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Review article

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Trends and environmental impacts of virtual water trade

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Abstract

Virtual water describes water embedded in the production of goods and offers meaningful insights about the complex interplay between water, trade and sustainability. In this Review, we examine the trends, major players, traded products and key drivers of virtual water trade (VWT). Roughly 20% of water used in global food production is traded virtually rather than domestically consumed. As such, agriculture dominates VWT, with livestock products, wheat, maize, soybean, oil palm, coffee and cocoa contributing over 70% of total VWT. These products are also driving VWT growth, the volume of which has increased 2.9 times from 1986 to 2022. However, the countries leading VWT contributions (with China, the United States, the Netherlands, Germany and India accounting for 34% of the global VWT in 2022) have remained relatively stable over time, albeit with China becoming an increasingly important importer. VWT can mitigate the effects of water scarcity and food insecurity, although there are concerns about the disconnect between consumers and the environmental impacts of their choices, and unsustainable resource exploitation. Indeed, approximately 16% of unsustainable water use and 11% of global groundwater depletion are virtually traded. Future VWT analyses must consider factors such as water renewability, water quality, climate change impacts and socioeconomic implications.

Sections

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Introduction

The availability, use and management of freshwater resources are becoming ever more pressing issues, with increasing water consumption[1–3] depleting rivers and lowering lake and groundwater levels[4–6], and pollution impairing freshwater availability[7,8] and environmental flows[9,10]. Globally, approximately 4 billion people face water scarcity[11], which poses a challenge to meet growing food demand. Agriculture takes centre stage in this challenge, as it consumes over 90% of global blue water[12]. Water demand is projected to increase by 55% by 2050, driven primarily by population growth and changing diets due to increasing prosperity[13,14].

Traditionally, freshwater availability, use and management have been addressed at a local, basin-wide and national scale. However, freshwater resources are subject to global changes, which calls for a global approach[2,15,16]. Although water availability issues are most evident at the local level, the accumulation of problems and their global ramifications have placed nearly 80% of the world's population at a high risk of water insecurity and endangered biodiversity, particularly in riparian habitats[17]. Local-level policies, such as biofuel production[18–20] or imposing restrictions on groundwater pumping, can have unintended consequences such as a decline in biodiversity[21], increased pollution, or groundwater resource depletion[22].

Countries trade water-intensive goods, and many rely on importing water-intensive products to alleviate the pressure on their water resources[23–25]. Importing in this way transfers the environmental consequences of production to the region producing and exporting the products, a phenomenon known as telecoupling[12,26,27]. The need to analyse the link between human consumption in one place and the appropriation of freshwater resources elsewhere has brought about the concepts of virtual water[23,28,29] and water footprint[30–32]. Virtual water refers to the total amount of freshwater 'embodied' in a product or service, including the water used for growing crops, for raising animals and for industrial production; the virtual water trade (VWT) describes the process by which water is effectively transferred between regions or countries through the exchange of these goods and services. Water footprint measures the total water used directly or indirectly by an individual, organization or nation. Water use is measured in terms of water volumes consumed (evaporated or incorporated into a product) and/or polluted per unit of time. Global estimates of the volume of VWT associated with the trade of agricultural products range between 545 km^3 and 2,850 km^3 (refs. 25,33,34). Approximately 85% of that VWT is green water, with the remaining 15% contributed by blue water[12] (Fig. 1). An additional 1,410 km^3 of virtual water is traded globally through wood products[35], manufactured products[34], biofuels[36] and other energy products[37].

In this Review, we examine and describe estimates of VWT, the socioeconomic and environmental impacts of VWT, and the extent of unsustainable VWT. We discuss evolving trends and patterns in VWT, the major importing and exporting countries, the products traded and the major drivers of VWT. We also review some of the criticisms directed at the policy relevance of the virtual water concept. We conclude by identifying knowledge gaps and scientific directions that could guide the evolution of virtual water analysis to enable more informed policies and sustainable practices. Further information on the development of virtual water, its limitations, assessment methods and VWT volumes can be found in refs. 38,39.

Virtual water trade

Global VWT estimates range from 960 $km^3\,yr^{-1}$ to 4,250 $km^3\,yr^{-1}$ (refs. 12,34,40), with agricultural products including processed food and textile products accounting for about 66%, wood products for 9%, and industrial, energy and mining products for the remaining 24% (more detail in Supplementary Data 2). Tracking VWT between countries has been achieved using either a bottom-up approach[23,28,32] or a top-down approach using multiregional input–output (MRIO) analysis[41–43]. Estimates of global VWT, the contribution of products to the total VWT, and a country's position as net importer or exporter vary widely depending on the method used for VWT analysis (bottom-up or MRIO), the products considered and the type of water data (consumptive water use or water withdrawal) (Fig. 2 and Box 1).

The virtual water network is constantly changing, with shifts in connections and dominant fluxes over time. Although some patterns remain consistent, such as the import of virtual water associated with livestock products into the United States and the export of virtual water associated with plant products from North and South America to Asia and Europe[44], the network's structure and trade patterns vary across commodity networks. In the following subsections, we highlight how water is transferred across borders through trade in agricultural products, energy and manufactured goods. We then discuss how VWT occurs through less traditional avenues such as transnational land acquisitions, food aid and migration. Each of these mechanisms demonstrates the interconnectedness of global water use, shedding light on the complex flows of virtual water that influence both local and global water resources.

VWT related to agricultural products

Agricultural products encompass crops and livestock produced through farming, including staples such as wheat, maize and soybeans and livestock-derived goods such as meat and dairy. Between 1986 and 2016, the volume of VWT associated with agricultural products rapidly increased[40,44,45]. Longitudinal data from 1986–2016, generated using a fast-track approach[40], showed that VWT related to agricultural products rose from roughly 940 km^3 in 1986 to almost 2,400 $km^3\,yr^{-1}$ in 2016[40] (Fig. 3). These data are assuming no change in evapotranspiration since the early 1960s, with any changes in the unit water footprint of traded products attributed solely to variations in yield. Applying the fast-track approach to update the data through to 2022, combining FAOSTAT trade data with water footprint calculations of traded products, reveals a further increase in VWT to approximately 2,774 $km^3\,yr^{-1}$ in 2022 (updated from ref. 40).

The global pattern of agricultural trade has seen substantial changes since 1986. Asian countries, particularly China, India and Indonesia, have experienced a substantial increase in volume of VWT and strengthened their global trade connections, which is particularly evident with the rise of imports to China, India, Pakistan and Europe[40,46,47]. By contrast, African countries have been less integrated into global trade, and their trade connections have remained weaker. The growing importance of China as a major importer[38,44,48], particularly of soybeans from the United States and Brazil[40,49] and palm oil from Indonesia and Malaysia, has reshaped portions of the global VWT network. In 2022, China accounted for 40% of global virtual water imports for soybeans, 10% for oil palm and 16% for livestock products (as per updated data of Tamea et al.[40]). A notable increase in virtual water imports of soybean and oil palm to China following the year 2000[40,44,50] has resulted in water conservation in China, while concurrently leading to deforestation in Indonesia and the Brazilian Amazon region[45].

Despite the changes described above, the trade patterns of the top traders of virtual water related to agricultural products have remained relatively stable between 1986 and 2022. The United States,

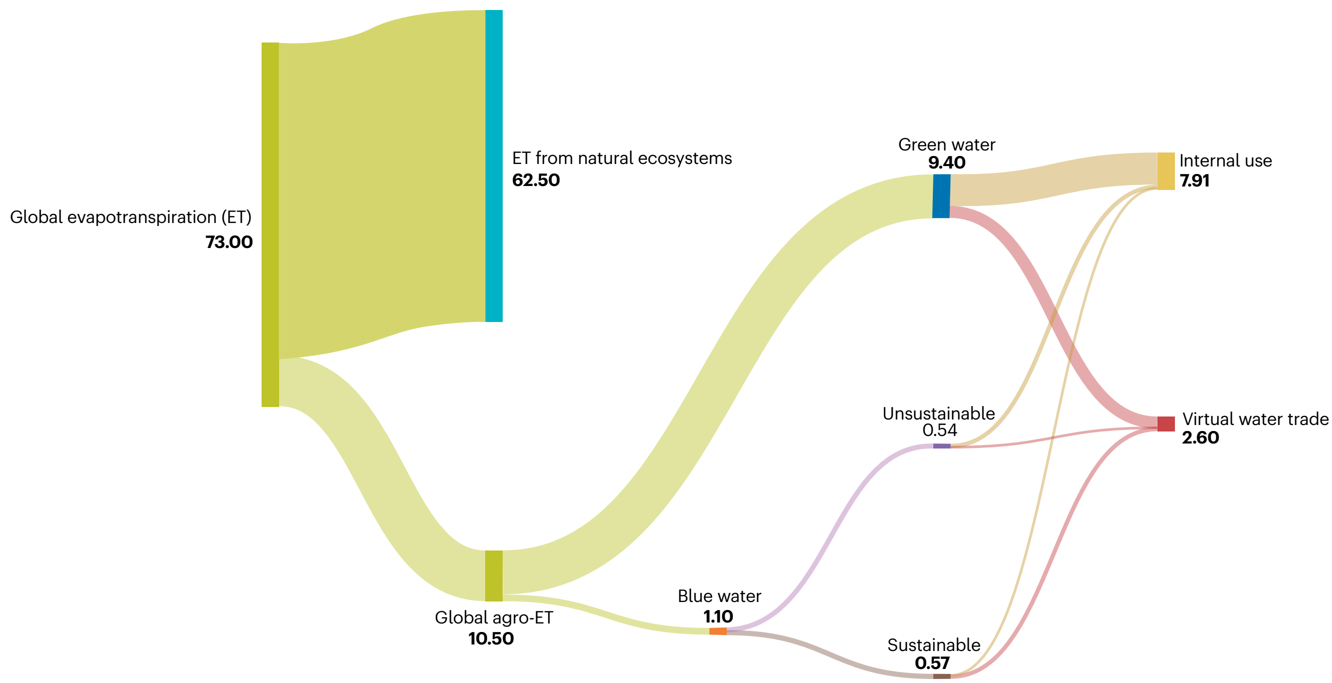

Fig. 1 | Green and blue water flows in agriculture. Unsustainable water and associated virtual water trade (VWT) as fractions of the global evapotranspiration (ET) from land masses. Data sources: global ET, irrigation water consumption and VWT proportion from ref. 38 (consistent with 2016 estimates from ref. 40); total water consumption in agriculture from ref. 51; unsustainable blue water consumption from refs. 130,131; blue VWT (15%) and green VWT (85%) from ref. 12. Detailed data and their sources are available in Supplementary Data 1 and 2. All flows are expressed in 10^{12} m^3 yr^{-1}. The figure highlights that 25% of the global ET from agricultural land is traded virtually.

Australia, Argentina and Brazil have remained consistent net exporters, whereas China, Japan, Italy, the United Kingdom and Egypt stayed net importers[40,44]. Pakistan, the Philippines, South Africa and Turkey shifted from net exporters to net importers[40,44]. In 1986, Japan, the United States, the former USSR, the Netherlands and China were the top importers, together accounting for 37% of the global VWT related to agricultural products. In 2022, the top five importers were China, the United States, Germany, the Netherlands and India, accounting for 34% of the global VWT; Brazil, the United States, Indonesia, India and Argentina were the top five exporters and contributed to nearly 36% of the virtual water export. The global VWT network has shown consistency in major exporting and importing countries, but changes in trade patterns and the roles of specific nations highlights the evolving nature of global water distribution. Understanding these shifts in VWT will be essential for managing global water resources more sustainably.

Although the global VWT related to agricultural products has increased across all commodities, it is largely shaped by a select few traded products, such as livestock products, wheat, maize, soybean, oil palm, coffee and cocoa[40,44,51]. Together, these products make up over 70% of the total global VWT[40] (Fig. 4). Livestock products, palm oil, soybean, coffee, cocoa and tea have experienced the largest increase in VWT (more than threefold) from 1986 to 2022. The growth in global agricultural VWT has been attributed to population growth, rising incomes and dietary changes[52–54]. The proportional contribution of each commodity group has changed over time as agricultural supply chains have become more diversified; for example, cereals have dropped from 31% to 21% of the total VWT related to trade in agricultural products.

VWT related to energy

Water is needed for energy generation[55–57], in processes such as fossil fuel extraction[58,59], generating electricity[59–62], bioenergy[36,63] and producing prospective energy carriers such as ammonia and hydrogen[64,65]. Climate change mitigation technologies such as carbon capture also require water[64,65]. Between 2012 and 2018, the global energy trade steadily grew, leading to increased energy-related VWT[34,66,67]. During this period, the global VWT of energy increased by 35%, reaching 211 km^3 in 2018[67–69]. Fuelwood, biodiesel and oil are the most common sources of VWT in energy, accounting for 43%, 24% and 22% in 2018, respectively[68]. Analyses of energy-related VWT typically only account for the water costs of fossil fuel extraction and do not include the historic water consumption of the biomass produced in previous geological times[70].

The virtual water related to cross-border electricity trading comprised approximately 7.5% of the overall energy VWT annually, amounting to 14 km^3 in 2018[68]. This magnitude is rising as the number of interconnections between countries and the water intensity of electricity production grow[71]. The VWT of energy is not limited to transactions that cross international borders; it also occurs within countries on a large scale[66,72,73]. In China, estimates of VWT range from 1 to 7 km^3 per year between provinces[72–74], and in the United States, 11 km^3 per year between states[66]. In 2016, approximately 2.4 km^3 of virtual water associated with coal was traded between Chinese provinces to support electricity production[75]; this volume of VWT is anticipated to increase owing to the expansion of coal-fired power plants in China[75].

The intricate interplay between VWT and energy production underscores the need for comprehensive assessments of water use in

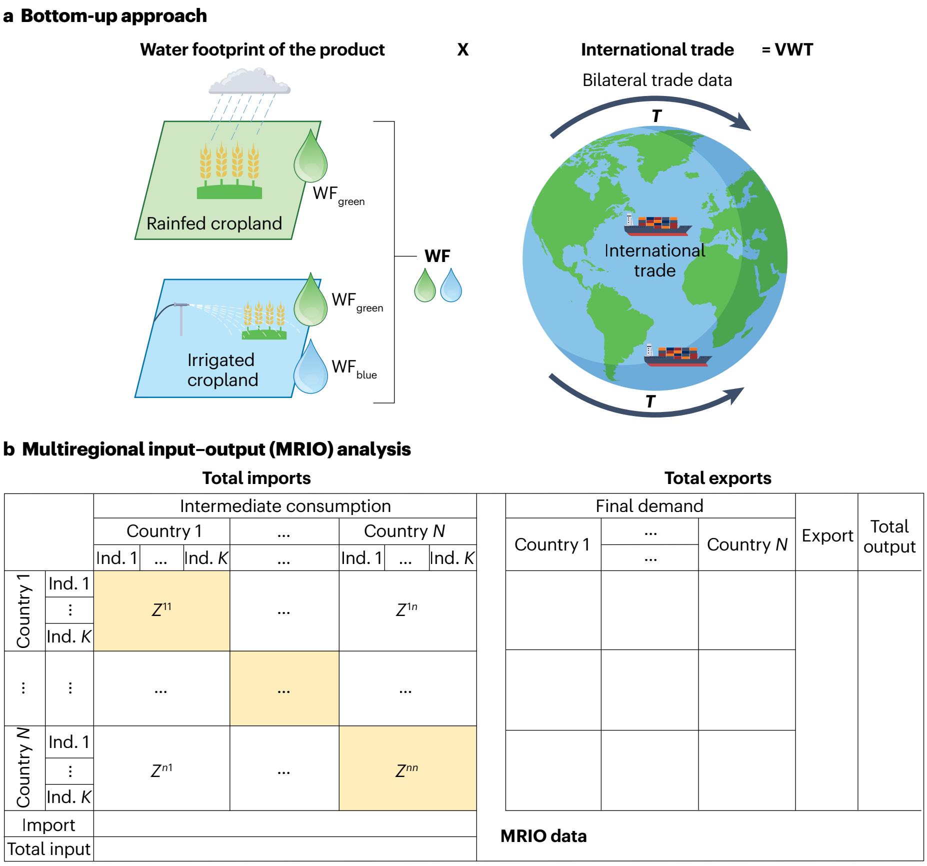

Fig. 2 | Virtual water trade analysis methods. **a**, A bottom-up approach for estimating virtual water trade (VWT), wherein the water footprint (WF, in $m^3\,t^{-1}$) is multiplied by international trade (T, in $t\,yr^{-1}$). WF_{green} and WF_{blue} represent the green and blue WF of the traded products. **b**, The MRIO approach for estimating VWT, wherein the entire regional, national or global supply chains are calculated for each product. Each submatrix on the main diagonal $Z^{i,i}$ (highlighted cells) represents domestic interactions within each industry in country *i*, while off-diagonal matrices $Z^{i,j}$ represent trade flows between countries *i* and *j* for each industry *k*. Ind., industry.

energy production to ensure the responsible management of water resources in the pursuit of energy security. This can be achieved by integrating water usage metrics into energy planning and policy-making, ensuring that energy projects account for the water footprint of various energy sources, including fossil fuels, bioenergy and renewables. Additionally, promoting technologies such as water-efficient energy production and fostering international collaboration to track and manage cross-border virtual water transfers linked to energy could help to mitigate the risks of water scarcity.

VWT related to other goods

Several MRIO assessments have analysed the VWT of manufactured goods, mining products, and oil and gas[35,42,76,77]. Trade in wood, manufactured and mining products accounts for 33% of the total global VWT[12,34,40]. The VWT embodied in the international trade of manufactured goods and wood products was 1,017 km^3 (ref. 34) and 376 km^3 (ref. 35), respectively. At the regional level, in 2007 approximately 7.7 km^3 of water was virtually traded through European Union inter-regional and global manufactured goods trade[77]. Most country-level studies of manufactured goods and mining products have focused on China's interprovincial and international trade. In 2007, about 67 km^3 and 1.4 km^3 of water were virtually traded through China's interprovincial and international trade of manufactured goods and mining products, respectively[78].

Recent data on VWT related to sectors such as manufactured goods, mining products, and oil and gas are limited, and these sectors have been less thoroughly explored than agriculture. Owing to the complexity and diversity of products involved, quantifying their water use is more challenging. The lack of detailed, updated studies means that the water embedded in the trade of industrial goods, mining products and energy remains underrepresented in VWT assessments. This gap highlights the urgent need for further research to understand the water demands of these sectors and their global trade dynamics. A comprehensive analysis of these industries would help to ensure more accurate global water resource management and policy-making.

VWT through transnational land acquisitions

Water ownership can be influenced by contracts and international investments, for example through the granting of property rights to foreign investors[79]. Water is frequently obtained through land ownership or long-term land leases[80,81]. Transnational land acquisitions have expanded rapidly in response to food price crises, resulting in the acquisition of nearly 90 million hectares of agricultural land between 2000 and 2020[82]. Although private companies account for over 90% of these acquisitions, governments or government-owned institutes account for a noteworthy 6%[82]. Globally, approximately 140 $km^3\,yr^{-1}$ of blue water and 47 million hectares of land have been appropriated for crop and livestock production through transnational land acquisitions[81]. Although land acquisitions have the potential to increase agricultural investment, job creation, agricultural productivity and food security in developing countries[80], these investments can compete for limited water resources at the expense of subsistence farmers[80]. They also harm local food security by shifting resources to the export market[83].

VWT through food aid

Food aid is critical to the global food system, especially during periods of crisis. In 2005, the VWT associated with food aid were about 10 km^3, equivalent to around 0.5% of the VWT associated with food trade and 2.0% of the water footprint associated with transnational land acquisitions[84]. The United States is the largest food aid donor, accounting for 82% of the VWT tied to food assistance. Ethiopia, Sudan, North Korea, Bangladesh and Afghanistan are among the nations receiving the largest amounts of virtual water embodied in food aid, collectively accounting for nearly 52% of the food-aid-related VWT[84].

VWT through migration

The trade of water-intensive goods can connect people to distant water resources, where they effectively exert pressure on these water bodies. Alternatively, people can directly use distant water resources without requiring the trade of goods by moving near to these water resources. By the end of 2022, more than 110 million people were either internally displaced or compelled to seek refuge outside of their country of origin owing to persecution, conflict, violence, or human rights violations[85]. A substantial portion of these displaced individuals sought refuge in water-scarce countries, influencing local water security discussions because of their impact on water availability[86,87]. Data from 2005–2016 showed that the global water footprint associated with refugee displacement rose nearly 75%, with minor effects in most countries but substantial implications for nations already facing severe water stress; for example, in Jordan, refugees were estimated to have contributed up to 75% of the country's water stress in 2016[86]. VWT could help to reduce migration from water-scarce regions by allowing countries to ease local water demands by importing water-intensive goods. By addressing water scarcity through trade, VWT lessens the pressure for people to relocate in search of water resources, which can reduce tensions and conflicts over limited supplies. In doing so, it can contribute to stabilizing regions at risk of water-related conflicts and potentially prevent wars[23,28,88].

Subnational VWT

Assessing VWT at the subnational level yields insights for local analysis and decision-making[89–91]. For example, tracing a city's hydrological dependencies through its virtual water imports can reveal water scarcity risks associated with the city's supply chains[92,93]. Subnational assessments can link specific water-stressed basins or aquifers to the cities and regions they support, and emphasize the environmental damage at locations that produce goods for their consumption.

Subnational assessments have revealed that much of the water used in the arid western United States is to produce feed for cattle and ultimately beef products, which are shipped to consumers around the country and globe[94]. This activity has ultimately affected water supplies for over 40 million people and endangered ecosystems around the critically overexploited Colorado River[94]. Similarly, major aquifers, such as the Central Valley, High Plains and Mississippi Embayment aquifer systems in the United States, are being depleted to produce crops and livestock products for both domestic and international markets[95]. Much of the virtual groundwater from these depleted aquifers is destined for cities such as Los Angeles, San Francisco, Sacramento, Houston and New Orleans[95]. Cities increase their dependencies on groundwater and accelerate aquifer depletion during drought[96]. Only 10% of unsustainable water use is for export[97], indicating that interregional trade is a major driver of non-renewable groundwater use in the United States.

Subnational VWT has been compared to large interbasin water projects in China[98,99] and India[100], demonstrating how both water infrastructure and food transport infrastructure move water resources within countries. The subnational VWT often moves water from water-scarce to more water-abundant regions and greatly exceeds physical water transfers, raising questions about the sustainability and hydrologic efficiency of VWT[98,100–102]. For example, in 2007, approximately 26.3 km^3 of physical water was transferred within China, whereas the volume of interprovincial VWT was 201 km^3 (ref. 99). Substantial amounts of blue and grey water are also transferred virtually through the electricity grid[66,103,104], demonstrating the dependency of the energy sector and its consumers on water resources and revealing further potential risks of water shortages.

Virtual water savings

Many countries save their water resources by importing water-intensive products and exporting products that are less water-intensive. VWT can result in global water saving, particularly when highly water-productive areas export to areas with low water productivity[25,32]. Studies show that global water savings between 240 km^3 yr^{-1} (ref. 45) and 450 km^3 yr^{-1}

Box 1 | Bottom-up and MRIO-based approaches for calculating virtual water trade (VWT)

The bottom-up approach tracks VWT in agricultural products at a national or subnational level, without tracing the entire industrial supply chain. This method involves collecting detailed water-use data directly from individual production units to measure water usage at each stage of the production process. The data are then summed to estimate the total water footprint of a product[12,32,177]. It provides detailed product-level information, especially for agricultural products, allowing for a precise understanding of water-use efficiencies and identifying specific stages of production where water conservation measures can be implemented. However, this approach offers limited insights into industrial and service-related products and is data-intensive, time-consuming, and challenging to scale up. It also fails to distinguish clearly between intermediate and final users in terms of water consumption and so does not provide a comprehensive representation of supply chain effects[43,128].

By contrast with the bottom-up approach, the multiregional input–output (MRIO)-based approach uses aggregated data at a national, regional or sectoral level. This approach applies economic or trade models and average water-use coefficients to estimate water usage for the production of goods and services based on their economic value or production volume. Although the MRIO-based approach is simpler and has less error propagation than the bottom-up approach and, unlike that method, covers the entire economic sector, it is less accurate as it relies on aggregated data and averages, often relies on water withdrawal data rather than consumptive water use[99,178,179], does not provide a clear breakdown of VWT per product[180–182], and can focus on specific provinces[183–185], countries[186–188] or regions[77,189].

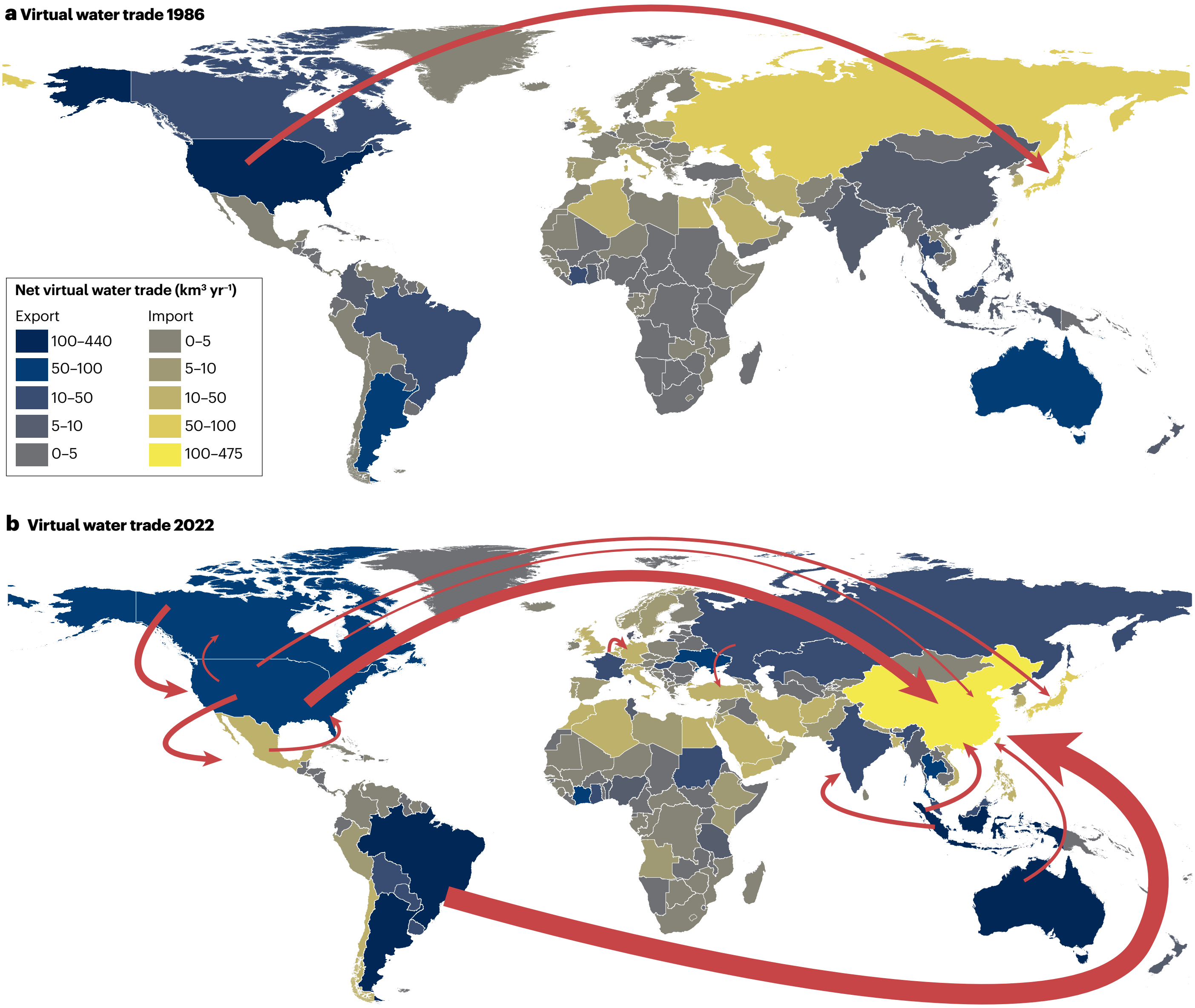

Fig. 3 | Comparisons of virtual water trade between 1986 and 2022. a, Country-level balance of virtual water trade (VWT) in 1986[40]. Arrows represent VWT volume and direction of related products; only flows above 15 $km^3\,yr^{-1}$ are shown and only consumptive water use (green water and blue water) was considered. Data for 1986 are from ref. 40. See Supplementary Data 3 for further details. **b**, Same as in panel **a** but for 2022 (updated from ref. 40). Global VWT has remained relatively stable between 1986 and 2022, with Australia, Brazil, Canada and the United States remaining the main virtual water exporters in both 1986 and 2022; however, China is now a major importer.

(ref. 25) are achieved owing to international trade[105]. A substantial portion of global water savings is attributed to the trade in cereal crops, with oil crops and livestock products following closely. The anticipated impact of climate change includes a notable increase in global water savings. This is primarily attributed to a reconfiguration of the wheat trade, which is expected to result in a substantial rise in the export of wheat from water-efficient regions to regions characterized by less-efficient water usage[106].

Almost 95% of industries use more water through their supply chains than they do in their own production processes[107]. Therefore, most companies could save water primarily by working with their suppliers. If every United States industry reduced its water use to match the most efficient in its sector (the top quartile), 16.9 km^3 of water could be saved annually, and streamflow depletion in many overused rivers could drop by 6–23%[107]. Such findings link water savings to alleviating water scarcity at scales meaningful to policy-makers and water resources management — a notable limitation in most other virtual water savings research performed at country level or that does not assess differences in water use efficiency within sectors[108].

The water savings concept usefully highlights whether a trade is direct in a 'water-efficient' way; however, it suffers from at least two limitations. First, it compares current trade patterns with a hypothetical autarky, which is not the real counterfactual of a world without trade. Second, it is based on water footprint alone, which does not consider local water availability and so could be seen as beneficial even in a situation where exports come from unsustainable but productive agriculture, for example crops irrigated with overexploited groundwater.

Drivers of VWT

The role of trade in reducing water access disparities between nations and achieving global water savings is well known[109–111]. However, trade in agricultural goods is often not driven by water requirements and endowments[24,112,113]. Numerous other factors collectively influence global production and trade trend, such as population, gross domestic product (GDP), distance between exporting and importing nations, demand, raw materials, labour, technical expertise, trade policies and bilateral agreements[38,45,114,115]. These factors can be incorporated into models to identify the key determinants of VWT volume and direction[52,54,116,117] (Fig. 5) and offer valuable insights into VWT mechanisms, driving forces, trade patterns and future projections. Factors influencing VWT can be categorized into two types, as discussed below: natural factors, such as meteorological conditions, water endowment, arable land and trade distances; and socioeconomic factors, such as GDP and population.

Natural factors

Virtual water exports positively correlate with the amount of rainfall in agricultural areas of the exporting countries[114,116]. Conversely, virtual water imports are inversely correlated with water endowment[117], where a 1-mm increase in rainfall leads to a decrease of 0.006 km^3 in virtual water imports[54]. Interestingly, blue water scarcity has been shown to have little effect on VWT[112,118,119]; this is likely because economic priorities and government policies often lead to continued production and exports despite limited water supplies.

Virtual water imports are inversely correlated with arable land[117]. Gross cropped area explains 40% of the total VWT increase across 131 countries, based on the average data from 1995 to 1999[119]. Green water is an important determinant of effective water availability and needs to be accounted for in virtual water analysis[119]. An increase in irrigated areas by 1,000 ha is associated with a decrease in the net virtual water import of cereals of 0.016 km^3 (ref. 54). Additionally, the net virtual water export of dates increases by 0.006 km^3 for every 1,000-ha increase in irrigated area[54]. An increase in the opportunity cost of land to agricultural use and non-agricultural use will reduce virtual water export and increase virtual water export, respectively[120]. Under future socioeconomic and climate change scenarios, VWT of renewable surface water and groundwater is projected to triple by 2100[121]. It is unknown how future agricultural green water scarcity will affect VWT[122].

There are some exceptions to the trends above. Although precipitation and irrigated land explain the VWT of staple crops, they do not explain the export of cash crops such as dates, olives and tomatoes[54]. Further, both virtual water imports and exports increase proportionally with the amount of rainfall if considering arable land, specifically[114].

Finally, the distance between trading partners influences VWT. Geographical distance between partners is inversely related to both virtual water imports[117] and exports[52].

Social factors

GDP, population and virtual water imports are positively correlated[114,116,117,123]. GDP and population are key determinants for explaining staple crop virtual water imports, but do not explain why cash crops such as dates, olives and tomatoes are exported[54]. An increase in GDP is associated with a decrease in the net virtual water import of cereals by 0.06 $m^3\ \$^{-1}$ (ref. 54) and a doubling of GDP results in an 80% increase in virtual water export[123]. Population plays a crucial role in both the activation and deactivation of trade links[115] and an increase in population results in a proportional or 1.6-fold increase in virtual water import[52,54].

Environmental and socioeconomic impacts

The environmental and social impacts of telecoupling or VWT extend beyond the direct interactions between sending and receiving systems, affecting spillover systems as well[26,27,124] (Fig. 6). Spillover effects can manifest in various forms, such as transboundary pollution, biodiversity loss and climate change, which all affect regions not directly involved in trade. Additionally, socioeconomic disruptions, such as market instability and resource conflicts, can arise in regions neighbouring or connected to the trading regions, exacerbating inequalities and triggering social unrest. The interconnected nature of global systems necessitates a comprehensive approach to managing telecoupling effects, considering the well-being of all affected regions and not just those directly involved in trades[2,26,27].

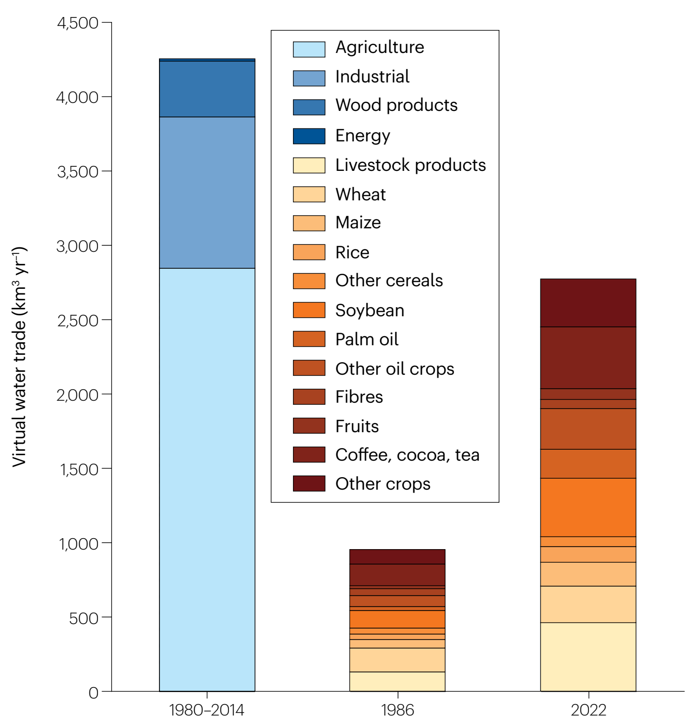

Fig. 4 | Agricultural virtual water trade. The contribution of different products to virtual water trade (VWT) during 1980–2014 (refs. 34–37,44), and the contribution of agricultural products for 1986 (ref. 40) and 2022 (updated from ref. 40; see Supplementary Data 2 and 4). Only consumptive water use (green water and blue water) is considered. Between 1980 and 2014, agricultural products accounted for 66% of total VWT, with wood products at 9% and industrial, energy and mining products at 24%. Agricultural VWT is driven largely by livestock, wheat, maize, soybean, oil palm, coffee and cocoa.

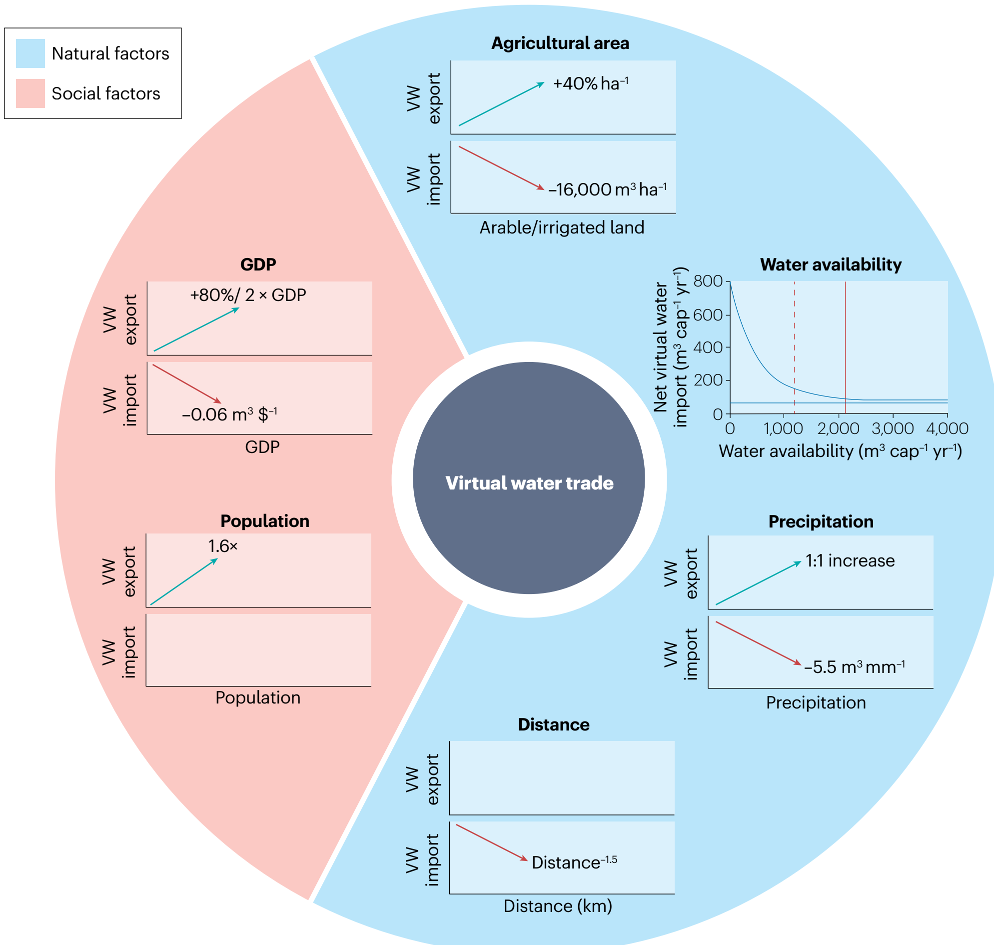

Fig. 5 | Drivers of virtual water trade. Natural factors (blue) and social factors (red) influencing virtual water trade (VWT). The labelled green and red arrows show where virtual water (VW) export and import are directly or indirectly proportional to each factor, respectively. The vertical lines for water availability represent the threshold of renewable water resources (m^3 per capita per year) for the periods 1980–1984 (solid line) and 1996–2000 (dashed line). When the water availability at the country level falls below this threshold, there is a link between net cereal imports and water availability. Virtual water imports and exports are either positively or negatively correlated with factors such as population, gross domestic product (GDP), precipitation, distance between trading partners, and the extent of irrigated land (Supplementary Data 5).

Between the two approaches for VWT analysis, the bottom-up approach enables better impact analysis than MRIO as it identifies specific points in the production process where water use is substantial and highlights opportunities for improvement, making it ideal for understanding water usage effects and implementing targeted conservation measures[125–127]. However, a major issue is the challenge of identifying the geographic origin of products when they are re-exported, which creates a disconnect between producing and consuming countries and makes it difficult to accurately identify the affected regions[40,43,128]. The top-down approach, which is based on MRIO models, can address this limitation as it tracks the flow of goods and services through multiple regions, accounting for intermediate trade and re-exports[129]. However, it relies on aggregated data and averages, which can obscure local variations and details, limiting its precision in identifying inefficiencies or impacts at a granular level[43,127,128]. These limitations restrict its ability to analyse detailed water usage effects within supply chains and accurately allocate responsibility to final consumers. A combination of both approaches will be necessary for a comprehensive analysis of VWT impacts.

Environmental impacts

The globalization and intensification of the agricultural system to meet global demand have resulted in the depletion of surface water[1,130,131] and groundwater[5,132,133] resources. For example, heavy use of water from the Colorado River means that is completely depleted before it reaches the ocean for much of the year[1,9] and this vulnerability casts doubt on the ability of this river system to meet future surface water allocation to the seven Basin states[134–136].

A substantial amount of VWT is associated with the unsustainable use of surface water[130,131] and groundwater[5,95,132]. Globally, roughly 52% of the blue water footprint is deemed unsustainable, and around 15–17% of this unsustainable portion is traded virtually[130,131] (Fig. 7a); for example, access to vegetables and berries in the United States has been related to unsustainable VWT from Mexico[137]. Groundwater is being depleted in parts of the High Plains Aquifer, Central Valley, Mississippi Embayment, western Mexico, North Arabia, Upper Ganges and North China Plain to produce agricultural products for domestic and international markets[4,5,95,133]. The rapid depletion of groundwater in these and other aquifers has jeopardized global food security[5,132,138]. An important driving force behind groundwater depletion is production for exports[132]. Substantial non-renewable groundwater flows (Fig. 7b) embodied in the international trade were found from the United States to China, Mexico and Japan, from Mexico to the United States, from Pakistan to Iran, and from India to China[132]. Global groundwater depletion increased by 22% from 2000 to 2010, rising from 240 km^3 to 292 km^3 (ref. 132). About 11% of this depleted groundwater was traded virtually through the international crop trade[132].

Socioeconomic impacts

The virtual water literature often overlooks the socioeconomic ramifications of trade, including factors such as employment, income and productivity. These aspects are now discussed, providing a framework for understanding how trade influences socioeconomic issues and, by extension, how VWT affects these issues.

Trade liberalization has been linked to increased productivity through various mechanisms such as economies of scale, resource reallocation, innovation and technology upgrades[139,140]. Trade plays a pivotal role in job creation by expanding skilled employment opportunities through exports, foreign direct investment and specialization. However, it can also trigger job displacement in sectors that are struggling to compete with cheaper or more abundant imported goods. For example, in 2011, the United States, European Union and China recorded 15 million, 66 million and 121 million jobs attributable to export-oriented production, respectively[139]. When considering overall employment trends, the proportion of jobs linked to exports varies between regions: from 10% in the United States and Japan to a substantial 28% in the European Union, the Republic of Korea and New Zealand[139].

Research on how trade openness on unemployment rates is contradictory. One study of 20 OECD countries suggests that a 10% rise in trade openness from 1983 to 2003 led to a reduction in unemployment of around 0.75%[141]; however, another analysis of 97 nations found a positive relationship between trade liberalization and unemployment[142]. The link between VWT and unemployment becomes clear when countries have a "comparative advantage in sectors characterized by significant labour market frictions"[142]. Despite mixed data on unemployment, trade liberalization contributes to economic growth, typically resulting in an average growth increase of 1.0–1.5%, which can translate to income gains of 10–20% over a span of 10 years (ref. 143). The 24% global rise in incomes that has taken place from 1990, with the poorest 40% of the global population experiencing a 50% increase, can be attributed to increased trade[143].

VWT has a crucial role in famine relief and addressing regional food crises, helping to prevent large-scale migration from water-scarce regions and potentially mitigating conflicts and wars[23,28,144]. VWT can also reduce inequality in access to water for food production among countries[109,110,145]. The international food trade diversifies food sources[146–148], supplements domestic production[147,148], bridges seasonal differences[146], stabilizes prices[148] and aids knowledge transfer[149]. Trade can also promote a healthier and more balanced diet by providing access to a more diversified and nutritious range of foods[147].

Although trade offers numerous benefits for enhancing food security, there are still potential challenges. Over-reliance on imports can expose nations to supply chain disruptions and price volatility in global markets. Further, this reliance increases the impact of regional wars, which can lead to substantial disruptions in the movement of

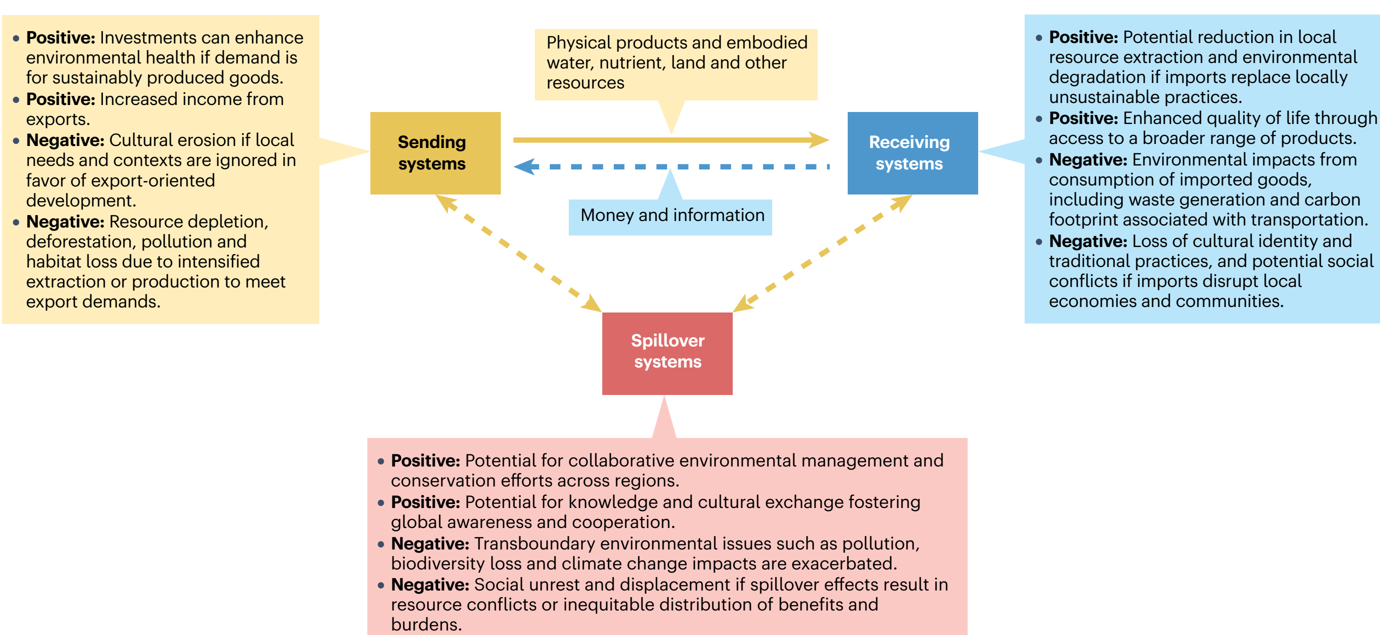

Fig. 6 | Framework of telecoupled systems. A telecoupled framework[26,27,124] depicting sending systems (regions or systems that export goods, services, information or resources; yellow), receiving systems (those that import these goods, services, information or resources; blue) and spillover systems (regions or systems indirectly affected by the interactions between sending and receiving systems; red), and the positive and negative considerations for each. The telecoupled framework shows how environmental and social impacts are interconnected across sending, receiving and spillover systems.

goods and services and potentially affect the food and water security of large populations[150,151]. Negative socioeconomic consequences can also result from VWT; for example, although virtual water import has helped to conserve water in the water-scarce Bohai Bay area of China, it has also reduced local GDP, employment and economic welfare[152]. VWT can negatively influence the resilience of the global food system[153] and increase vulnerability of the global food supply to external shocks[154]. Further, it might inadvertently disconnect consumers from the environmental impacts of their choices[2,27,155].

Policy relevance and criticism of virtual water

The sheer volume of virtual water embedded in international trade and production has brought substantial attention to water issues, including in policy circles. At times, however, social scientists have criticized virtual water literature, especially where it goes beyond descriptive analyses that account for the water footprint of human activities and ventures into policy recommendations[119,156,157]. Criticism is often linked to one of the following three issues.

The first key criticism of VWT studies is their narrow focus on water, often overlooking other crucial factors of production that play a key role in shaping international trade patterns. Central to economic analysis are country-specific, sector-specific or firm-specific production functions that explain output in terms of many factors. Water is one production factor next to capital stock, various types of labour (skilled and low-skilled), agrochemical inputs and land. VWT analyses seldom include relevant production factors beyond water, or frame the investigation in terms of economic trade theories or other relevant frameworks[157–159]. For example, analyses often do not consider the Nobel-Prize-winning Hecksher–Ohlin theory, a theory of comparative advantage that explains what goods countries export and import by considering the relative abundance of their resources and intensity with which those resources are used across sectors[160,161]. The theory posits that if, for example, low-skilled labour or capital is abundant in a country, this labour or capital tends to be relatively cheap, which makes exports that intensively use these comparatively abundant resources more competitive in global markets. Hence, international trade flows embed capital and different types of labour in the same way that they embed virtual water. The United States is a major exporter of agricultural products, not just because of its abundance of water or land, but also because of its vast capital stock, as agriculture is a capital-intensive activity in industrialized countries. Empirical analysis suggests that although water is a factor that determines international trade flows, it has far less impact than the available labour or capital resources in a country[162]. Therefore, informed policy decisions require taking all relevant factors of production into account, including capital, labour, energy and land, and their interactions, as well as calculating the water content of production and trade. By considering these factors, the true environmental and socioeconomic costs and benefits of VWT can be better assessed, leading to more informed decision-making and sustainable resource management practices.

The second criticism is that informed policy advice should be underpinned by specific, empirical evidence. Technological change, water-related policy actions and long-term structural changes

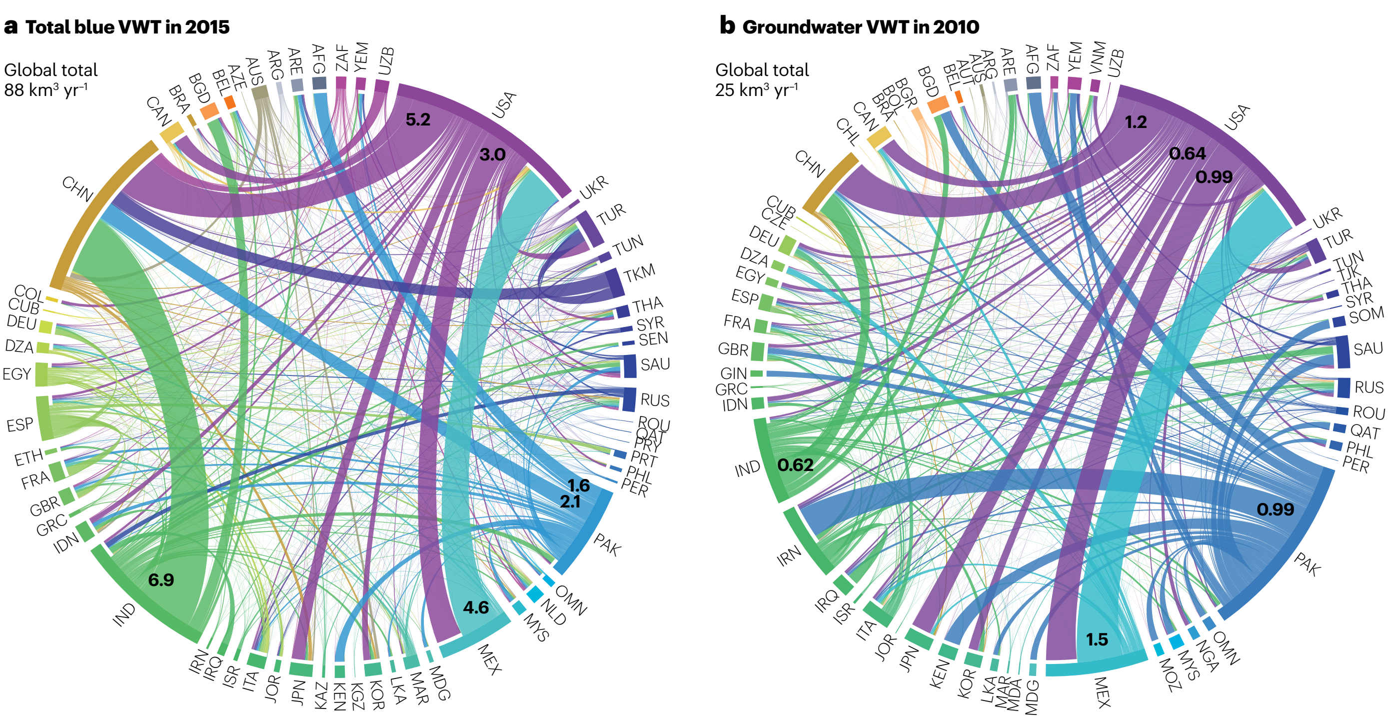

Fig. 7 | Unsustainable virtual water trade. a, Plot representing total blue virtual water trade (VWT) in 2015[130]. The sizes of the ribbons represent the relative volumes of unsustainable VWT; the colour of the ribbons represents the exporting country. Bold numbers show larger flows (in km^3 yr^{-1}). The global total unsustainable VWT is provided at the top left. Detailed data and full definitions of country abbreviations are provided in Supplementary Data 6 and 7. **b**, Same as in panel **a**, but for groundwater VWT in 2010[132]. The United States dominates unsustainable blue surface and groundwater virtual water exports, whereas China dominates unsustainable blue surface and groundwater virtual water imports.

Glossary

Autarky
A situation in which a country, region or economy is self-sufficient and does not rely on external trade or imports.

Blue water
Water in surface water bodies and aquifers that contributes to surface and groundwater runoff (blue water flows); blue water can be diverted or extracted by human action (for example with systems of wells, canals and gates) and used for various purposes. In agriculture, blue water is used for irrigation.

Blue water footprint
The amount of surface water or aquifer water that is consumed or incorporated in a product to produce a unit mass of that good; the water footprint of an individual, community or nation is the total amount of water consumed to produce all their goods and services.

Comparative advantage
When countries specialize in producing goods and services with the lowest opportunity cost compared with other sectors and countries; this is driven by differences in technology (Ricardo's theory) and the availability and use of resources (Heckscher–Ohlin theory) across countries and sectors.

Consumptive water use
The part of water withdrawn that is evaporated, transpired, incorporated into products, consumed by humans or livestock, or otherwise not available for immediate use.

Ecological unequal exchanges
The asymmetric flow of natural resources and waste between wealthier and poorer nations, leading to environmental degradation and resource depletion in the latter.

Environmental flows
The water needed to support freshwater ecosystems to ensure the ecological health and services of rivers, wetlands and other water bodies.

Global water saving
Where commodities are produced in countries where they require less water (per unit mass) and are exported to countries where their production would require more water.

Green water
Rainwater contributing to soil moisture stored in the unsaturated portion of the soil profile and used by plants for evapotranspiration (green water flow).

Grey water
The amount of freshwater required to dilute pollutants in water to meet water quality standards.

Hecksher–Ohlin theory
The theory that countries will export goods that use their abundant factors of production (such as labour or capital) and import goods that require factors they lack, based on differences in resource endowments.

Hydrological unequal exchange
The unequal distributions of hydrological impacts and benefits between regions or countries due to global patterns of trade and water exploitation.

Opportunity cost
The value of the next best alternative that is foregone when a decision is made; it represents the benefits or value you give up by choosing one option over another.

Telecoupling
The interactions between socioeconomic and environmental factors over long distances.

Unsustainable VWT
The fraction of virtual water trade that relies on unsustainable water consumption associated with losses of environmental flows, groundwater stocks, or other environmental impacts.

Virtual water
The water consumed in the production of goods; the adjective 'virtual' stresses that virtual water is not physically present in the goods.

Virtual water trade
(VWT). The trade of water that is virtually embodied in the traded commodities. VWT does not correspond to physical transport but stresses how trade is associated with a global displacement of water use.

Water consumption
The fraction of water withdrawal that is 'lost' to the atmosphere as evapotranspiration and therefore is not returned to surface or groundwater blue water stocks or flows.

Water footprint
The amount of water that is consumed or incorporated into a product to produce a unit mass of that good; the water footprint of an individual, community or nation is the total amount of water consumed to produce all their goods and services.

Water withdrawal
The extraction of blue water from streams, lakes or aquifers.

(for example, decreasing share of GDP contributed by agriculture) determine countries' overall water use and their trade over time[163]. There is a need for granular studies that clearly identify and quantify the direct impact of specific water-related policies, such as water pricing, as well as non-water policies, such as trade liberalizations, on VWT. Separating the impact of such policies from structural or technological changes will reveal their exact water-related consequences and effectiveness in a given setting[164]. In the absence of such detailed studies, the VWT literature might not be robust enough to inform policy. Empirically linking specific decisions to their water-related consequences and understanding causality could help to develop effective strategies for sustainable water resources management.

Third, much of the VWT literature focuses on agricultural commodities and their direct virtual water use. Even though agriculture is responsible for most of the world's water consumption, it is less than 10% of the value of global trade and in many instances just a few per cent of the GDP of a country. Agricultural products are, however, crucial to food security and important inputs for textiles or food-processing manufacturing operations that command a much higher share of global trade and GDP. Policies that affect non-agricultural sectors might therefore have non-negligible implications for agricultural water use through supply chains. Bringing supply chains into virtual water analysis requires a more prominent use of standard input–output tables that specify intersectoral input use and calculate the total direct and indirect virtual water of the different sectors. Calculation of virtual water also could be made more meaningful by defining water intensities in terms of water use per dollar of output, rather than relying solely on physical measures[163,165].

Hydrological unequal exchange and water justice

Theories of comparative advantage maintain that there will be aggregate benefits from trade if countries specialize in the production of goods that require more inputs (skilled labour, natural resources or capital) that are domestically more abundant (relative to other countries) and trade them with one another. There are many formulations of comparative advantage theories. The simplest models do not consider hidden costs (externalities) associated with increased international trade due to comparative advantage. When externalities are ignored, some models refer to these international transactions as 'ecological unequal exchanges'[166,167]. From a hydrological point of view, there is also a 'hydrological unequal exchange' associated with the overexploitation of resources; its overuse can lead to irreversible environmental damage or permanent loss of groundwater stocks. Interestingly, hydrologically unequal exchange does not necessarily occur from the Global South to the Global North and does not always entail unaccounted environmental losses for the Global South[38]. Some of the major VWT associated with agricultural trade originates from the United States, which exports crops at lower prices than production costs partly as a result of subsidies to the agricultural sector[166,168]. Indeed, the United States ranks as the second most prolific net virtual water exporter after Brazil[169], the number one unsustainable virtual water exporter (followed by India, Pakistan and Mexico[130,132]) and the biggest virtual grey water exporter followed by Canada and the Netherlands[170]. Regardless of the wealth and political or economic power of the country bearing the cost of environmental impacts, hydrological unequal exchange still underlies the trade of agricultural goods produced with unsustainable water use. Better metrics of hydrological unequal exchange are needed to account for environmental damage from loss of environmental flows (virtual water exports from unsustainable water use)[130] and the increased concentration of pollutants (virtual grey water exports)[170].

Water use by agriculture can have important local distributional justice implications, affecting farmers' access to water and their livelihoods[80,81,171]. Although recent research has provided quantitative tools to assess the sustainability of water footprints[131,172] and VWT, at present frameworks evaluating the local (subnational) impacts on water justice are missing and are at the centre of active debate[173–175]. Thus, whether VWT is just or unjust will depend on who at the subnational scale benefits from or is negatively affected by trade (for example as a result of environmental impacts, loss of livelihoods or food insecurity), underlying power relations and the water appropriation process[80].

Summary and future perspectives

The global VWT ranges from 960 km^3 yr^{-1} to 4,250 km^3 yr^{-1}, with agricultural products accounting for about 66% of trade, wood products for 9%, and industrial, energy and mining products for the remaining 24%. Between 1986 and 2022, the global volume of VWT related to agricultural products almost tripled. Major changes in recent agricultural trade include the increasing importance of China as a major importer, a substantial increase in soybean exports from the United States and Brazil to China, and a substantial increase in palm oil exports from Indonesia and Malaysia to China, India, Pakistan and Europe. The global VWT is mainly influenced by a few key traded products, including livestock products, wheat, maize, soybean, oil palm, coffee and cocoa, which collectively account for over 70% of the total global VWT.

The concept of virtual water has enhanced understanding of global water resource management and trade dynamics. Improving the accuracy and granularity of data related to VWT could support in refined analysis of underlying trends, determining the factors that influence VWT and evaluating its socioenvironmental impacts. Comprehensive databases that incorporate regional variations in water availability, production techniques and trade patterns will be essential. Furthermore, integrating virtual water data with other socioeconomic and environmental indicators will provide a more holistic view of the interactions between water resources, trade dynamics and sustainability. Expanding virtual water analysis from bilateral trade to a network perspective[147,176] could reveal complex interdependencies and vulnerabilities within the global trade system. Research should also explore the resilience of trade networks to disruptions, the role of key players and the implications of supply chain dynamics on water security.

The accuracy and applicability of virtual water could be enhanced through developing hybrid approaches that combine the detailed nature of the bottom-up method with the comprehensive scope of the MRIO method. The bottom-up method involves analysing detailed, product-level data to calculate the water footprint of specific goods and services. It offers high specificity but requires extensive data. Conversely, the MRIO method uses economic input–output tables to capture the water embedded in trade across various regions and sectors, providing a comprehensive system-wide perspective. The extensive use of MRIO could prevent potential double-counting when tracking VWT between countries using trade data.

Improving the policy relevance of virtual water could be achieved through detailed studies on the direct effects of water-related and non-water policies. These would involve assessing the environmental and socioeconomic impact of virtual water trade. Additionally, studies could move beyond focusing solely on water and include factors like labour, land use and biodiversity loss, greenhouse gas emissions, capital and energy use to better understand the environmental and socioeconomic impacts of trade. Understanding how consumption patterns and per capita water footprints affect VWT is crucial for developing sustainable trade policies.

In addition, analysing how VWT affects livelihoods, income distribution and employment opportunities can provide insights into equity and social justice considerations. There is a crucial need for future research to prioritize the development of frameworks that specifically evaluate the local (subnational) impacts of water footprints and VWT, particularly within the context of water justice[94,131,173]. A comprehensive understanding of justice implications in VWT requires examining underlying power relations and the water appropriation process.

The transmission of local shocks through the global supply chain, such as those arising from climate, social, economic and environmental factors, has highlighted the need for a comprehensive research framework that addresses the multifaceted impacts of climate change and other local shocks on VWT. Such a framework would allow for the identification of potential hotspots where food security risks might be particularly pronounced. Specific research areas could include: investigating the regional and temporal variations in water availability resulting from climate change, considering factors such as altered precipitation patterns, changing temperatures and extreme weather events; exploring how shifts in production patterns, water availability and demand dynamics affect the global flow of virtual water, the availability and affordability of essential food products; and identifying regions and sectors most vulnerable to climate-induced changes in VWT. When identifying vulnerable regions and sectors, factors such as socioeconomic conditions, water stress levels and reliance on virtual water imports should be considered.

Although climate change is a critical factor influencing VWT, it is essential to recognize that socioeconomic factors will continue to have a substantial impact on future trends. Population growth, shifts in dietary patterns and economic development play crucial roles in determining water use and trade patterns. These socioeconomic factors interact with climate change, amplifying the challenges of water management and trade. Hence, addressing socioeconomic factors is equally important for ensuring sustainable water use and trade practices. Policies and strategies that promote water-efficient technologies, sustainable agriculture and equitable water distribution will be essential in mitigating the impact of these factors on VWT in the future.

Despite having several limitations, virtual water remains a useful tool for broad-scale assessments of water-related impacts on trade and consumption. However, the environmental and social implications of water consumption are highly context dependent, varying substantially based on factors such as location and season. Therefore, although VWT can highlight the movement of water-intensive goods and the associated water footprints, it does not inherently account for the broader environmental or social implications of this trade.

Moving forward, a more comprehensive approach to water management should consider not just the volume of water consumed but also the local water availability, ecosystem resilience and societal needs. This comprehensive approach would help to guide policies and practices that promote sustainable water use and ensure the equitable distribution of water resources. As societies continue to navigate the complex intersection of water, trade and sustainability, innovative research in virtual water analysis will play a pivotal role in shaping a more water-secure future.

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Author contributions

M.M.M., M.M.K., B.W.D., J.A.C., C.D. and L.R. researched data for the article. M.M.M., P.D. P.d'O., C.R. and L.R. made a substantial contribution to the discussion of content. M.M.M., M.M.K., P.D. and P.d'O. wrote the article. M.M.M., M.M.K., B.W.D., J.A.C., A.C., C.D., P.D., P.d'O., L.M., C.R., L.R. and L.Z. contributed to reviewing and editing the manuscript before submission.

Competing interest

The authors declare no competing interests.

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