techniques for groundwater depletion estimates, which have been extensively

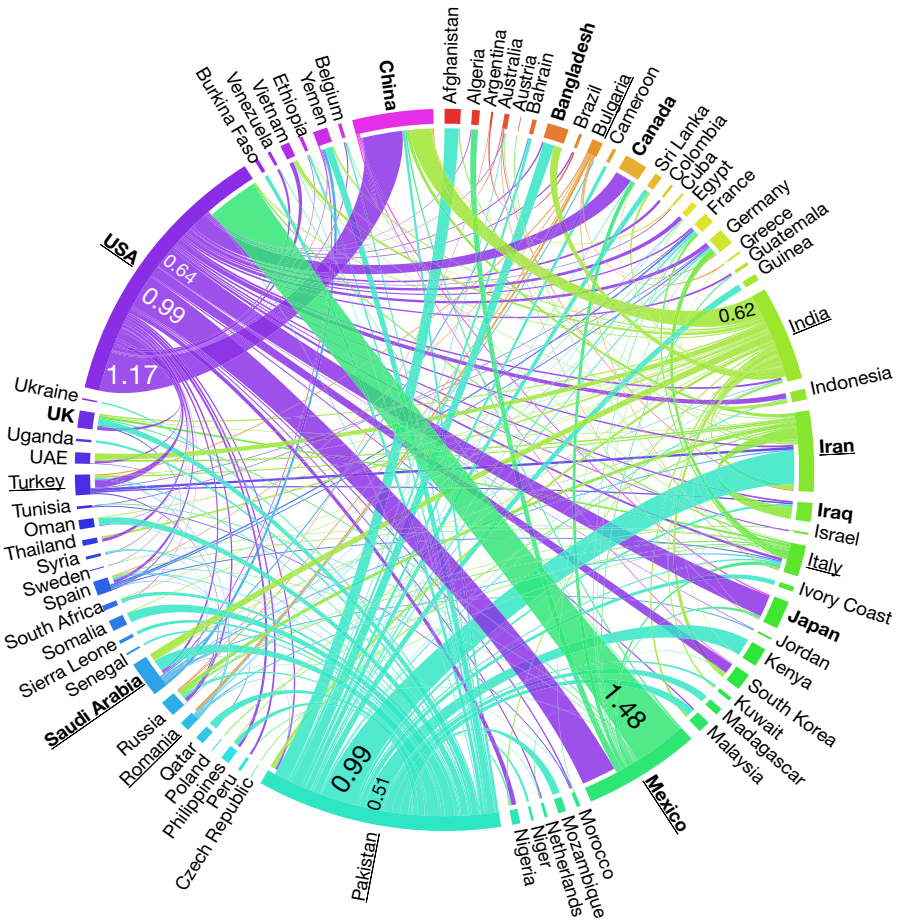

Figure 3 | Embedded groundwater depletion in international trade of crop commodities in 2010. Volumes are in units of cubic kilometres per year. The top ten importers are shown in bold font and the top ten exporters are underlined. Ribbon colours indicate the country of export. Note that, for clarity, we display only the links with a weight of at least 1% that of the largest link (that is, the top 1.8% links which account for 81% of total flow and involve 71 countries).

validated (see Methods), further work is required to reduce the associated uncertainties[1]. Besides, further modelling efforts are needed to project the exhaustion time of aquifers and establish trends based on future water supply and demand patterns.

Our results, which identify the regions, crops and trade relationships most reliant on overexploited aquifers, can help target efforts to improve the sustainability of water use and food production. Solutions to minimize GWD could include, in the producing countries, water-saving strategies[21] such as improving irrigation efficiency and growing more drought-resistant crops, together with targeted measures, such as metering and regulation of groundwater pumping. These policy efforts need to be further supported by local analysis that takes into account socio-economic, cultural and environmental aspects[22]. We also identify importing countries, which should support sustainable irrigation practices in their trade partners.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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Author Contributions C.D., Y.W. and M.J.P. designed the research. Y.W. carried out the simulation to estimate non-renewable groundwater abstraction per crop class. T.K., M.J.P. and C.D. processed the trade data. C.D. performed the analysis. C.D. wrote the paper with help from Y.W., M.J.P. and T.K.

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METHODS

Simulation of nonrenewable groundwater abstraction for crop water use. Water used by irrigated crops is obtained from three sources: local precipitation contributing to soil moisture available for root water uptake (green water), irrigation water taken from rivers, lakes, reservoirs, wetlands and renewable groundwater, and irrigation water abstracted from non-renewable groundwater[23].

Here, we explicitly quantify globally the amount of nonrenewable groundwater abstraction to sustain current irrigation practice (GWD) separately for 26 crop types based on the MIRCA2000 dataset[24], for years 2000 and 2010. Irrigated cropland areas from MIRCA2000 are scaled to year 2010 based on national irrigated cropland areas annual data (FAOSTAT; http://www.fao.org/faostat/en/#data/RL). We use a global hydrological and water resources model[1,5] to simulate crop water use for the 26 irrigated crop types, and available blue and green water to meet this demand at a 0.5° spatial resolution (about 50 km at the Equator). To distinguish non-renewable groundwater abstraction from renewable water sources, we keep track of the amount of groundwater pumped for each irrigated crop on the basis of crop growing areas and seasons, including multi-cropping practices and considering sub-grid variability of different crop types[5]. We subsequently compare this amount with simulated groundwater recharge to estimate non-renewable groundwater that is withdrawn for separate crops. We then obtain country-level groundwater depletion GWD(i, K, n) (in kilograms of water) per crop class K in each country i and year n by summing the gridded groundwater depletion per crop class over the grid cells within the country's boundaries. All model simulations by PCR-GLOBWB have been conducted at the 0.5 degree resolution, including groundwater depletion, groundwater recharge, and irrigation return flow. The results have then been aggregated to the country scale to match the trade data.

Note that groundwater recharge used in this calculation is based on a long-term average (1960–2010)[5,25], which reduces potentially large inter-annual variability. Besides, natural groundwater recharge from precipitation is averaged over each grid cell, but return flow from irrigation is simulated for separate crop areas of each grid cell. For example, higher return flow occurs from the rice-growing fraction of the grid cell compared to other crop-growing fractions (such as wheat and maize), owing to flooding irrigation practice. Irrigation return flow, that is, percolation losses from irrigation water supply, is constrained by the reported country-specific loss factor based on ref. 26, where different irrigation types (such as flooding irrigation, sprinklers and drip) and the associated conveyance and management loss factors are considered.

We also note that the global model used to estimate groundwater depletion has been extensively validated in earlier work. For example, simulated river discharge, total water storage, total water withdrawal and total consumptive water use, and surface and groundwater withdrawal have been validated against discharge station data from the Global Runoff Data Centre (more than 3000 stations), GRACE (NASA Gravity Recovery and Climate Experiment) satellite observations, and country statistics from FAO AQUASTAT, EUROSTAT, USGS (United States Geological Survey), Indian, Chinese, and Mexican national government statistics, respectively[1,5,25,27]. These comparisons show good agreement for river discharge and total water storage (R^2 greater than 0.8) for most of the catchments of the world. For water use, comparison with the reported value per country also shows a good agreement from 1970 to 2010, with R^2 being over 0.95. Although the correlations are high for most countries, deviations are relatively large (more than 20%) for several countries like Iraq, Lithuania, Puerto Rico, Mali, Djibouti and Bhutan. However, these countries have negligible groundwater depletion and the overall impact on GWD embedded in trade flows is thus very limited.

Estimated groundwater depletion has also been validated for over 30 regions and mostly compared well (R^2 about 0.8) with regional reported depletion values for areas including Northern India and Pakistan, North China Plains, High Plains Aquifer, Central Valley California, Arabian Peninsula, and Mexico[25].

Food production and trade data. We use detailed trade matrices data (FAOSTAT; http://www.fao.org/faostat/en/#data/TM) to calculate the trade T of a commodity c, from a country i to another country j in year n (2000 or 2010), noted $T(i, j, c, n)$. To smooth out annual variability in trade data, we use a three-year average around each year of interest. We note that the portion of production not exported internationally may be traded within the country's boundaries, but we do not focus on this here.

We first aggregate these trade matrices T for 360 commodities c (excluding those not present in trade data, mostly fodder crops, Extended Data Tables 1 and 2) into the primary crop equivalent of 130 primary crops (listed in Extended Data Table 1), using the following conversion factor based on the extraction rate R from FAO commodity trees[28]: $(1/R(c)) \times (R(c)/\sum_{c' \in branch} R(c'))$. The first term is based on the definition of the FAO extraction rate, where $R(c)$ is the FAO extraction rate for commodity c, and the second term avoids counting a primary crop twice (such as raw wheat) if two by-products in the same branch (such as wheat bran and wheat flour) originating from this primary crop are traded. We also include estimates of feed crops embodied in traded animal products[29]. The trade matrices obtained are noted $T_{pe}(i, j, c, n)$: trade from country i to j of commodities derived from primary crop c in year n, in primary crop equivalent.

Second, we correct trade flows by applying the origin-tracing algorithm developed in ref. 16. This is an important preliminary stage to the multiplication of trade flows by the water coefficient in the country of export. Some reported trade in the published FAOSTAT detailed trade matrices data (http://www.fao.org/faostat/en/#data/TM) can be re-exports (including after processing) of crops grown in a third country. This correction method aims to re-assign trade flows to the original country of production, addressing reported exports in excess of domestic production, based on production and trade data (FAOSTAT; http://www.fao.org/faostat/en/#data/QC and http://www.fao.org/faostat/en/#data/TM), so that the GWD intensity of the country of production is applied rather than that of an intermediary country.

A potential source of uncertainty in the trade data relates to differences in reports by importers and exporters for the same trade link. For instance, country A reports an import volume from country B different from that of the export volume reported by country B to country A. This can be due to actual factors such as shipments leaving and arriving in different years or being rerouted while at sea, but can also be due to differences in reporting quality among nations. To test how this uncertainty affects the overall outcome of our study, we performed the calculations with two different trade datasets: import–export and export–import.

In the first trade dataset, import–export, we use reported import data, with reported export data only used to fill data gaps. Assuming that imports reporting is more reliable than exports reporting owing to customs records at the port of entry, we present our main results based on this version. In the second trade dataset, export–import, we use the reported export data, with reported import data only used to fill data gaps. We find that the distributions of national GWD exports and imports obtained using import–export trade data are very similar to those obtained with export–import trade data (Extended Data Fig. 4). For top trading nations, we find that varying trade data has a relatively small effect on national GWD imports and exports: less than 15% variation (Extended Data Table 3), with the exceptions of Bulgaria's exports (41% or 0.19 km^3) in 2010, Iran's exports in 2000 (22% or 0.48 km^3) and India's imports in 2000 (57% or 0.45 km^3).

GWD intensity and GWD in trade. The groundwater depletion intensity (the GWD per unit crop) of each crop class in each country and year is obtained as follows:

$$\mathrm{GWC}(i, K, n) = \mathrm{GWD}(i, K, n) / \sum_{c \in K} P(i, c, n) \tag{1}$$

where GWC(i, K, n) is the groundwater depletion intensity (or 'content') of crops in class K, country i and year n (in kilograms of water per kilogram of crop); $P(i, c, n)$ is the production of raw commodity c in country i and year n (in kilograms of crop), obtained from FAOSTAT (http://www.fao.org/faostat/en/#data/QC); and GWD(i, K, n) is the non-renewable groundwater abstraction for irrigation of crops in class K, for country i and year n (in kilograms of water). We obtain the list of raw commodities (c) belonging to each of the 26 MIRCA crop classes by using the MIRCA list[24] and selecting the crops with extraction rate $R(c) = 1$. We then assume that, for country i and year n, each raw commodity in a class K (for example, lemon and orange in the citrus class) has a GWC equal to GWC(i, K, n).

The variability in GWD intensities across countries with GWD may be explained by two major factors: the crop's water productivity and the mix of rainfall and irrigation water sources. For example, Pakistan and India have relatively similar water use for rice (3,300 and 2,900 litres per kilogram, respectively[30]), but because India has more surface water resources, it uses eight times less GWD per unit rice than Pakistan (148 litres per kilogram versus 1,280 litres per kilogram; see Supplementary Table 1).

Then we use the GWC coefficient to convert trade flows into virtual water flows, as follows:

$$\mathrm{GWT}_{pe}(i, j, c, n) = \mathrm{GWC}(i, K, n) \times T_{pe}(i, j, c, n) \tag{2}$$

where $\mathrm{GWT}_{pe}(i, j, c, n)$ is the GWD embedded in trade from country i to j of commodities derived from primary crop c in year n (kilograms of water), $T_{pe}(i, j, c, n)$ is the trade from country i to j of commodities derived from primary crop c in primary crop equivalent (kilograms of crop) in year n, and K is the crop class to which primary crop c belongs. Finally, we obtain the GWD embedded in trade per crop class with the following sum: $\mathrm{GWT}_{pe}^{class}(i, j, K, n) = \sum_{c \in K} \mathrm{GWT}_{pe}(i, j, c, n)$.

Similarly, we calculate GWD embedded in production (GWP) by multiplying production by GWD intensity. We use food production data as three-year averages around 2000 and 2010 (FAOSTAT; http://www.fao.org/faostat/en/#data/QC), corresponding to the commodities belonging to the 26 crop classes represented in the groundwater estimates (see list in ref. 24).

We find that a smaller share of GWD associated with food production is traded, relative to the share of food production being traded, which can be explained by two phenomena. First, crops with relatively smaller GWD intensity may be more traded than others, or countries with relatively less GWD may be exporting more than other countries. The former is true for soybean, which is much more traded (61% of production) than more GWD-intense rice (6%); however, GWD-intense wheat is slightly more traded (25%) than average. The latter is directly illustrated with India, the country with most GWD, which exports only 7% of its cereal production, while France, with little GWD, exports 47% of its cereal production (FAOSTAT; http://www.fao.org/faostat/en/#data/TM). However, other countries with significant GWD are large food exporters, such as the USA, with 22% of cereal production exported (FAOSTAT; http://www.fao.org/faostat/en/#data/TM).

Code availability. The global hydrological model PCR-GLOBWB is an open source model that can be obtained from Utrecht University at http://www.globalhydrology.nl/models/pcr-globwb-2-0/. The algorithm for processing trade data is detailed in ref. 16, the corresponding code is available upon request (from T.K.). Similarly, the calculation of GWC and GWT is detailed in this section and the code is available upon request from C.D.

Data availability. The data sources for groundwater abstraction per crop are listed above. Food production, food trade, population, and national harvested area statistics are available in the FAOSTAT database (http://faostat.fao.org). The conversion factors from raw crop to processed crop commodities are given in Supplementary Table 2.

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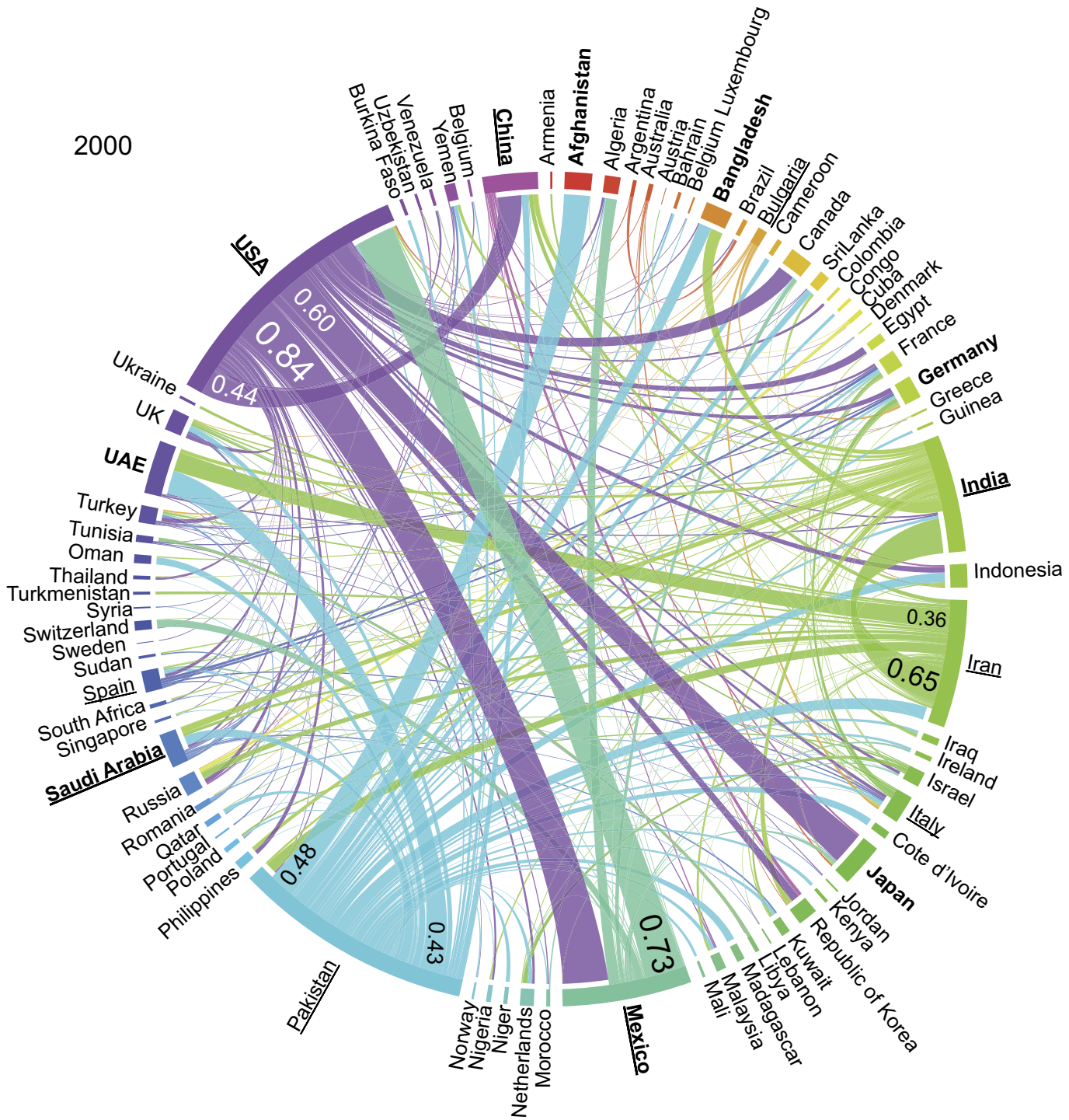
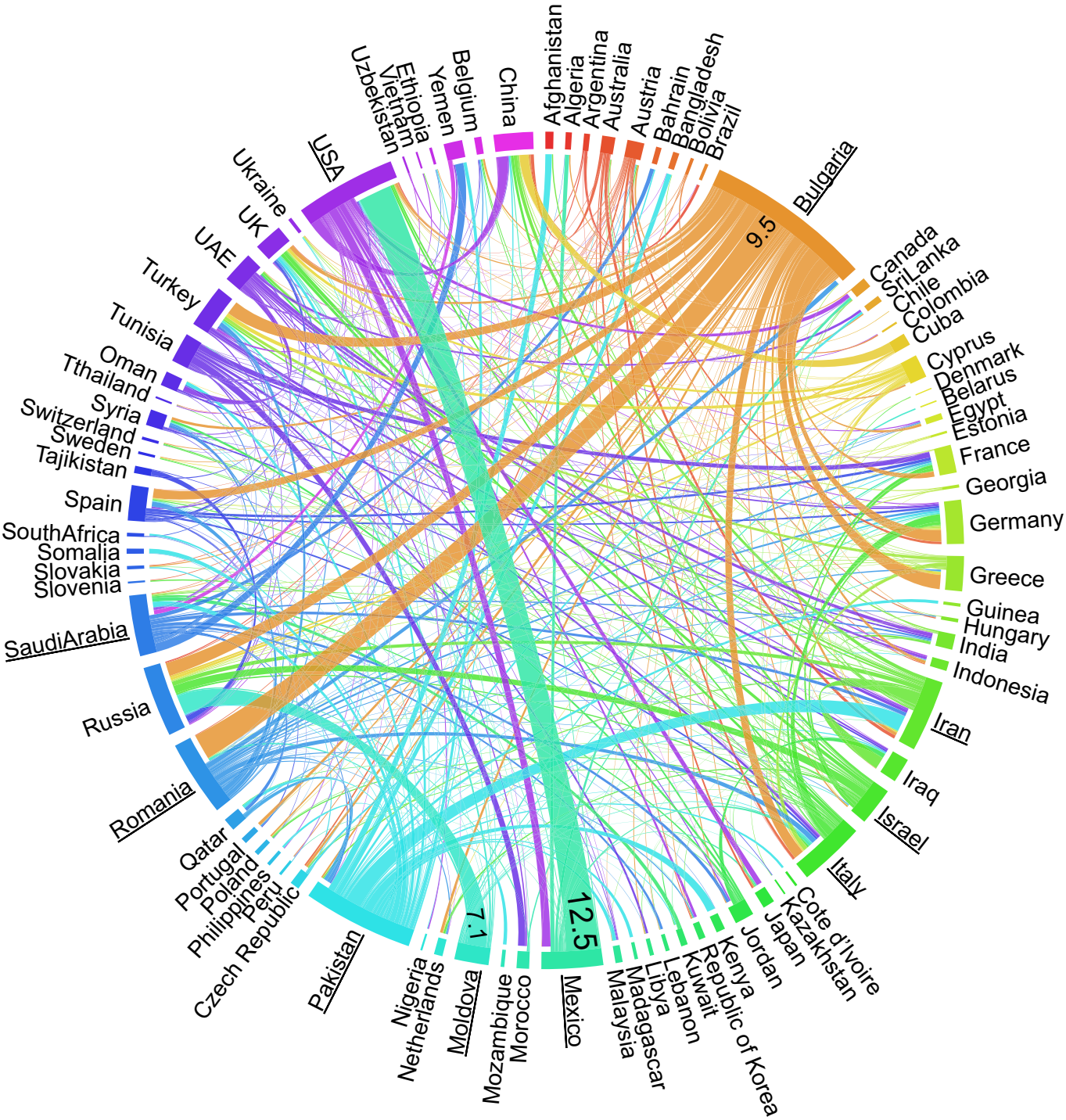
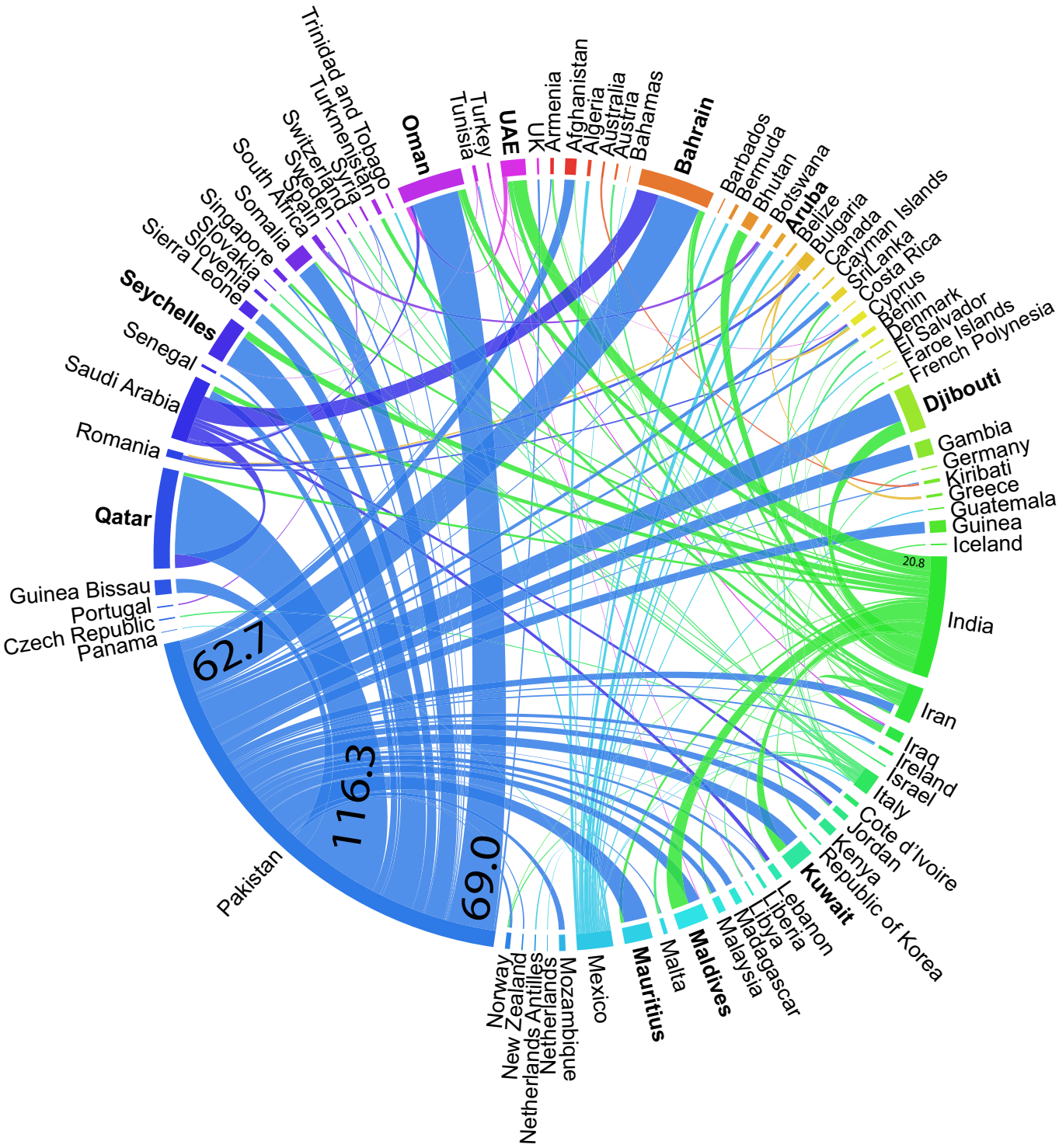


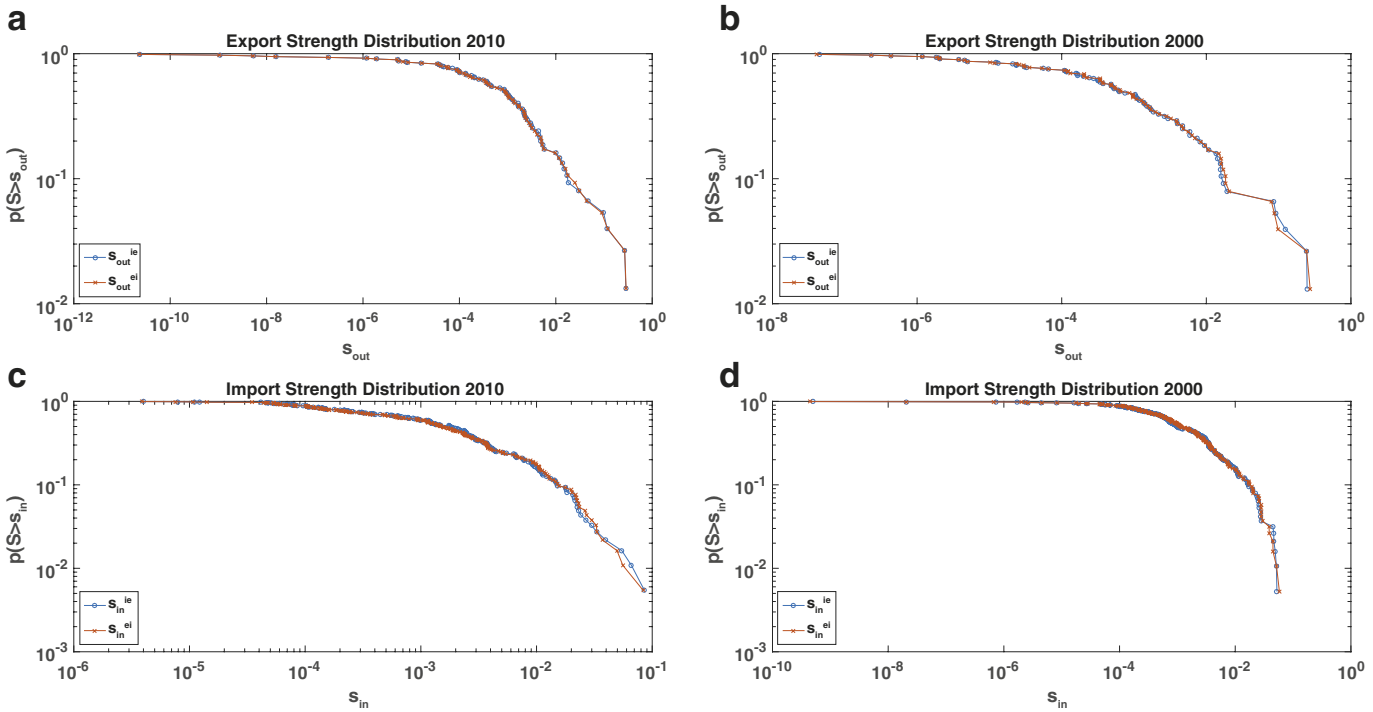
Extended Data Figure 1 | Embedded groundwater depletion in international trade of crop commodities in 2000. Volumes are given in units of cubic kilometres per year. The top ten importers are shown in bold font and the top ten exporters are underlined. Ribbon colours indicate the country of export. For clarity, we display only the links with a weight of at least 1% that of the largest link (the top 1.8% links that account for 81% of total flow and involve 72 countries).



Extended Data Figure 2 | Embedded groundwater depletion in crop exports per capita in 2010. GWD is given in units of cubic metres per capita of the exporting nation per year. The top ten exporters are underlined. For clarity, we display only the links with a weight of at least 1% that of the largest link (the top 3.2% links that account for 79% of total flow).



Extended Data Figure 3 | Embedded groundwater depletion in crop imports per capita in 2010. GWD is given in units of cubic metres per capita of the importing nation per year. The top ten importers are shown in bold font. For clarity, we display only the links with a weight of at least 1% that of the largest link (the top 1.6% links that account for 76% of total flow).



Extended Data Figure 4 | Comparison of GWD trade flows under two trade data versions. The exceedance probability p distribution of national GWD exports (s_{out}) (**a**, **b**) and imports (s_{in}) (**b**, **c**) using import–export (ie) and export–import (ei) trade data is shown for years 2000 (**b**, **d**) and 2010 (**a**, **c**).

Extended Data Table 1 | 130 primary crops used to aggregate trade flows of the 360 crop commodities considered, which are processed from these primary crops

.	Primary Crop	.	Primary crop (cont)	.	Primary crops (cont)
1	Wheat	44	Karite nuts (sheanuts)	87	Cherries sour
2	Rice paddy	45	Castor oil seed	88	Cherries
3	Barley	46	Sunflower seed	89	Peaches and nectarines
4	Maize	47	Rapeseed	90	Plums and sloes
5	Rye	48	Safflower seed	91	Strawberries
6	Oats	49	Sesame seed	92	Gooseberries
7	Millet	50	Mustard seed	93	Currants
8	Sorghum	51	Poppy seed	94	Blueberries
9	Buckwheat	52	Kapokseed in shell	95	Cranberries
10	Fonio	53	Seed cotton	96	Grapes
11	Triticale	54	Linseed	97	Watermelons
12	Canary seed	55	Hempseed	98	Melons other (inc.cantaloupes)
13	Grain mixed	56	Oilseeds nes	99	Figs
14	Cereals nes	57	Cabbages and other brassicas	100	Mangoes mangosteens guavas
15	Potatoes	58	Artichokes	101	Avocados
16	Sweet potatoes	59	Asparagus	102	Pineapples
17	Cassava	60	Lettuce and chicory	103	Dates
18	Yams	61	Spinach	104	Persimmons
19	Roots and tubers nes	62	Tomatoes	105	Kiwi fruit
20	Sugar crops nes	63	Cauliflowers and broccoli	106	Papayas
21	Sugar Raw Centrifugal	64	Pumpkins squash and gourds	107	Fruit tropical fresh nes
22	Beans dry	65	Cucumbers and gherkins	108	Fruit fresh nes
23	Broad beans horse beans dry	66	Eggplants (aubergines)	109	Turnips for fodder
24	Peas dry	67	Chillies and peppers green	110	Forage products
25	Chick peas	68	Onions shallots green	111	Coffee green
26	Lentils	69	Onions dry	112	Cocoa beans
27	Bambara beans	70	Garlic	113	Tea
28	Vetches	71	Beans green	114	Mate
29	Pulses nes	72	Peas green	115	Hops
30	Brazil nuts with shell	73	Carrots and turnips	116	Pepper (piper spp.)
31	Cashew nuts with shell	74	Maize green	117	Chillies and peppers dry
32	Chestnut	75	Mushrooms and truffles	118	Vanilla
33	Almonds with shell	76	Vegetables fresh nes	119	Cinnamon (canella)
34	Walnuts with shell	77	Bananas	120	Cloves
35	Pistachios	78	Plantains	121	Nutmeg mace and cardamoms
36	Kola nuts	79	Oranges	122	Anise badian fennel coriander
37	Hazelnuts with shell	80	Tangerines mandarins clementines satsumas	123	Ginger
38	Nuts nes	81	Lemons and limes	124	Spices nes
39	Soybeans	82	Grapefruit (inc. pomelos)	125	Peppermint
40	Groundnuts with shell	83	Apples	126	Pyrethrum dried
41	Coconuts	84	Pears	127	Jute
42	Oil palm fruit	85	Quinces	128	Manila fibre (abaca)
43	Olives	86	Apricots	129	Tobacco unmanufactured
				130	Rubber natural

nes, not elsewhere specified. Some of these crops are used for both direct human consumption and as feed for livestock. GWD associated with feed crops is accounted for via trade of animal products.

Extended Data Table 2 | Crops in the GWD data (from MIRCA crop classes) that are excluded from the trade analysis

FAO Code	Name	MIRCA class	FAO Code(cont'd)	Name	MIRCA class
68	Popcorn	2	135	Yautia Cocoyam	26
636	Maize for forage and silage	2	136	Taro Cocoyam	26
637	Sorghum for forage	7	299	Melonseed	26
156	Sugarcane	12	420	Broad Beans Green	26
157	Sugarbeets	13	423	String Beans	26
195	Cowpeasdry	17	430	Okra	26
197	Pigeonpeas	17	459	Chicory Roots	26
210	Lupins	17	558	Berries	26
512	Citrus fruit nes	18	641	Alfalfa for forage	26
226	Areca Nuts Betel	24	642	Greenoil seeds for silage	26
275	Tung Nuts	24	643	Legumes for silage	26
310	Kapok fruit	24	644	Cabbage for fodder	26
461	Carobs	24	647	Beets for fodder	26
541	Stone Fruit other	24	648	Carrots for fodder	26
547	Raspberries	24	649	Swedes for fodder	26
591	Cashewapple	24	655	Vegetables roots fodder nes	26
777	Hemp fibre and tow	24	773	Flax fibre and tow	26
800	Agave fibres nes	24	778	Kapok fibre	26
821	Fibre crops nes	24	782	Jute Like Fibers	26
638	Rye for forage	5	788	Ramie	26
639	Grasses nes for forage	25	789	Sisal	26
640	Clover for forage	25	813	Coir	26
92	Quinoa	25	839	Natural Gums	26

Trade volumes of the excluded fodder crops and grasses are negligible relative to other crops included in our trade analysis. Sugar beet and sugar cane are included as a generic sugar crop related to the primary crop 'sugar raw centrifugal'.

Extended Data Table 3 | Largest GWD imports and exports and variability across two trade data versions

Rank	Top Trader	GWP (km^3)	GWT (km^3)	Var (%)	Var (km^3)	Top Partner
2010 EXPORTS						
1	Pakistan	27.5	7.3	4.7	0.34	Iran
2	USA	16.2	6.9	3.2	0.22	China
3	India	73.5	3	4.9	0.15	China
4	Mexico	11.1	2.5	5.8	0.15	USA
5	Iran	33.3	1.2	1.6	0.02	Iraq
6	Italy	2	0.8	5.5	0.04	Germany
7	Bulgaria	1.2	0.5	41.3	0.19	Romania
8	Saudi Arabia	12.5	0.4	5.1	0.02	Yemen
9	Romania	1.1	0.4	13.8	0.05	Italy
10	Turkey	2	0.4	1.9	0.01	Iran
2010 IMPORTS						
1	China	24	2.2	0.7	0.02	USA
2	USA	16.2	1.7	13	0.22	Mexico
3	Iran	33.3	1.4	6.2	0.09	Pakistan
4	Mexico	11.1	1	3.2	0.03	USA
5	Japan	0.4	0.9	2.6	0.02	USA
6	Saudi Arabia	12.5	0.8	6.7	0.05	Pakistan
7	Canada	0	0.7	15.5	0.11	USA
8	Bangladesh	0	0.6	0.2	0	Pakistan
9	UK	0	0.6	0.1	0	Pakistan
10	Iraq	0	0.6	0.5	0	Iran
2000 EXPORTS						
1	USA	12.9	4.4	2.2	0.47	Mexico
2	Pakistan	23.9	4.3	10.8	0.1	Afghanistan
3	Iran	28.4	2.2	21.7	0.48	India
4	Mexico	11.4	1.6	5.3	0.09	USA
5	India	58.9	1.5	7.9	0.12	Bangladesh
6	Italy	1	0.3	7.7	0.03	Germany
7	China	11.8	0.3	6.3	0.08	RepublicofKorea
8	Spain	0.7	0.3	0.1	0.02	France
9	Saudi Arabia	13.6	0.3	6.1	0.03	Yemen
10	Bulgaria	1.5	0.3	10.3	0.03	Italy
2000 IMPORTS						
1	USA	12.9	0.9	9.5	0.09	Mexico
2	UAE	0.7	0.9	0.1	0	Pakistan
3	Mexico	11.4	0.9	9.3	0.08	USA
4	China	11.8	0.8	17.4	0.14	USA
5	Japan	0.1	0.8	4	0.03	USA
6	India	58.9	0.8	56.7	0.45	Iran
7	Bangladesh	0	0.5	0	0	Pakistan
8	Afghanistan	0	0.5	0.1	0	Pakistan
9	Germany	0	0.5	9.6	0.05	USA
10	Saudi Arabia	13.6	0.5	1	0	Pakistan

The groundwater depletion exported (imported) and used by ten countries with most depletion exports (imports), and the top partner importing from (exporting to) them in 2010 and 2000 are indicated using the groundwater depletion in national food production (GWP) and exports or imports (GWT). 'Var' is the difference between GWT with the export–import trade dataset and GWT with the import–export trade dataset, indicated in absolute (km^3) and relative (%) terms.

Extended Data Table 4 | Ten largest exporters of GWD per capita of exporting nation in 2010

Rank	Top exporter	Exported GWD ($m^3 per cap$)	Top Partner
1	Bulgaria	61.9	Romania
2	Pakistan	42.7	Iran
3	USA	22.1	China
4	Mexico	21.2	USA
5	Romania	18.4	Italy
6	Iran	15.9	Iraq
7	Saudi Arabia	15.7	Yemen
8	Israel	14.9	Russia
9	Moldova	14.4	Russia
10	Italy	12.9	Germany

Exported GWD is in cubic metres per capita.

Extended Data Table 5 | Ten largest importers of GWD per capita of importing nation in 2010

Rank	Top importer	Imported GWD ($m^3 per cap$)	Top Partner
1	Qatar	148.2	Pakistan
2	Bahrain	112	Pakistan
3	Oman	97.7	Pakistan
4	Djibouti	77.7	Pakistan
5	Seychelles	63.7	Pakistan
6	Maldives	48.1	India
7	Kuwait	42.6	Pakistan
8	Mauritius	42.4	Pakistan
9	UAE	40.7	India
10	Aruba	35	USA

Imported GWD is in cubic metres per capita.

Extended Data Table 6 | Share of population dependent on GWD via food imports

Year	Crop Class	Pop (%) importing 90% GWD	Crop Class	Pop (%) importing 80% GWD
2010				
	Sunflower	89	Sunflower	90.6
	Maize	76.8	Cotton	87.8
	Citrus	65.5	Maize	86.8
	Grapes / Vine	63.4	Wheat	79.9
	Cotton	56.1	Citrus	75.4
	Sorghum	44.2	Sorghum	70.6
	Wheat	37	Grapes / Vine	70.5
	Groundnuts / Peanuts	32.6	Millet	45.7
	Rice	29.7	Others annual	43.1
	Date palm	27.6	Rice	41
2000				
	Maize	87	Maize	94.5
	Sunflower	80.1	Sunflower	92.6
	Sorghum	79.7	Wheat	87.2
	Wheat	79.4	Sorghum	84.8
	Rice	75.1	Rice	81
	Citrus	64.9	Groundnuts / Peanuts	78.2
	Grapes / Vine	45.3	Citrus	74.8
	Groundnuts / Peanuts	38.2	Others annual	69.5
	Others annual	23.5	Grapes / Vine	62
	Date palm	21.2	Cotton	61.3

Shown is the percentage of the world population importing at least 90% or 80% of a certain crop class from countries that have GWD associated with the production of these crops in years 2000 and 2010, for the ten most important crop classes in regards to this indicator.