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The asymmetric impacts of international agricultural trade on water use scarcity, inequality and inequity

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Abstract. Freshwater is closely interconnected with multiple sustainable development goals (SDGs). Virtual water transfer associated with agricultural trade may help to mitigate water scarcity (SDG6). However, the resulting impacts on water scarcity distribution among income groups (SDG1) and subsequent effects on water use inequality and inequity (SDG10) remain largely unclear. Here, we develop an integrated framework to reveal the asymmetric impacts of international agricultural trade on water use scarcity, inequality, and inequity between and within developing and developed countries. We find although agricultural trade generally relieves water scarcity globally, it disproportionately benefits the rich and widening both the water scarcity and inequity gap between the poor and the rich. Notably, in developing countries, population (35%) suffering from both increased water scarcity and inequity are the poorest group (per capita income is 16% lower than average), while the relatively poor (13% population) in developed countries often simultaneously benefit from decreased water scarcity and reduced inequity synergies. Our results thereby highlight striking asymmetric and generally more favorable trade-induced water impacts for developed countries, urging future water and trade policies striving for a better balance across multiple critical SDGs and achieving sustainable development for all.

Freshwater plays an essential role in supporting sustainable development due to its intrinsic interconnections with multiple sustainable development goals (SDGs), including clean water and sanitation (SDG6)[1], reduced inequalities (SDG10)[2,3], and no poverty (SDG1)[4,5] among others[6]. Across the globe, over 2 billion people reside in countries afflicted by severe water scarcity, and ~1.2 billion people still lack basic drinking water services, threatening clean water accessibility (SDG6)[7]. The distribution of this scarcity is profoundly unfair (SDG10), with ~80% of those affected living in rural areas[7], and ~50% in the least developed countries[7], which could further jeopardize water-dependent economy (e.g., irrigated agriculture) and impede the progress of ending poverty (SDG1)[4,5]. Agricultural trade is widely identified as an important policy instrument in balancing food supply and demand, and its associated virtual water transfer (10-30% of water use[8]) can significantly reshape global water scarcity. The resulting uneven water scarcity exacerbation or alleviation via virtual water transfer across regions[9,10] might further lead to heterogeneities in water use inequalities and inequities, thus driving asymmetric impacts across different population groups.

Prior virtual water studies[11] have extensively evaluated trade-induced global blue[12-14], green[15], and grey[16-18] water flows, most of which only focus on total water savings or losses. More recent efforts have integrated both water supply and demand side to elucidate how such virtual flows could consequently affect regional water scarcity[19-21], groundwater depletion[22], and climate risks[23]. Yet, very few studies have touched on the further implications of water use inequality and inequity[24-27], with most of them being conducted at a relatively coarse resolution (e.g., incapable of characterizing the impacts for the poor at a fine scale[25-27]), and simply treating the agriculture sector as a whole (e.g., incapable of differentiating crop-specific impacts[24]) (Supplementary Table 1). Therefore, the disparities of trade-induced water scarcity alleviation or aggravation within and across different economic strata, and the associated water use inequality remains largely unclear. Failure to integrate changes in regional water scarcity with local poverty and inequality makes it difficult to understand how international trade affects different population groups, especially the most vulnerable. Consequently, this hinders an informed design of targeted water and trade policies in balancing multiple critical SDGs and achieving sustainable development for all.

We further distinguish water use inequity from inequality. Water use inequality metrics such as Gini coefficient[2,3], Theil index[2,28], and interquartile ratios (e.g., P90/P10)[29] quantify the uneven access to water use among population or regions, thus it can only tell whether everyone gets the same amounts of water allocation. However, our study defines water use inequity, which is largely absent in current virtual water literature[24-27], to differentiate the impacts on different income groups (e.g., categorized by GDP per capita levels), especially the poorest population who are usually among the most vulnerable[30]. Striving for an equal water distribution but ignoring the differentiated needs for different population may largely impede the achievement of SDG 1, as the poor have a larger reliance on water-dependent economy and a lower capacity in adapting to water shortage, thus it is harder to eradicate extreme poverty without pro-poor water resource distribution[4,5]. With growing awareness on environmental justice and the welfare of the most vulnerable, it is critical to fill this important research gap to provide an up-to-date, systematic, and global consistent analysis on trade-induced impacts on water scarcity, inequality, and inequity.

Here, we build an integrated framework to comprehensively assess the synergies and trade-offs of changing water scarcity, inequality, and inequity embodied in international agricultural trade, focusing on different levels of GDP per capita (i.e., low, lower-middle, upper-middle, and high) in both developing and developed countries. Specifically, we simulate the global up-to-date grid-level annual average irrigation water consumption for 26 crop species under production-based and consumption-based accounting using a physical trade flow (PTF) model based on FAOSTAT bilateral trade data[22], and superimpose them with gridded GDP per capita information[31]. We then compare the multi-scale changes in water scarcity (measured by population-weighted water scarcity index, WSI), water use inequality (unequal access to water use, measured by the *absolute value* of concentration index, |CI|) and inequity (the magnitude of skewed allocation, either pro-poor or pro-rich, measured by the *sign* of CI)[32-36] (Methods). Based upon detailed data fusion, we provide an integrated framework to reveal trade-induced changes in water use scarcity-inequality-inequity pattern within and across different global economies, highlighting the challenges faced by the most vulnerable population, as well as targeting the critical trading-partner-specific and crop-wise trade flows and their underlying factors.

Asymmetric impacts on water use scarcity

International agricultural trade generally alleviates water scarcity for most of global population to varying degrees, particularly in Northern China, Europe, and northern parts of Africa (Fig. 1a and Supplementary Fig. 1). Despite the general benefits with global WSI reduction, special attention should be paid to exceptions for developing regions such as India and Pakistan, and developed regions including eastern parts of Australia and central USA (Fig. 1a and Supplementary Fig. 2).

Overall, developed countries experience a much more significant water scarcity alleviation due to international agricultural trade than developing countries. In developing countries, 62% population experience decreasing water scarcity compared with 37% suffering from water scarcity increases. Notably, people exposed to increasing water scarcity in developing countries are ~8% poorer than that of people with decreased water scarcity, indicating international trade disproportionally disfavors those who tend to have lower economic levels or less adaptive capacity (i.e., lack of sufficient wealth to afford alternative access to water such as pumping groundwater) (Fig. 1b). In comparison, international trade relieves water scarcity for 75% population in developed countries, while increases the WSI of 22% population (15 percentage points less than that in developing countries) (Fig. 1b,c). In addition, average GDP per capita in developed countries is roughly twice of that in developing countries, demonstrating the former has much larger adaptative capacity yet less trade-induced water scarcity exposure (Fig. 1b,c).

Focusing on changes of population belonging to different water scarcity levels, a significant asymmetric pattern also emerges (Fig. 1d). In developing countries, population with no/low water scarcity (WSI < 1) increases slightly by ~1.3% due to international trade, while increasing by 10.7% in developed countries, indicating a much higher degree of water scarcity alleviation in developed countries (Supplementary Table 2). Similarly, population exposed to extreme water scarcity (WSI > 2) decreased by merely 1.1% in developing countries compared with roughly 10.2% decreases in developed countries (Supplementary Table 2). We further categorize people into four income groups (i.e., low, lower-middle, upper-middle, and high) for both developing and developed countries. The asymmetry impacts are particularly evident for the poorest (i.e., low and lower-middle income). For example, the number of population with no/low water scarcity dramatically increases by 20% for the lower-middle income group in developed countries, while increasing by merely 0.1% in developing countries (Fig. 1d). Heterogeneities within developing countries are also substantial: population with no/low water scarcity increases by 56% for the top 1% richest, largely surpassing the 2% increases for the 1% poorest (Supplementary Table 3). Although international agricultural trade generally relieves water scarcity globally, these asymmetric changes disproportionally favor the rich (e.g., people in developed countries or the richest group within developing countries), therein widening the water scarcity gap between the poor and the rich.

Asymmetric impacts on water use inequality and inequity

International agricultural trade reshapes water use allocation, which leads to concerns on water use equality (i.e., equal access to water use for all) and equity (i.e., water use allocation is skewed in favor of the poor) (Supplementary Figs. 3-7 and Table 4). Trade-induced inequality and inequity increment generally occurs at northern parts of Africa (e.g., Algeria) and Saudi Arabia, while China and some African countries (e.g., Ethiopia) experience both improved equality and equity (Fig. 2a). Trade-offs with increased inequity yet decreased inequality are most common across the globe, mainly occurring in southern parts of Africa (e.g., DR Congo) and Europe (e.g., Luxembourg) (Fig. 2a). Notably, depending on whether our identified water use inequity leads to the loss of water-related opportunities and whether such loss is trade-induced[37], we find that trade-induced water use inequity in Algeria is considered as 'unjust' as the opportunity of minimum water access is lost; yet the increased post-trade water inequity in Luxembourg is only 'regrettable' as water availability is sufficient both before and after trade (Supplementary Fig. 8 and Tables 5-6).

In developing countries, 29% of its population are simultaneously exposed to trade-induced increasing inequality and inequity (towards pro-rich), who are also with the lowest income (Fig. 2b); Among this, 70% experiences unjust inequity (Supplementary Table 6). In contrast, only 9% of the population in developed countries are facing co-occurrences of increasing inequality and inequity (Fig. 2c), among whom 60% population suffer from an unjust inequity (Supplementary Table 6). Nevertheless, developing countries are not completely deprived of trade benefits. In fact, 34% of the population in developing countries are characterized by decreased inequality and reduced inequity, whereas only 8% of the population in developed countries fall into this category (Fig. 2b,c). Interestingly, population with high income in both developing and developed countries are more likely to face trade-offs: the group with the highest income in developing countries (dominated by South America and Russia) experiences increased inequity but decreased inequality; while the richest in developed countries (dominated by Europe) are exposed to decreased inequity but increased inequality (Fig. 2b,c).

The distribution of water use favors higher-income populations in both developing and developed countries under either production-based (CI_{pro}) or consumption-based (CI_{con}) accounting (Fig. 2d,e), yet it presents asymmetric impacts on low-income groups between developing and developed countries. In developing countries, when the poor uses water for local consumption, the water use allocation favors the relatively affluent members of this group (CI_{con}: 0.215); international trade further pushes the inclination even more concentrated on those affluent members (CI_{pro}: 0.280), resulting in 30% greater inequality and inequity (Fig. 2f). Conversely, the relatively poor in developed countries starts from a pro-poor water allocation with better equity (CI_{con}: -0.146) than that in developing countries from the consumption perspective, and international trade further enhances the pro-poor allocation by 65% (CI_{pro}: -0.241), albeit at the cost of greater inequality (Fig. 2g). The complete asymmetric patterns across different economies and population can be found in Supplementary Fig. 9.

Synergy and trade-off of water scarcity-inequality-inequity

International agricultural trade simultaneously reshapes water use scarcity, inequality, and inequity via virtual water transfer, thereby resulting in synergies and trade-offs among the three metrices across global economies. As shown in the schematic figure (Supplementary Fig. 3) and Supplementary Table 4, synergies denote that international trade not only alleviates the country's water scarcity ($\Delta WSI < 0$), but also prioritize water to the poor ($\Delta CI < 0$) and bring it closer to the line of absolute equality ($\Delta|CI| < 0$). Trade-offs imply the country improves one or two aspects while sacrificing the others due to international trade.

Our quadrant analysis reveals that developing and developed countries exhibit asymmetric synergy and trade-off characteristics (Fig. 3). Developing countries are dominated by the third (42% population experience both scarcity and inequity alleviation, synergy) and the first quadrants (35% population suffer from both water scarcity and inequity aggravation, worse-worse). Compounding the plight of these worse-off 35% population is the fact that they are also the poorest ($9,114 per capita, 16% lower than the average) among the four quadrants (Fig. 3a,c). Moreover, 24% population in developing countries grapple with the compounded challenges of intensified water scarcity, inequality, and inequity due to international agricultural trade.

In comparison, none of the population in developed countries experiences the simultaneous exacerbation of water scarcity, inequality, and inequity. Population in developed countries mainly fall in the second (43% population face reduced inequity yet increased scarcity, trade-off) and fourth quadrants (36% population experience reduced scarcity yet exacerbated inequity, trade-off). Only 9% of population in developed countries suffer from both worsen water scarcity and increased inequity, and their income is much higher ($42,048 per capita), suggesting the worse-off population in developed countries are likely to have greater adaptive capacity and more financial resources to mitigate the potential consequences (Fig. 3b,d). Even more beneficially, the third quadrant with the lowest income is also the one experiencing the greatest synergies in both water scarcity and inequity alleviation. Thus, international trade disproportionately benefits the relatively more vulnerable within developed countries yet threatening the most vulnerable within developing countries (Fig. 3b,d).

Driving factors in water scarcity, inequality, and inequity

Drawing from the four quadrants of developing and developed countries based on factors such as population, trade volume, and geographical distribution (Supplementary Fig. 10), we select eight countries to investigate their respective crop- and trading partner-specific contributions in water scarcity, inequality, and inequity. The relative importance of individual crop (or trading partner) is estimated as multiples of median (MoM)[38-40] via dividing crop-specific (or trading-partner-specific) impacts by the median among all crop-specific (or trading-partner-specific) impacts in each country (*Methods*, Figs. 4 and 5).

The international trade of staple food crops is the major driving factor for changing water scarcity, inequality, and inequity in most selected countries because of its large trade volume (Fig. 4). For instance, rice and wheat exports dominate the simultaneous aggravation of the three water metrices in India. Cash crops and fruit crops trade can sometimes serve as critical driving factors (Fig. 4), as certain countries rely heavily on importing (e.g., Japan) these crops for domestic consumption or exporting (e.g., Pakistan) them for economic benefits. In particular, cotton, grapes, and citrus exports lead to exacerbated water scarcity and inequity yet reduced inequality in Australia.

Concerning trading partner-specific contributions, we find that, among our selected countries, changes in water scarcity, inequality, and inequity for developing countries are more likely due to trading with other developing countries (Fig. 5). Specifically, 91% and 75% of India and Argentina's increasing water scarcity result from trades with other developing countries, which also contribute 59% and 58% of Nigeria and China's alleviated water scarcity (Fig. 5 and Supplementary Table 7). Similarly, developing countries also generally take more responsibilities for the inequality and inequity change in India (92%), Nigeria (37%), China (80%), and Argentina (89%). In comparison, developed countries are more diversified: Japan's 76% of water savings and 64% of increasing water inequity yet decreasing inequality are attributed to trading with other developed countries; while for Australia and Sweden's changing water metrics, developing and developed countries contribute almost equally; and developing countries contribute more to USA's increasing water scarcity and inequality yet decreasing inequity (Fig. 5).

We thereby identify the dominant trading-crop and trading-partner for each of our selected eight countries in affecting water scarcity, inequality, and inequity (Supplementary Table 8), and further explore the driving factors of these targeted trade flows regarding their comparative advantages in econo-geograph, agricultural production, water availability, and food demand using the drivers identification framework of virtual water trade[11] (Supplementary Tables 8-11). For instance, Iran's rice imports notably exacerbate India's water scarcity, inequality, and inequity, primarily driven by comparative advantages in natural resources, as India has more arable land suitable for rice cultivation and more water availability than Iran (Supplementary Tables 9 and 10). In comparison, Australia's cotton export to China takes the largest responsibility for the increasing water scarcity and inequity in Australia, whose exports are mainly driven by Australia's lower food demand and less severe water scarcity compared to China (Supplementary Table 11).

Discussion and Conclusions

Along with a growing body of studies on the change of water scarcity through virtual water transfer[11], our study is among the first attempts to reveal how international agricultural trade relocates water uses between the poor and the rich, thereby affecting the associated water use inequality and inequity among different income groups. We reveal an asymmetric change in water scarcity, inequality, and inequity between developing and developed countries embodied in international agricultural trade, with more resourceful population (e.g., those residing in developed countries or the more affluent group within developing countries) often benefiting significantly more, thereby widening the vulnerability gap between the rich and the poor.

Despite general trade-induced water scarcity alleviation in both developed and developing countries, the increment in population with no/low water scarcity among the relatively poor is asymmetric - up by 20% in developed countries, compared to merely 0.1% in developing countries. Meanwhile, water use inequity decreases by ~65% in developed countries (pro-poor) while increasing by ~30% in developing countries (pro-rich), although both of them experience a greater water use inequality due to agricultural trade. The diverging pattern is also distinct as that in developing countries, people suffering from both increased water scarcity and inequity are the poorer, while the relatively poor in developed countries often benefit from synergies between reduced water scarcity and inequity due to international agricultural trade. Developed countries tend to import crops to meet the domestic food demand leveraging their comparative advantages in econo-geography, thereby largely alleviating water scarcity and inequity among their relatively poor; while the drivers of changing water scarcity, inequality, and inequity for developing countries are more likely to be natural resources (e.g., arable land area and water availability) and agricultural production efficiency, thereby often putting them in the positions of exporters that achieve economic gains at the expenses of increasing water scarcity and inequity (Supplementary Tables 8-11).

Our study calls for a joint consideration of multiple SDGs in water and trade policies design. Previous virtual water studies mostly focus on SDG6 and emphasize the general benefits of water savings and water scarcity alleviation embodied in trade[11,12]. However, we further reveal that despite largely alleviated water scarcity, many countries, such as Nigeria and Japan, are exposed to amplified water use inequity (hindering SDG10) via disproportionately allocating more water uses towards the rich, thereby compromising water resources critical for basic living and economic activities for the poor and could consequently hinder the progress of eradicating extreme poverty (SDG1)[4,5]. Importantly, integrating equity (SDG10) and water scarcity alleviation (SDG6) can not only contribute to poverty eradication (SDG1), but also promote the achievement of SDG2 (zero hunger by favoring irrigation water uses), SDG3 (good health and well-being by improving water quality for the poor), SDG5 (gender equality), and SDG4 (quality education by reducing water-related labor work for women and kids[1]). Therefore, an integrated prioritization of mitigating water scarcity, inequality, and inequity, should be better factored into water and trade policy making, which requires concerted efforts to align the interconnected issues throughout multiple SDGs[6,41,42].

Water policies designed to address the needs of low-income groups can help to lessen inequity and create opportunities for sustainable development. For example, developing countries exposed to increasing water scarcity and inequity can provide water subsidies or financial support to poor households to help them pay for the water bills[43], cap the water price to make it more affordable for the poor[44], and invest in the installation of community water points (e.g., public taps and water fountains) to ensure basic water needs are met[45] and offset the poor's water losses due to international agricultural trade. In addition to supply-side solutions, demand-side practices such as drip irrigation[46] and crop switching[47] to improve agricultural water use efficiency in both crops production and consumption regions are likely to increase water availability for the poor and enhance agricultural sustainability[48], especially in countries like India[49] that rely heavily on agriculture yet face growing inequity. Trade policies such as diversifying staple food trades (e.g., reducing rice consumption or switching to other food types) and trading partners towards reduced water scarcity, inequality, and inequity can be another option. For example, China experiences a larger water use inequity due to rice imports from Pakistan and Thailand, while lessening inequity through wheat imports from USA (Supplementary Table 12). For the beneficial trades, the government can promote fair trade by lowering tariffs[50,51], lowering import quotas[52], and simplifying technical regulations[53] to ensure marginalized groups to engage more in trade opportunities; in cases where trades pose challenges to water equity, diversified trading networks can then serve as a buffer against potential water risks[54].

Limitations and caveats apply to our study. First, our study defines 'water inequity' on top of 'inequality' (e.g., whether everyone gets the same water amounts*)* to bring an additional layer of message on pro-rich water use allocation, thus it factors into different adaptive capacities between the poor and the rich, providing more critical information to understand the impacts of food trade on different income levels, especially those most vulnerable. That said, our definition of 'water inequity' is somewhat narrowed, as there are many other dimensions of 'inequity'[37,55-58]. In addition to focusing on income differences and the poorest population group, future studies can further extend our framework to incorporate other components (e.g., gender, class, and race differences, whether it affects human rights[37], and etc.). We also conduct supplementary analyses based on the framework of water-related opportunities to explore whether our identified water inequity leads to the loss of water-related opportunities and whether such loss is trade-induced, such that to provide more comprehensive information of water use justice (Supplementary Fig. 8 and Supplementary Tables 5-6). Second, following earlier work[59,60], we integrate grid-level irrigation water consumption together with the FAOSTAT inter-country bilateral trade data to track the agricultural trade flow and the resulting water impacts. This, however, does not factor into the impacts of intra-country trade flow within each individual country across the globe, thus our current study can only evaluate the impacts resulting from international agriculture trade, and future work can consider incorporating intra-country trade flows when such information is available.

The intensification of global agricultural trade network has led to increasing interdependence across countries, making it more important than ever to work together to address sustainability challenges that affect the humanity. Our study, via building one of the first integrated 'water use scarcity-inequality-inequity' framework, helps to shed light on how international trade simultaneously transmits and pools water scarcity, inequality, and inequity, highlighting the necessities of considering the impacts on different population groups (especially the most vulnerable) in designing water and trade policies to better address multiple sustainable development goals in a synergistic approach and to achieve sustainable development for all.

Daunting challenges, such as unfair water use reallocation between the poor and the rich, and the unequal benefits between developing and developed countries embodied in global trade, can be further intensified by growing population and food demand, increased cross-sector water use competition, accelerating climate change, and unpredictable crises (e.g., COVID-19). Building upon our integrated trade-induced water scarcity-inequality-inequity framework, future assessments can be effectively applied to facilitate better-informed water and trade policies design under either changing climate, varying socioeconomics, or unpredictable crises. In addition, as our analysis primarily focuses on the economics aspect (i.e., GDP per capita) regarding water use inequity, more dimensions of inequity (e.g., gender, class, and race) can be incorporated in our built integrated framework, particularly with global consistent datasets of future population, age distribution, gender ratio, as well as the dynamically evolving intra-country and international trading patterns to capture the impacts of both domestic and foreign trade flow.

[*~3798 words*]

Methods

Crop-specific water consumption for irrigated agriculture production

To provide up-to-date policy implications, we focus on the most recent years with available data (2017-2019) and report the 3-yr average results when evaluating agricultural trade-induced water scarcity, inequity, and inequality changes.

We simulate recent year (2017-2019) grid-level (1/12°×1/12°) irrigation water consumption for 26 individual crop species using the Global Crop Water Model (GCWM) in light of daily soil water balances[61] with the input of climate variables (e.g., temperature, wind speed, precipitation, etc.), crop-specific planting areas, cropping calendars, etc[62]. Specifically, irrigation water consumption is the amount of crop evapotranspiration that is not compensated by effective precipitation[61-63]. Crop evapotranspiration is calculated by multiplying K_c (the coefficient expressing the difference in evapotranspiration among 26 crops and different growth periods) and ET_0 (potential evapotranspiration)[61-63]. The ET_0 is calculated through Penman-Monteith Equation (equation 1) recommended by FAO[63].

$$ET_0 = \frac{\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.33u_2)} \tag{1}$$

Where, ET_0 denotes potential evapotranspiration (mm/d); Δ denotes saturated water pressure curve slope (kPa/°C); R_n denotes ground surface radiation (MJ/(m·d)); G denotes soil heat flux (MJ/(m²·d)); γ denotes wet and dry constant (kPa/°C); T_{mean} denotes daily average temperature (°C); u_2 denotes wind speed at 2 meters (m/s); e_s denotes saturated water pressure (kPa); e_a denotes actual water pressure (kPa).

More information about GCWM is available in earlier literature[61,62]. Although GCWM captures the impacts of inter-annual and intra-annual climate variability on irrigation water use, it fixes irrigated area at MIRCA2000 (Monthly Irrigated and Rainfed Crop Areas around the year 1998-2002)[64] due to data unavailability for alternative years. Following earlier studies[23,65,66], we further scale GCWM-simulated results based on country-level area equipped with irrigation from FAO database[67] to factor into the impacts of irrigated area changes on irrigation water use (equation 2).

$$Irr_{c,i,t} = \frac{AEI_{c,t}}{AEI_{c,t0}} \cdot Irr_{GCWM,c,i,t} \tag{2}$$

Where, $Irr_{c,i,t}$ and $Irr_{GCWM,c,i,t}$ respectively denote adjusted and GCWM-simulated irrigation water use in country c in year t for crop i; $AEI_{c,t}$ and $AEI_{c,t0}$ denote area equipped with irrigation infrastructure in country c in year t and the reference year (1998-

2002) respectively. We further aggregate GCWM simulated water consumption to the spatial resolution of 0.25°×0.25° to match water availability data based on runoff from ERA5[68].

Grid-level consumption-based crop-specific water consumption

Production-based water use tracks a country's actual water uses for all crops produced within the country, potentially including water uses for exported crops, while consumption-based water use represents total water uses for all crops that end up being consumed in a country, although some crops and associated water uses occur outside of the country. Primarily following the same method as in Dalin et al.[22], we use the FAOSTAT bilateral trade data[67] to track the agricultural trade flow and estimate the resulting consumption-based irrigation water consumption. Combining with the production data from FAOSTAT, we further adjust the trading matrix following the origin-tracing algorithm proposed by Kastner et al[69] to address the re-export issue. Using the algorithm by Kastner et al[69], we obtain a normalized matrix of trade flows whose values represent the proportion of a country's production that is ultimately consumed in each country.

Then, the agricultural consumption-based water use can be calculated as follows (equation 4):

$$\begin{bmatrix} C^1 \\ C^2 \\ C^3 \\ \vdots \\ C^n \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & A^{13} & \cdots & A^{1n} \\ A^{21} & A^{22} & A^{23} & \cdots & A^{2n} \\ A^{31} & A^{32} & A^{33} & \cdots & A^{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & A^{n3} & \cdots & A^{nn} \end{bmatrix}^T \begin{bmatrix} P^1 \\ P^2 \\ P^3 \\ \vdots \\ P^n \end{bmatrix} \tag{3}$$

Where, C^r denotes the consumption-based water use in country r; P^r denotes the production-based water use in country r; T denotes the transpose of the matrix; A^{rs} denotes the proportion of production in country r that is ultimately consumed in country s. Following Hoekstra et al.[59], we obtain grid-level consumption-based water uses (0.25°×0.25°) by breaking down crop-specific country-level water uses into each grid cell based on each crop's production-based water use share to the country total volume.

Change of water scarcity due to agricultural trade

Integrating grid-level (0.25°×0.25°) water consumption and water availability (natural runoff minus environmental flow requirement)[70], we calculate water scarcity index (WSI) in each grid and assume that individuals in the same grid face the same levels of water scarcity (equation 4). Production-based WSI (WSI_{pro}) and consumption-based WSI (WSI_{con}) are calculated via dividing production-based and consumption-based total water consumption by grid-level water availability excluding environmental flow, respectively[70]. Total water consumption under production-based accounting is estimated by summing up irrigation water consumption for crops production plus industrial and domestic water consumption[71], while consumption-based accounting is calculated by adding consumption-based irrigation water consumption with industrial and domestic water consumption. In this work, we focus on the water impacts due to trade of agricultural products, which account for a dominating share (over 85%[72]) of total water consumption.

$$WSI = \frac{WU}{WA} = \frac{W_{irr} + W_{ind} + W_{dom}}{R - EF} \tag{4}$$

Where, WSI denotes the water scarcity index; WU denotes total water consumption; WA denotes total water availability; W_{irr}, W_{ind}, and W_{dom} denotes the irrigated, industrial, and domestic water use respectively; R denotes total runoff, and EF denotes the environmental flow required to sustain freshwater ecosystems, which accounts for 80% of the total runoff[2,60,73]. Grid-level annual average runoff data is obtained from the ECMWF Reanalysis v5 (ERA5) dataset at a spatial resolution of 0.25°×0.25°, produced by the Copernicus Climate Change Service (C3S)[68]. Following earlier studies[71,73], we downscale country-level industrial and domestic water use according to population distribution downscaled by Goldewijk et al.[74] to obtain gridded industrial and domestic water consumption.

Production-based scenario simulates the real-world water use which have already taken agricultural imports and exports into consideration, where consumption-based scenario allocates irrigation water not used for local consumption to where those crops are finally consumed. Hence, the effects of international agricultural trade on the water scarcity are estimated by subtracting consumption-based water scarcity index (WSI_{con}) from production-based WSI_{pro} (WSI_{pro}- WSI_{con}). In the meanwhile, we divide the water scarcity into three levels ($WSI < 1$; $1 \le WSI < 2$; $WSI \ge 2$) in ascending order of severity, and compare the number of population changes falling into each of the three categories before and after international agricultural trade[70].

To evaluate the asymmetric impacts on different population groups, we first categorize global population into developed and developing countries according to International Monetary Fund (IMF)[75]. We then further equally divide each population group (i.e., developed country and developing country) into four sub-groups based on grid-level GDP per capita downscaled by Kummu et al.[31], including: low, lower-middle, upper-middle, and high GDP per capita groups. To align with the geographical units of concentration index, we also calculate the population-weighted country-level water scarcity index for cross-country comparison (equation 5).

$$WSI_c = \frac{\sum_i WSI_i \cdot Pop_i}{Pop_{tot}} \tag{5}$$

Where, WSI_c denotes population weighted water scarcity index for country c; WSI_i denotes WSI of grid i within country c; Pop_i denotes the population of grid i within country c; Pop_{tot} denotes the total population of country c.

Change of water use inequality and inequity due to agricultural trade

We estimate the change of water use inequality and inequity embodied in agricultural trade by comparing the production- and consumption-based concentration curve and concentration index (production minus consumption). The concentration curve plots the cumulated share of water use against cumulated share of population ranked by GDP per capita[35]. The concentration index (CI) can be determined by calculating twice the area bounded by the concentration curve and the line of absolute equality (equation 6)[36].

$$CI = 1 - 2\int_{0}^{1} L_w(p)dp = 1 - \sum_{i=0}^{n-1}(P_{i+1} - P_i)(W_{i+1} + W_i) \qquad (6)$$

Where, $L_w(p)$ denotes the concentration curve; n denotes the population amount; i denotes the order of GDP per capita rank; W_i denotes the cumulated share of water use of the top i people; P_i denotes the cumulated share of population of the top i people. We assume that water use is equally allocated among people in the same grid due to lacking individual-level dataset covering the globe. Absolute equality is represented by $CI = 0$, which indicates equal water distribution among all population, with a larger absolute value (e.g., $CI = 1$ or $CI = -1$) indicating a higher inequality regarding water allocation within the population group[32-36].

We also distinguish inequity from inequality with the aid of concentration index. If $-1 \leq CI < 0$, the concentration curve will be located above the line of absolute equality, indicating that water use concentrates more on the poor people; if $0 < CI \leq 1$, the concentration curve will be located below the line of absolute equality, indicating that water use concentrates more on the rich people[35,36]. As water resource is the cornerstone of human society development; If the allocation of water use is more concentrated on the poor ($-1 \leq CI < 0$), it means that the poor may have more opportunities to develop irrigated agriculture, hydropower, and other water-consuming industries, potentially increasing their capacity to adapt to water shortage and narrowing their economic gap with the rich. For this reason, we define that a pro-poor water use allocation shows more equity than the pro-rich one. We calculate the *CI* either within a certain country or a certain GDP per capita group (see above) to explore different water use distribution patterns among different geographical and social units, as well as focusing on the differences between people in developing and developed countries. Supplementary Fig. 3 provides a schematic illustration of possible combinations of water use inequity and inequality changes due to international trade, showing inequality and inequity can change towards either the same or the opposite directions. Our work focuses on both water use inequality and inequity to simultaneously factor into whether water resource is used evenly (equality) and prone to the population who need it more (equity). The changes of inequality and inequity are calculated by equations 7-8:

$$\Delta Inequality = |CI_{pro}| - |CI_{con}| \quad (7)$$

$$\Delta Inequity = CI_{pro} - CI_{con} \quad (8)$$

Where, $\Delta Inequality$ (i.e., Δ|CI|) and $\Delta Inequity$ (i.e., Δ|CI|) denote the effects of agricultural trade on the water use inequality and inequity respectively, CI_{pro} and CI_{con} denote production-based and consumption-based concentration index.

Crop-specific and trading-partner-specific contributions

We select 8 countries based on the development stage (e.g., developing or developed countries), the type of synergy and trade-off between water scarcity and inequity (e.g., win-win, lose-lose, and two types of trade-offs), population, spatial coverage, and the amount of trade flow (Supplementary Fig. 10). Specifically, we first select the most populous developing and developed country within each of the synergy and trade-off type, respectively, to cover as much influenced population as possible. However, none of the eight selected countries is distributed in South America and Australia, while three ones are in Europe. In order to cover as many continents as possible, we keep one European country (i.e., Sweden, where water use allocation has shifted from concentrated on the rich (CI_{con} > 0) to the poor (CI_{pro} < 0), making it important). In the remaining two vacant categories (i.e., two European countries are dropped), we choose Australia and Argentina, the most populous South American country in the category. In this way, the eight selected countries are India, Nigeria, China, Argentina, Australia, Japan, Sweden, and USA, with a relatively wide spatial coverage, and consisting of 47% of the total population.

We further identify the critical crop species or trading partners that primarily drive the agricultural trade-induced changes in water scarcity, inequality, and inequity for selected countries. To evaluate crop-specific contribution in each selected country, we only consider its agricultural trade for each individual crop in turn, while assuming no trade flow for the remaining crop species. Similarly, we evaluate trading-partner-specific contribution by only considering the selected country's agricultural trade with each individual trading partner, while assuming no trade flow between the selected country and other trading partners. By comparing and analyzing various crop-specific and trading-partner-specific scenarios, we decompose each individual crop type and trading partner's contribution, and further estimate their relative importance to provide targeted opportunities for reinforcing synergies and mitigating trade-offs among water scarcity, inequality, and inequity embodied in agricultural trade using the equations 9-14 below. The relative importance is determined by multiple of the median value (MoM), which is widely-used in previous studies[38-40].

$$WSI_{Imp_{ic}} = WSI_{ic_{pro},others_{con}} - WSI_{con} \tag{9}$$

$$RI_{WSI_{Imp_{ic}}} = \frac{WSI_{Imp_{ic}}}{\left|WSI_{Imp_{median}}\right|} \tag{10}$$

$$Inequality_{Imp_{ic}} = \left|CI_{ic_{pro},others_{con}}\right| - |CI_{con}| \tag{11}$$

$$RI_{Inequality_{Imp_{ic}}} = \frac{Inequality_{Imp_{ic}}}{\left|Inequality_{Imp_{median}}\right|} \tag{12}$$

$$Inequity_{Imp_{ic}} = CI_{ic_{pro},others_{con}} - CI_{con} \tag{13}$$

$$RI_{Inequity_{Imp_{ic}}} = \frac{Inequity_{Imp_{ic}}}{\left|Inequity_{Imp_{median}}\right|} \tag{14}$$

Where, WSI_Imp_{ic}, $Inequality\_Imp_{ic}$, and $Inequity\_Imp_{ic}$ denote the impacts of crop i or trading partner c on the overall change of water scarcity, inequality, and inequity respectively for a certain country; $WSI_{ic\_pro,others\_con}$ and $CI_{ic\_pro,others\_con}$ denote the water scarcity index and concentration index when the crop i or trading partner c is under production-based accounting while other crops or countries are under consumption-based accounting (only crop i or trading partner c is traded); WSI_{con} and CI_{con} denote the consumption-based water scarcity index and concentration index for all crops and countries (no trade, or assuming that domestic production meets the consumption); $RI\_WSI\_Imp_{ic}$, $RI\_Inequality\_Imp_{ic}$, and $RI\_Inequity\_Imp_{ic}$ denote the relative importance of crop i or trading partner c's contribution to the overall change of water scarcity, inequality, and inequity respectively for a certain country; WSI_Imp_{median}, $Inequality\_Imp_{median}$, and $Inequity\_Imp_{median}$ denote the median WSI_Imp_{ic} , $Inequality\_Imp_{ic}$, and $Inequity\_Imp_{ic}$ among all the crops or trading partners respectively.

Data availability

Data used to perform this work can be found in the Supplementary Information. Numerical results for Figs. 1–5 are provided with this paper as Source Data, any further data that support the main findings of this study are available from the corresponding authors upon request. Source data are provided with this paper.

Code availability

Computer code or algorithm used to generate results that are reported in the paper and central to the main claims are available from the corresponding authors upon request.

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Author Contributions

Y.Q. designed this study. W.G., C.H., S.S. and M.K. led the data analysis. Y.L., Q.Z., F.Z., X.W. and F.W. contributed to the discussion and interpretation of the results. W.G. and Y.Q. wrote the paper with input from all co-authors.

Competing interests

The authors declare no competing financial interests.

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Figure captions

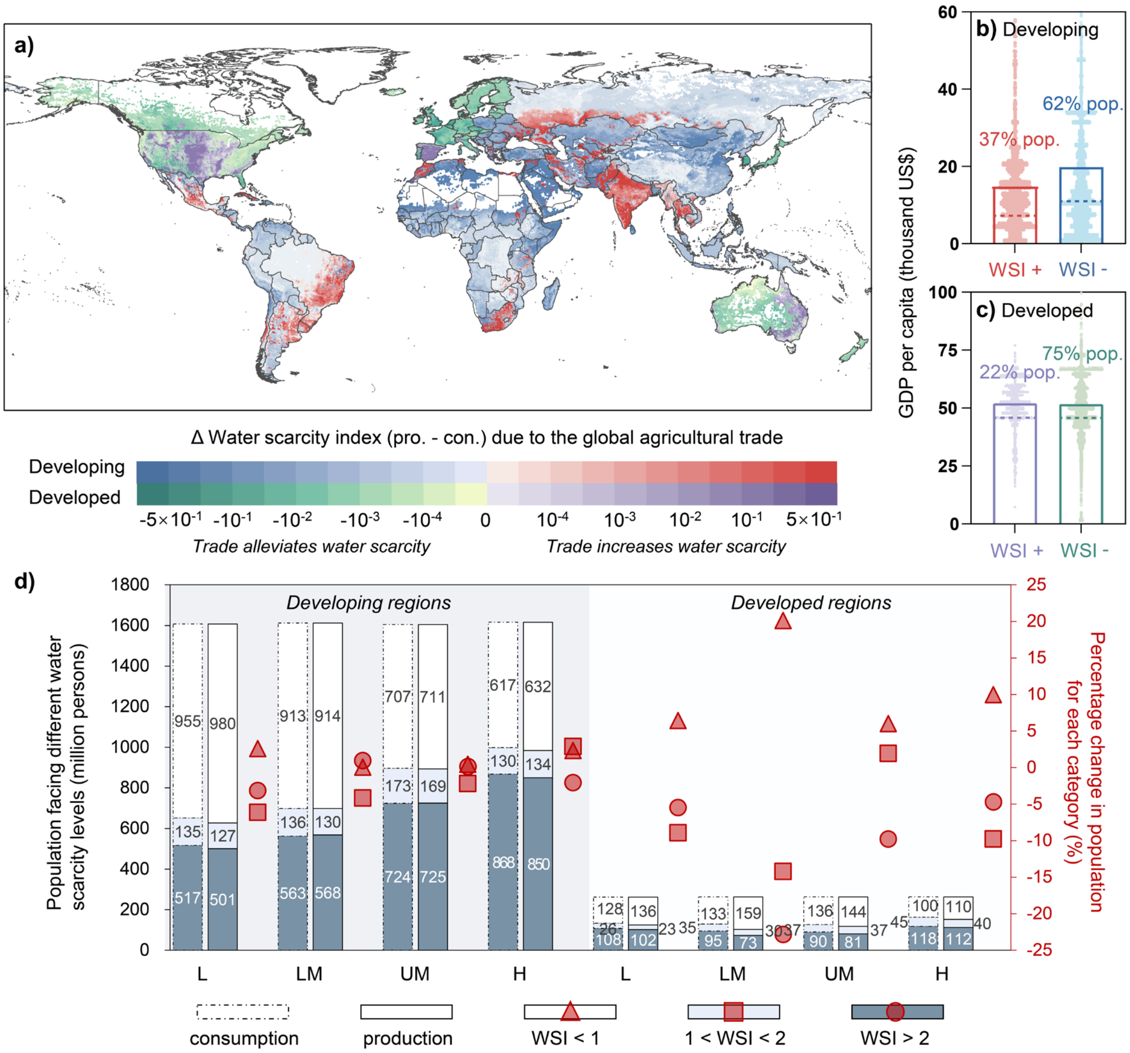

Figure 1 | Asymmetric change of water scarcity embodied in international agricultural trade across developing/developed countries and populations. a, The spatial distribution (0.25°×0.25°) of WSI changes due to international agricultural trade. Global basemaps are based on Natural Earth[76] and plotted with R 3.5.1. **b,** The distribution of GDP per capita for people with increased and decreased water scarcity index in developing countries and **c,** developed countries due to agricultural trade. Each point denotes the GDP per capita (constant 2015 US$) for a grid cell. The height of the bar denotes the arithmetic mean of grid-level GDP per capita, and the dashed line denotes the population-weighted average. The share of people with increased and decreased water scarcity index (WSI) is indicated above the bar. **d,** Absolute (the left y-axis) and percentage (the right y-axis) changes in the population facing different water scarcity levels due to international agricultural trade for different groups (L: low GDP per capita, LM: lower-middle GDP per capita, UM: upper-middle GDP per capita, and H: high GDP per capita) in developing and developed countries. Results are based on the average of year 2017-2019.

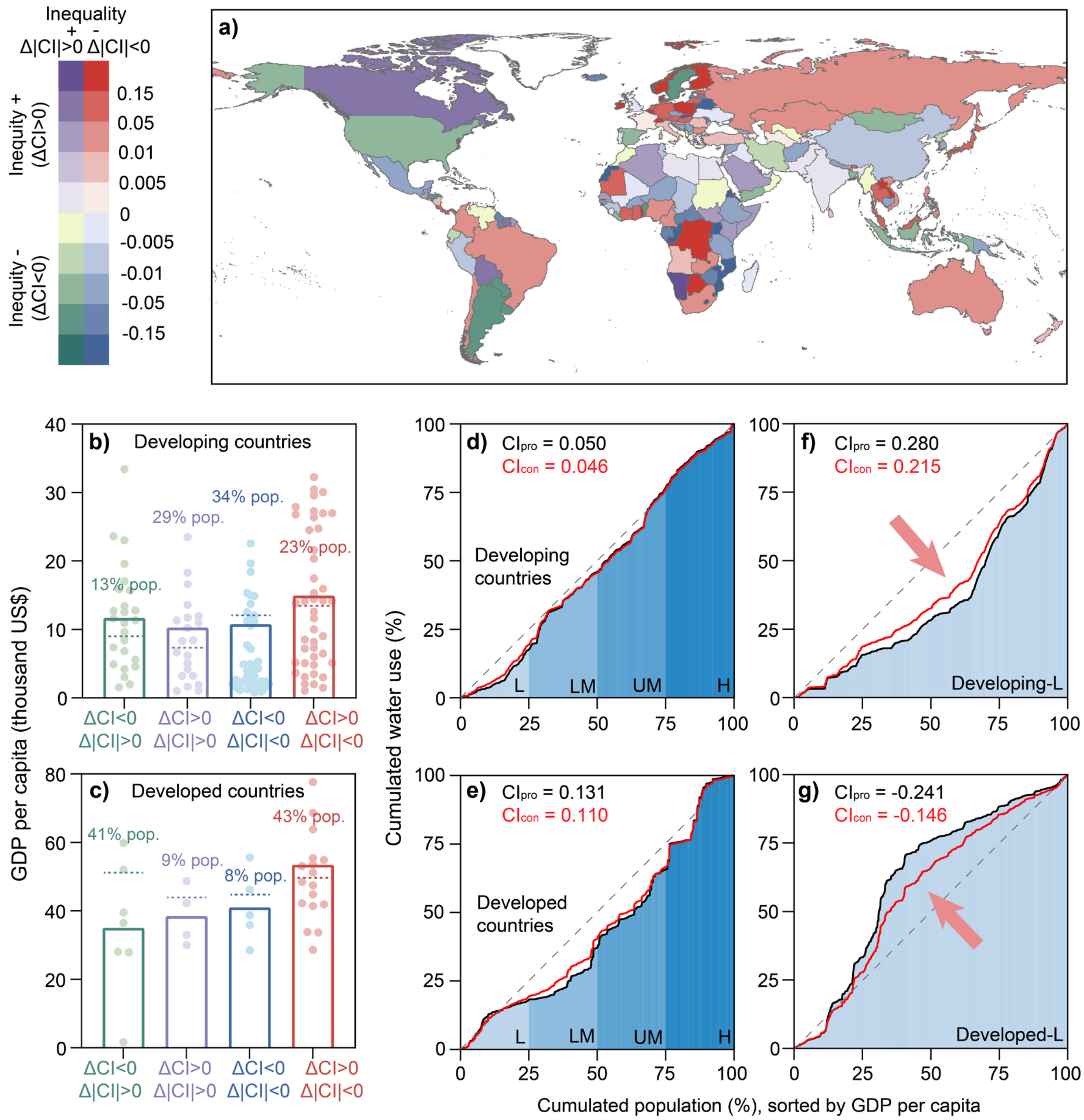

Figure 2 | Asymmetric changes of water use inequality and inequity embodied in international agricultural trade across developing/developed countries and populations. a, Country-level water use inequality and inequity changes due to international agricultural trade. Increases (Δ|CI| > 0) and decreases (Δ|CI| < 0) of water use inequality are obtained by subtracting the absolute value of consumption-based concentration index ($|CI_{con}|$) from the absolute value of the production-based ($|CI_{pro}|$). The pro-poor (ΔCI < 0) and pro-rich (ΔCI > 0) denoting changes in water use inequity are obtained by subtracting CI_{con} from CI_{pro} directly. Global basemaps are based on Natural Earth[76] and plotted with R 3.5.1. **b,** The distribution of GDP per capita for people with increased (Δ|CI| > 0, pro-rich) and decreased (Δ|CI| < 0, pro-poor) water use inequality and inequity in developing countries and **c,** developed countries. Each point denotes GDP per capita (constant 2015 US$) for one country. The height of the bar denotes the arithmetic mean of countries, and the dashed line denotes the population-weighted average. The proportion of people with increased/decreased water use inequality and inequity (four categories) is indicated above the bar. **d,** The concentration curve illustrating water use inequality and inequity for developing countries, **e,** developed countries, **f,** the low GDP per capita group in developing countries, and **g,** the low GDP per capita group in developed countries. The dashed line denotes the status of absolute equality (CI = 0) that everyone has equal water consumption. The black solid line denotes production-based concentration curve and the red line denotes consumption-based concentration curve. Production-based concentration index (CI_{pro} in black) and consumption-based concentration index (CI_{con} in red) are shown at the upper-left corner of the panels with the corresponding colors. The direction of the arrows in **f** and **g** points from consumption-based (before trade) to production-based (after) concentration curve.

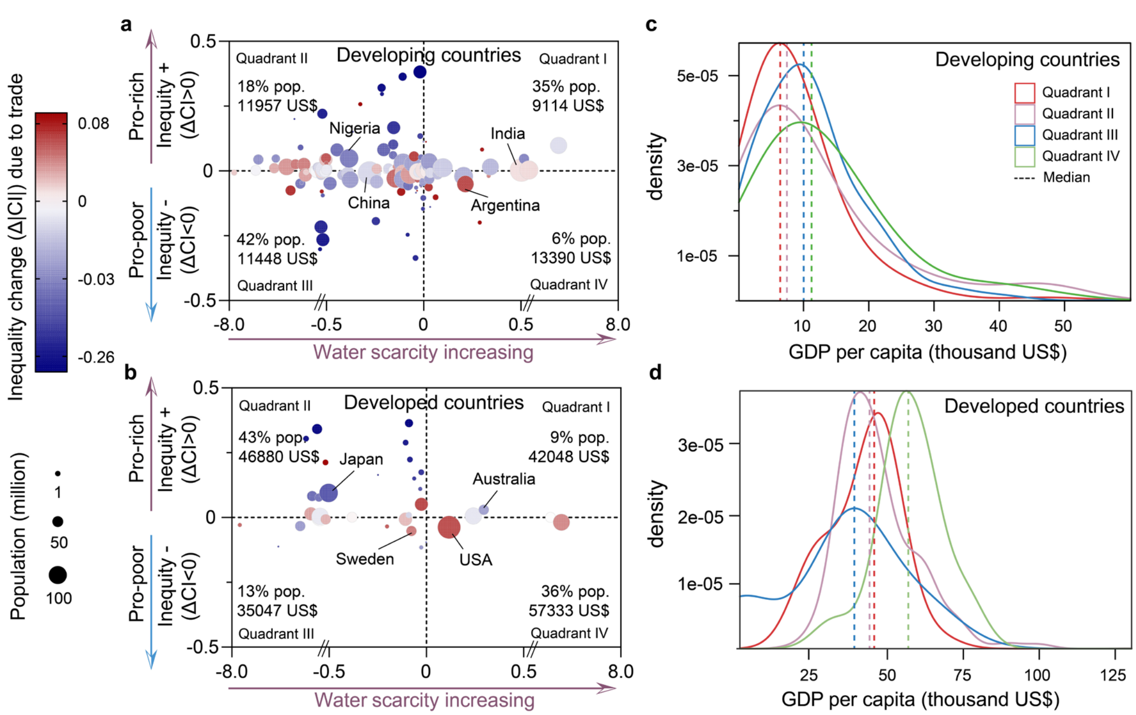

Figure 3 | Synergies and trade-offs between water scarcity, inequality, and inequity embodied in international agricultural trade. a,b, Country-level changes in population-weighted water scarcity, water use inequality and inequity in developing countries (**a**) and developed countries (**b**). Each circle denotes one country. The size of circles represents the population amount and the colour denotes the increase (red) and decrease (blue) magnitude of water use inequality. The coordinate of each circle denotes changes in water scarcity (x axis) and water use inequity (y axis). For countries whose absolute WSI changes range from 0.5 to 8 (separated by double slashes in x-axis), they are plotted in a compressed x-axis (the same length as 0-0.5) using the normalization method for clear visualization. That is, for the absolute WSI changes larger than 0.5, |plot data| = min + (1 − min)(|original data| − min)/(max − min), min = 0.5, max = 8; the sign of plot data is consistent to the original data. According to the changing direction of water scarcity and water use inequity, the countries can be divided into four quadrants. I: increased water scarcity and increased water use inequity (lose–lose); II: (trade-off); III: (trade-off) and IV: (synergy). Quadrant-specific population share and population-weighted GDP per capita (constant 2015 US$) are denoted in each quadrant. c,d, The density plot for grid-level population-weighted GDP per capita in each quadrant in developing countries (**c**) and developed countries (**d**). The dashed line denotes the median of GDP per capita in each quadrant, and the peak of each density plot denotes the mode of GDP per capita in each quadrant.

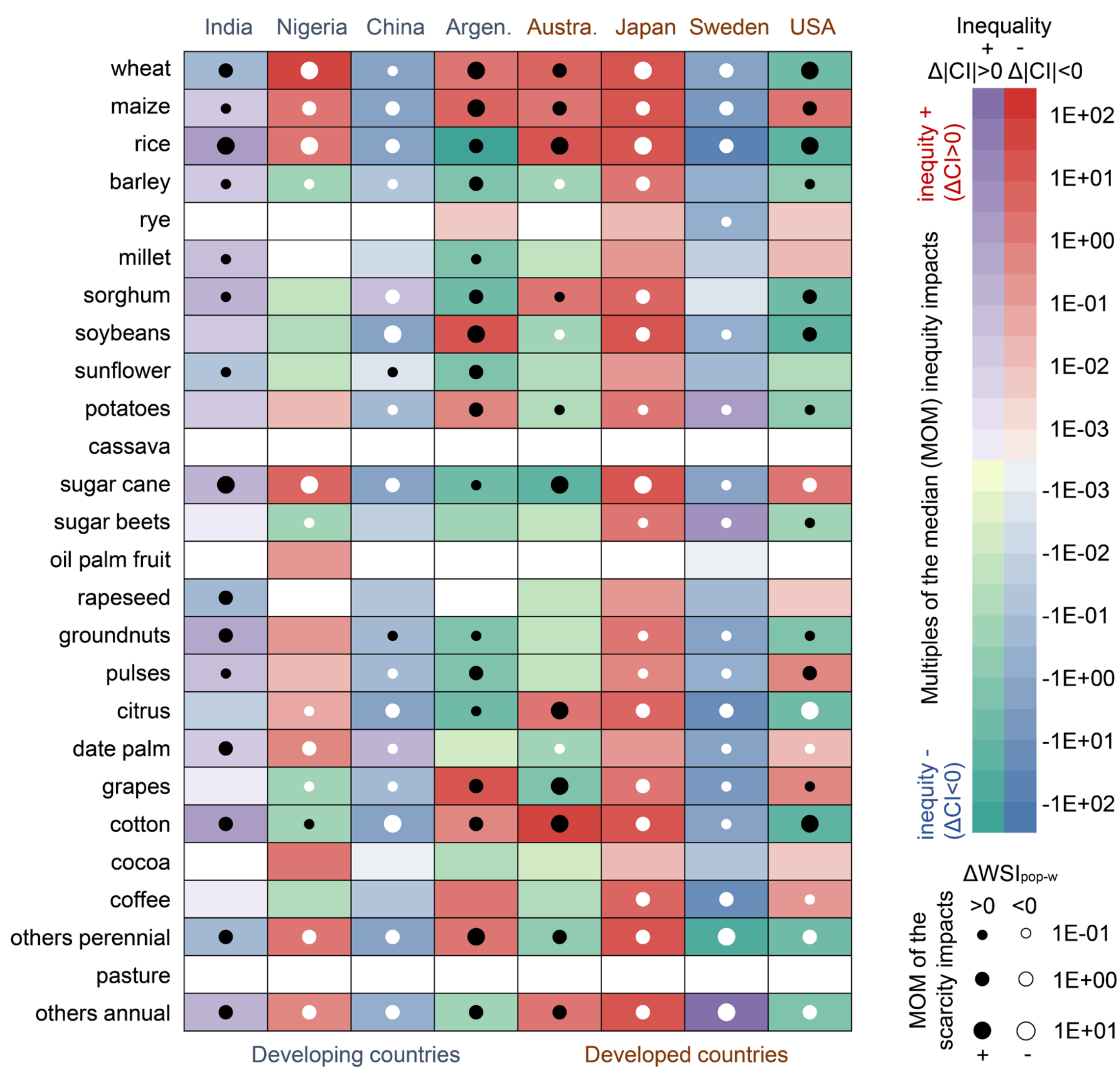

Figure 4 | Relative importance of crop-specific contribution to the change of water scarcity, inequality, and inequity due to international agricultural trade for eight selected countries. Black (white) circle denotes water scarcity increase (decreases) due to crop-specific agricultural trade. The size of the circle denotes the relative importance of crop-specific water scarcity impacts. Relative importance is calculated through dividing the change of water scarcity for a certain crop in a certain country by the median value of all the changes, identified as multiples of the median (MoM) value. The color of the heatmap denotes the relative importance of crop-specific contribution to increased or decreased water use inequality and inequity.

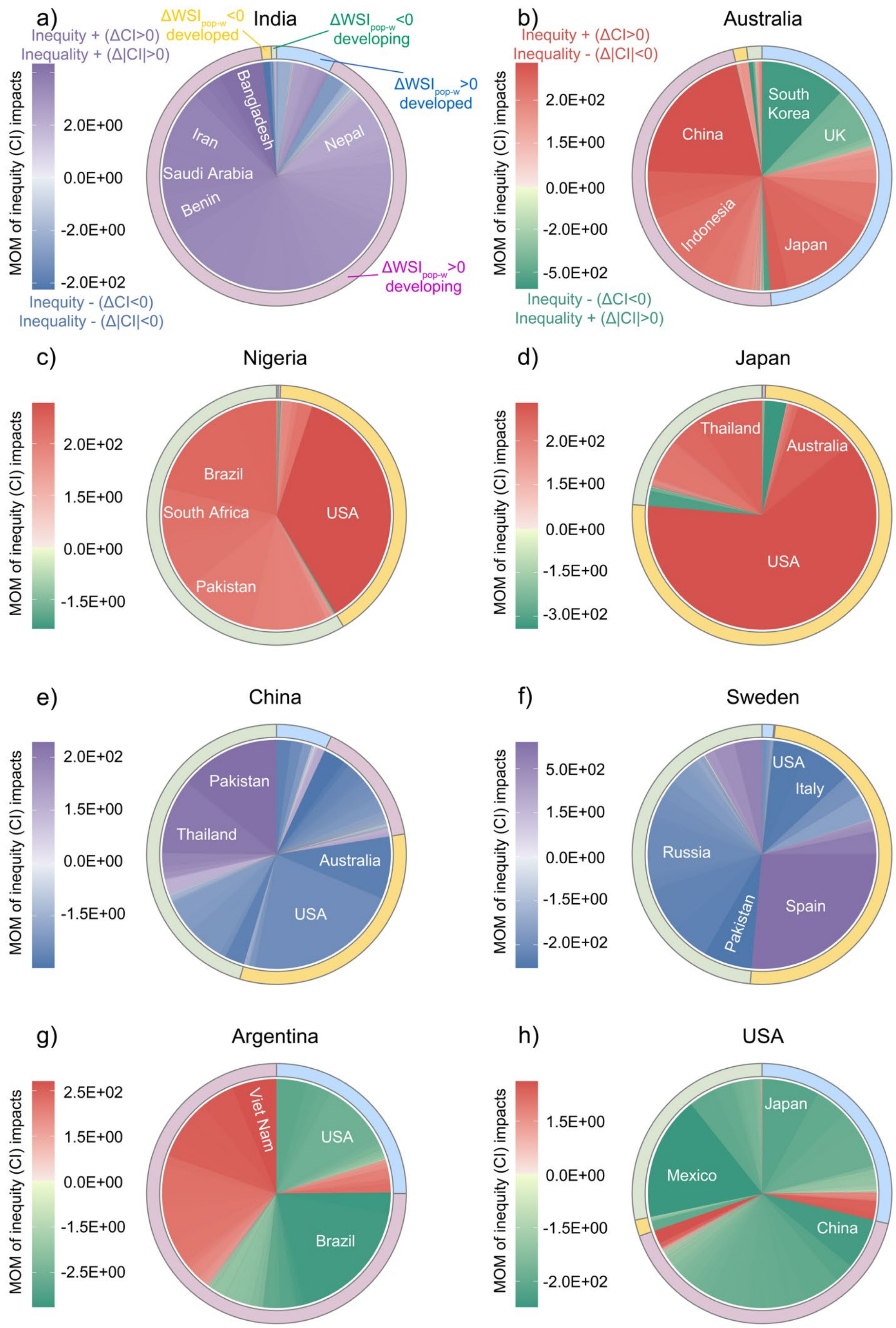

Figure 5 | Relative importance of trading-partner-specific contribution to the change of water scarcity, inequality, and inequity due to international agricultural trade for eight selected countries. The color of the pies denotes the relative importance of trading-partner-specific contribution to increased or decreased water use inequality and inequity. Relative importance is calculated through dividing the change of water use inequity and inequality for a certain trading partner by the median value of all the changes, identified as multiples of the median (MoM) value. In the meanwhile, the share of the pies denotes the relative importance of trading-partner-specific contribution to increased (ΔWSI > 0) or decreased (ΔWSI < 0) water scarcity. In addition, the ring outside of the pie chart consists four categories of trading partners, as shown in the texts alongside the ring of India (**a**). Eight selected countries are **a,** India, **b,** Australia, **c,** Nigeria, **d,** Japan, **e,** China, **f,** Sweden, **g,** Argentina, and **h,** USA. The critical information presented by the figure is listed in Supplementary Table 7 and 12.

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