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Water Inequity in Global Agricultural Trade

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Water Inequity in Global Agricultural Trade

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UNU-INWEH specializes in addressing critical global security and development challenges at the intersection of water, environment, and health. Through research, capacity development, policy engagement, and knowledge dissemination, the institute bridges the gap between scientific evidence and the practical needs of policymakers and UN member states, with particular attention to low- and middle-income countries. By collaborating with a diverse array of partners—including UN agencies, governments, academia, the private sector, and civil society—UNU-INWEH develops solutions that advance human security, resilience, and sustainability worldwide.

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Glossary of Abbreviations

SDG	Sustainable Development Goals
GDP	Gross Domestic Product
PTF	Physical Trade Flow
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
CI	Concentration Index
WSI	Water Scarcity Index
DR Congo	Democratic Republic of the Congo
Pro	Production-Based
Con	Consumption-Based

Executive Summary

Two siblings drink from a remote tap in rural sub-Saharan Africa. Photo by Riccardo Niels Mayer, Adobe Stock.

Freshwater is a cornerstone for the fulfilment of multiple United Nations' 2030 Sustainable Development Goals (UN SDGs). Despite its significance, water scarcity remains a severe global issue, affecting over 2 billion people, creating a major barrier to achieving the UN SDGs. The agricultural sector, heavily dependent on water, plays a pivotal role in this context. Agricultural trade, by virtually transferring the water embedded in traded goods, significantly influences regional water availability, water use inequality, and equity. This report by the United Nations University Institute for Water, Environment and Health (UNU-INWEH) provides a comprehensive investigation of these impacts, aiming to inform policies that harmonize water management, trade, and social equity.

The analysis makes an effort to distinguish between water use inequality and inequity. Inequality in water use refers to the uneven distribution of water resources among different regions and populations, often quantified using metrics like the Gini coefficient. Inequity, on the other hand, highlights the disproportionate impacts on different income groups, emphasizing how poorer populations are more vulnerable due to their reliance on water-dependent economies and lower adaptive capacities. Addressing both inequality and inequity is essential for achieving the SDGs, particularly those related to poverty eradication and social justice.

International agricultural trade reshapes global irrigation water consumption, influencing water scarcity, inequality, and inequity across countries with affecting national incomes. The report reveals that international agricultural trade generally alleviates water scarcity for a significant portion of the global population, particularly benefiting regions like Northern China, Europe, and northern Africa. Developed countries experience more substantial water scarcity alleviation compared to developing countries, with 75% of their population benefiting from reduced scarcity. However, in developing countries, 62% of the population benefit from reduced water scarcity, but 37% of the population, who are 8% poorer on average, experience increased scarcity, reflecting the disproportionate impacts of international agricultural trades on lower-income groups.

Trade-induced increases in inequality and inequity are observed in regions such as northern Africa and Saudi Arabia, while improvements are seen in China and some African countries. Developing countries face higher instances of increased inequality and inequity (29% of the population). Among them, 70% experience what can be considered unjust, where limited or unequal access to water is not due to natural constraints, but largely driven by trade-related imbalances that severely exacerbate the water scarcity and undermine their quality of life. Developed countries see lower instances of such increases (9% of the population). Both groups of developing and developed countries experience agricultural water use favoring higher-income populations. In developing countries, trade exacerbates inequality and inequity among low-income groups, while in advanced economies, trade promotes a pro-poor water allocation perception (i.e., higher water equity) but increases inequality in practice.

The report underscores the importance of addressing both water scarcity and inequity in policymaking. While international agricultural trade can alleviate water scarcity, it often increases inequality and inequity, especially in developing countries. Policymakers should consider of the implications of the current and future water management policies and agricultural trade strategies on the poorest and most vulnerable populations. Aligning trade policies with sustainable water management practices can balance benefits and mitigate adverse impacts of virtual water trades around the world. Enhancing adaptive capacities by supporting developing countries in building resilience against water scarcity through investment in water infrastructure and adoption of efficient irrigation technologies is crucial. Robust monitoring systems should be established to continuously assess the impacts of trade on water scarcity, inequality, and inequity, using data-driven approaches to adapt policies dynamically.

Encouraging the adoption of sustainable agricultural practices that optimize water use efficiency, such as precision farming and crop diversification, and promoting research and development in drought-resistant crop varieties and innovative water-saving technologies are vital steps. Recognizing and addressing regional disparities in water availability and trade impacts, tailoring policies to local contexts, and facilitating regional cooperation to manage transboundary water resources effectively are essential for the fair distribution of costs and benefits.

Pump irrigation in rice fields. Photo by Faris Fitrianto, Adobe Stock.


Wheat harvest in Western Australia. Photo by Chris, Adobe Stock.

International agricultural trade has profound and complex impacts on global water use, significantly influencing water availability, inequality, and inequity. Achieving sustainable development requires integrated water and trade policies that address these multifaceted challenges, ensuring the benefits of trade are equitably distributed and that vulnerable populations are protected. By focusing on both water use equality and equity, substantial progress can be made towards multiple SDGs, promoting a more just and sustainable world.

This UNU-INWEH report will pave the way to inform future efforts to further explore the long-term impacts of trade on water resources under different climate change scenarios, the role of non-agricultural water use sectors in influencing trade-related water scarcity and equity outcomes, and the effectiveness of specific policy interventions in different socio-economic and geographical contexts. Engaging a broad spectrum of stakeholders, including governments, international organizations, the private sector, and civil society, is crucial to develop and implement comprehensive strategies that address the intertwined challenges of water scarcity, inequality, and inequity. By fostering collaboration and innovation, the global community can create resilient and inclusive systems that ensure sustainable water use and equitable growth for all population groups.

Key Findings

- International agricultural trade generally relieves water scarcity globally, especially in Northern China, Europe, and Northern Africa.
- Due to agricultural trade, the share of the relatively low-income population experiencing no or low water scarcity increases by 20% in developed countries, but by only 0.1% in developing countries, further widening the water scarcity gap between the two economies.
- Developed countries benefit more from food trade-induced water scarcity alleviation than developing countries.
- In developing countries, 62% of the population experience reduced water scarcity, while 37% face increased water scarcity because of food trade, with the latter being 8% poorer.
- In developed countries, 75% of the population benefits from reduced water scarcity as a result of food trades, and only 22% experience an increase.
- Trade-induced water impacts are highly asymmetric. In developing countries, 35% of the population who suffer from increased water scarcity and inequity are the poorest, while in developed countries, the poorest 13% benefit from reduced water scarcity and inequity.
- For the relatively poor in developing countries, water use becomes more concentrated among the affluent due to agricultural trade, leading to a 30% increase in inequity. In contrast, trade reallocates more water to the impoverished, enhancing equity by 65% for the relatively poor populations in developed countries.

1. Introduction

Solina Dam, Poland's largest, on Lake Solina in the Bieszczady Mountains. Photo by Mateusz Łopuszyński, Adobe Stock.

Freshwater plays an essential role in supporting sustainable development due to its intrinsic interconnections with multiple United Nations' Sustainable Development Goals (UN SDGs), including clean water and sanitation (SDG 6), reduced inequalities (SDG 10), no poverty (SDG 1), and zero hunger (SDG 2). Across the globe, over two billion people reside in countries afflicted by severe water scarcity, and approximately 1.2 billion people still lack basic drinking water services[1]. This lack of access to clean water (SDG 6) presents a significant barrier to health and well-being and jeopardizes progress toward other related SDGs[2]. The distribution of water scarcity is profoundly inequitable (SDG 10), with around 80% of those affected living in rural areas and approximately 50% residing in the least developed countries[1]. This inequity poses a substantial threat to water-dependent economies, such as irrigated agriculture, and impedes efforts to end poverty (SDG 1)[3,4]. Furthermore, as approximately 70% of the world's freshwater is used for agriculture[5], water scarcity directly impacts food production, making it a critical factor in reducing hunger and achieving food security (SDG 2).

Agricultural trade is widely identified as a critical policy instrument in balancing food supply and demand, with associated "virtual water" transfers (the water embedded in food and used in the production of traded agricultural goods) significantly reshaping global water scarcity[6,7]. However, the redistribution of water resources through trade can have uneven effects, alleviating water scarcity in some regions while exacerbating it in others[9,10]. These changes can lead to disparities in water use inequality and inequity, driving asymmetric impacts across different population groups.

Extensive research on virtual water has evaluated the global flows of blue (surface and groundwater)[8–10], green (rainwater)[11], and grey (polluted)[12–14] water. Most of these studies focus on the total water savings or losses from trade. Recent efforts have integrated both the supply and demand sides to examine how virtual water flows impact regional water scarcity[15–17], groundwater depletion[18], and climate risks[19]. However, few studies have addressed the implications for water use inequality and inequity[20–23], often relying on coarse data that fails to capture fine-scale impacts, particularly for the poor[21–23], and treating the agricultural sector as a monolithic entity without differentiating crop-specific impacts[20].

In analyzing the impacts, it is crucial to distinguish between water use inequality and inequity. Water use inequality metrics, such as the Gini coefficient[24,25], Theil index[24,26], and interquartile ratios[27], quantify the uneven access to water among populations or regions, indicating whether everyone receives the same amount of water allocation. However, this report defines water use inequity to differentiate the impacts on different income groups, especially the poorest populations, who are typically the most vulnerable[28]. Given this, the poor may require more water resources to develop their livelihoods, such as through irrigated agriculture and hydropower, which are crucial for their growth. Therefore, this report assumes that allocating water resources in a way that favors the poor would lead to higher equity than a pro-rich allocation. Striving for equal water distribution without considering the differentiated needs of various populations can impede the fulfilment of SDG 1, as the poor have a greater reliance on water-dependent economies and a lower capacity to adapt to water shortages. Therefore, addressing the specific needs of the poorest is essential for eradicating extreme poverty and ensuring sustainable development for all.

Dry riverbed near God's Eye Mountain in Kaobang, Vietnam. Photo by ilyaska, Adobe Stock.

To address this gap, this report develops an integrated framework to comprehensively assess the synergies and trade-offs of changing water scarcity, inequality, and inequity embodied in international agricultural trade. This framework focuses on different levels of GDP per capita (i.e., low, lower-middle, upper-middle, and high) in both developing and developed countries. Specifically, this analysis simulates 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[18], and overlay this with gridded GDP per capita information[29]. Then the analysis compares the multi-scale changes in water scarcity (measured by population-weighted water scarcity index), water use inequality (measured by the absolute value of the concentration index, |CI|), and inequity (measured by the sign of CI)[30–34] to provide a comprehensive understanding of the impacts and trade-offs. This detailed data fusion allows us to reveal trade-induced changes in water use scarcity, inequality, and inequity patterns within and across different global economies. Detailed information about the study method and analysis components can be found in Appendix I.

This report by the United Nations University Institute for Water, Environment and Health (UNU-INWEH) highlights the challenges faced by the most vulnerable populations and emphasize the need for targeted water and trade policies that balance multiple critical SDGs. By identifying critical trading-partner-specific and crop-wise trade flows and their underlying factors, the framework provides a robust basis for designing informed and equitable policies to support sustainable development for all.

This investigation underscores the importance of integrating changes in regional water scarcity with local poverty and inequality considerations. It illustrates the complex interactions between international trade, water resources, and socioeconomic factors, emphasizing the need for a nuanced approach to policy-making. Ensuring that the benefits of trade are equitably distributed and that the most vulnerable populations are protected is essential for achieving the overarching goals of sustainable development and environmental justice.

African woman transporting fresh water. Photo by Riccardo Niels Mayer, Adobe Stock.

2. Unequal Impacts of International Agricultural Trade on Global Water Scarcity

Harvester working in the wheat field in Ukraine. Photo by Lalsstock, Adobe Stock.

International agricultural trade generally alleviates water scarcity for much of the global population, with significant benefits observed in regions such as Northern China, Europe, and northern parts of Africa. These regions experience a notable reduction in their Water Scarcity Index (WSI) due to the trade of agricultural products, which generally helps with redistributing water resources more efficiently on a global scale. However, the impacts of trading food and its embedded water are not uniform across the globe. Certain areas, particularly in developing countries like India and Pakistan, and in developed regions such as eastern Australia and central USA, do not benefit equally from agricultural trades. In these regions, the trade-related alleviation of water scarcity is either minimal or even negative, leading to increased water stress for some populations.

In developed countries, the benefits of international agricultural trade on water scarcity are substantial. Approximately 75% of the population (785 million) in these regions experiences a reduction in water scarcity due to trade, while only 22% (230 million) faces an increase. This discrepancy is partly due to the higher GDP per capita in developed countries, which is roughly twice that of developing countries. This higher income level indicates a greater adaptive capacity, meaning that developed countries are better equipped to manage and mitigate water scarcity through infrastructure and technology, such as advanced irrigation systems and efficient water management practices.

Young African girl carrying a heavy water container. Photo by Riccardo Niels Mayer, Adobe Stock.

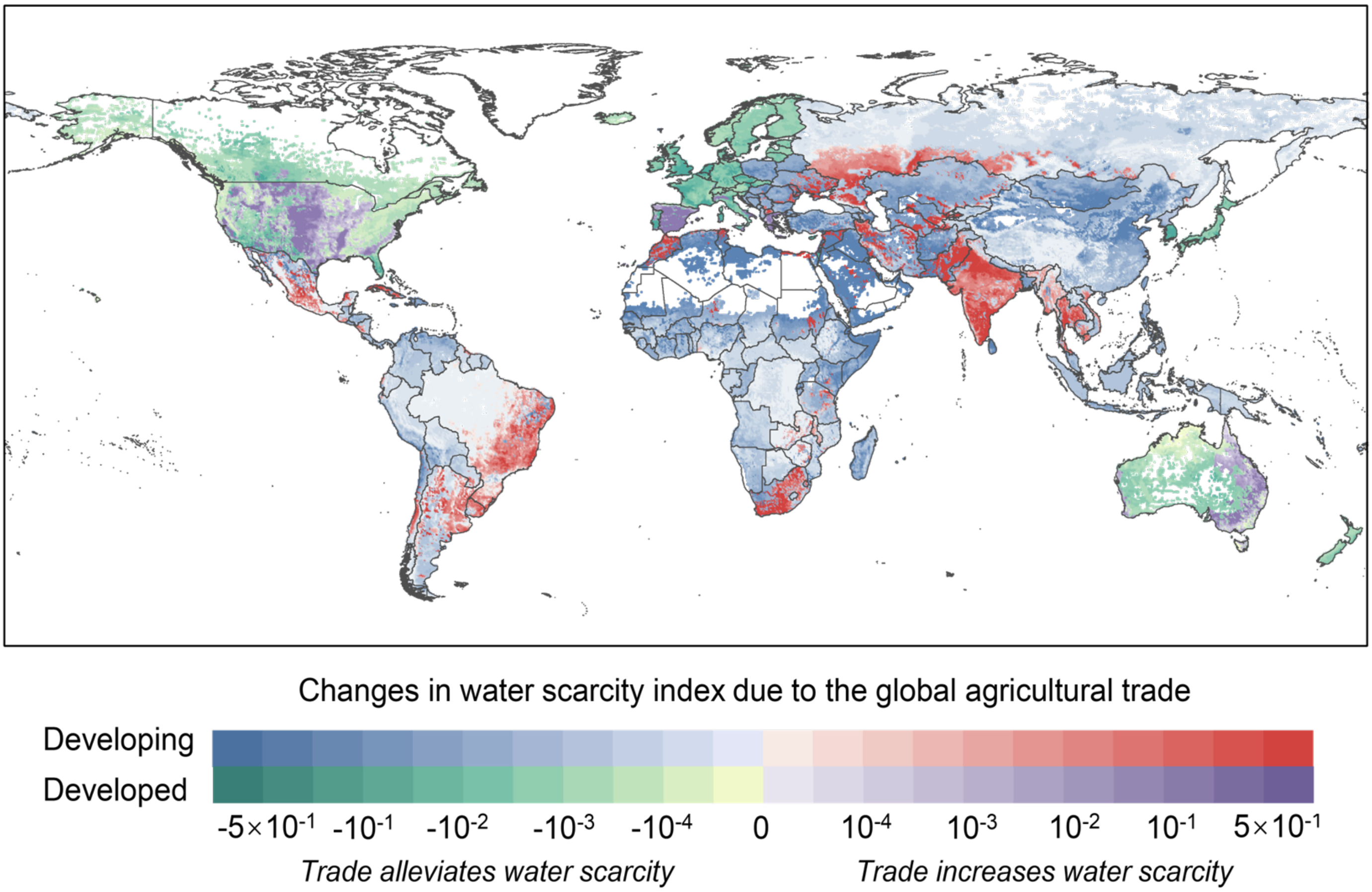

Figure 1. Grid-level water scarcity changes embedded in international agricultural trade. The map illustrates the spatial distribution (0.25°×0.25°) of changes in water scarcity index due to international agricultural trade.

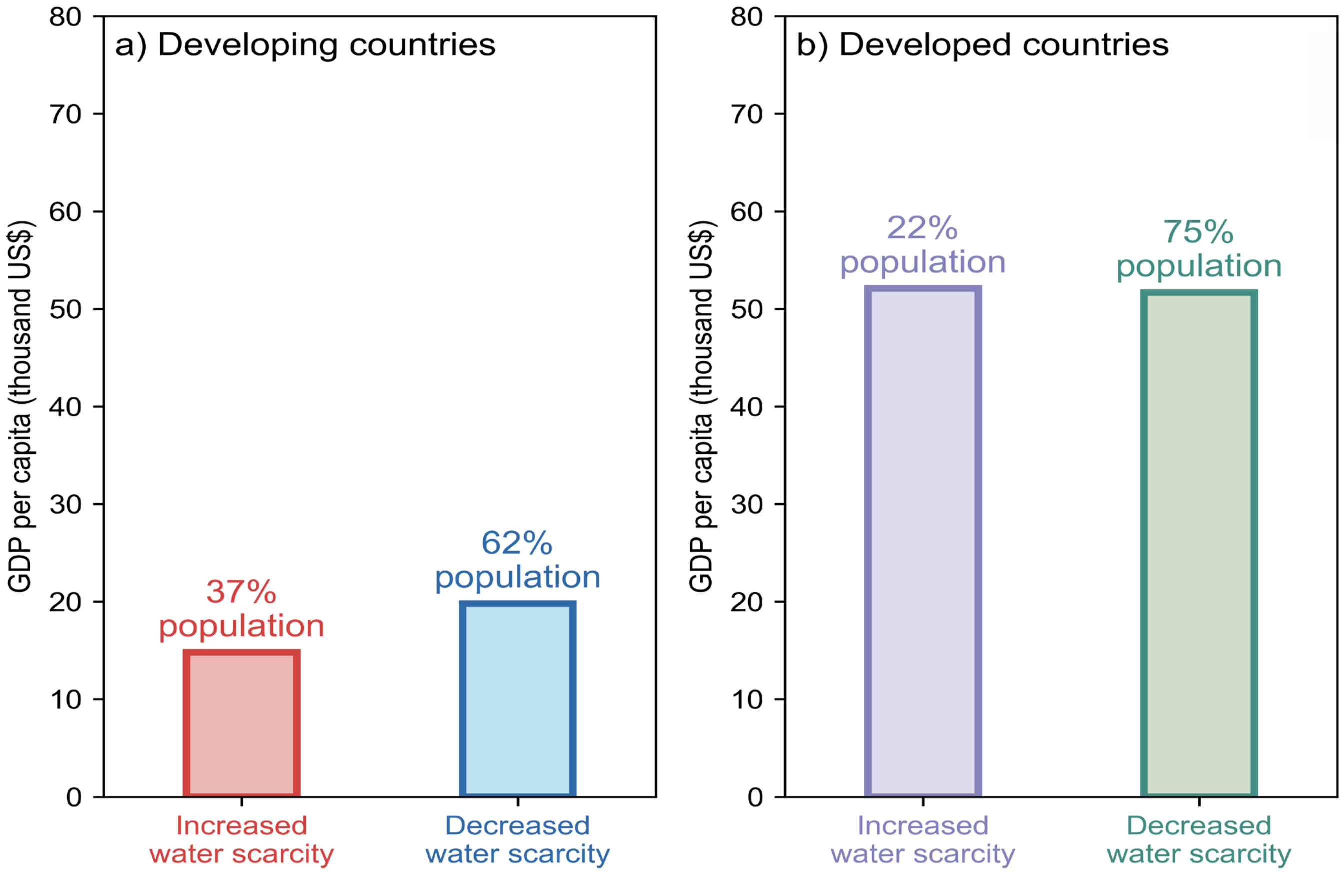

Figure 2. Average GDP per capita and population share for people with increased or decreased water scarcity index in developing (a) and developed (b) countries. The share of population with increased or decreased water scarcity due to international agricultural trade is indicated above the bar. A small share of the population (1% in developing countries and 3% in developed countries) is in regions not affected by agricultural trade.

Individuals are collecting water from a local source in Rwanda. Photo by Amir Aghakouchak.

Conversely, in developing countries, the benefits of international agricultural trade on water scarcity are less pronounced and more unevenly distributed. About 62% (3993 million) of the population in these regions experiences a decrease in water scarcity due to trade, while a significant 37% (2383 million) suffers from increased water scarcity. The populations facing increased water scarcity in developing countries are, on average, 8% poorer than those experiencing decreased scarcity. This disparity suggests that poorer communities, which often lack the resources and infrastructure to adapt to changes in water availability, are disproportionately affected by the negative impacts of international trade.

Analyzing population exposure to different levels of water scarcity reveals further disparities. In developing countries, the population experiencing no or low water scarcity (WSI < 1) increases slightly by about 1.3% due to international trade (from 3193 million to 3235 million). In contrast, in developed countries, this increase is much more significant, at 10.7% (from 497 million to 550 million). Similarly, the population exposed to extreme water scarcity (WSI > 2) decreases by only 1% in developing countries (from 6680 million to 6609 million), compared to a substantial decrease of 10% in developed countries (from 411 million to 369 million). These figures highlight a significant asymmetry in how international trade impacts water scarcity across different regions.

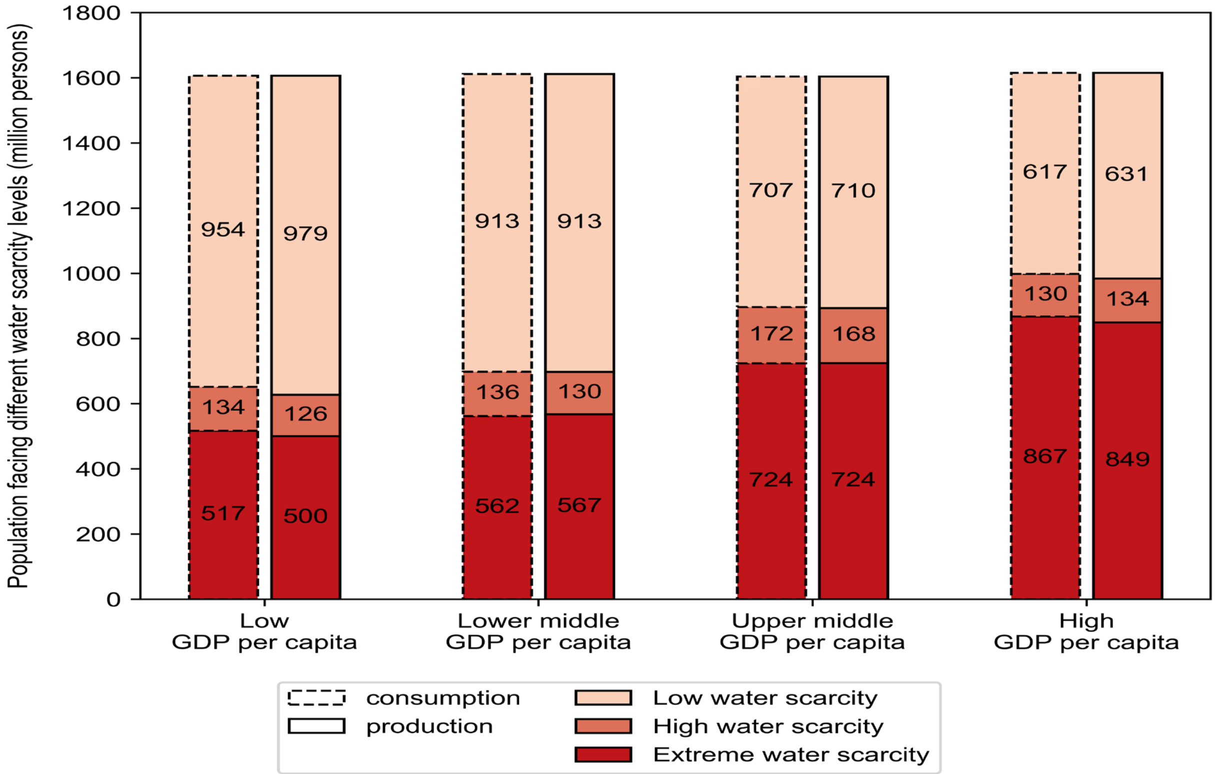

Figure 3. Population facing different water scarcity levels under production- and consumption-side accounting for different groups in developing countries. The population in developing countries is categorized into four quartiles according to GDP per capita, namely low GDP per capita, lower-middle GDP per capita, upper-middle GDP per capita, and high GDP per capita. Low water scarcity indicates water scarcity index lower than 1; High water scarcity indicates water scarcity index larger than 1 but lower than 2; Extreme water scarcity indicates water scarcity index larger than 2.

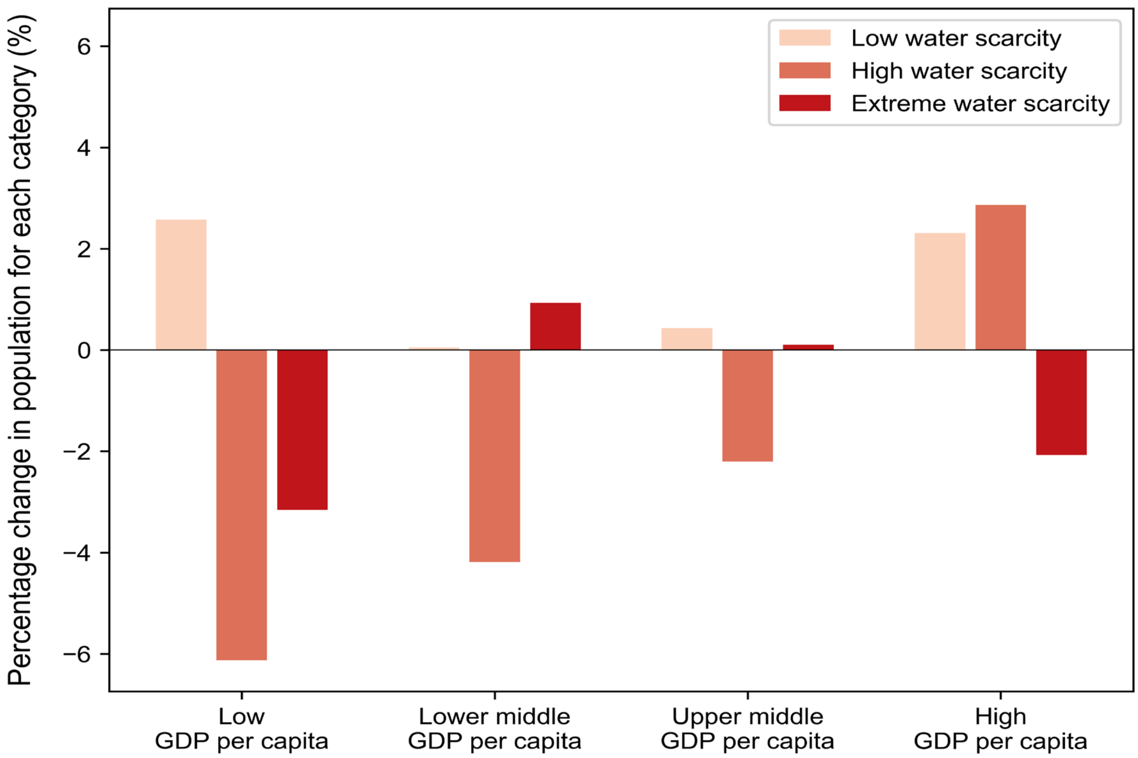

Figure 4. Percentage changes in the population facing different water scarcity levels due to international agricultural trade for different groups in developing countries. The percentage change is calculated as (production-side accounting – consumption-side accounting) / consumption-side accounting. The population in developing countries is categorized into four quartiles according to GDP per capita, namely low GDP per capita, lower-middle GDP per capita, upper-middle GDP per capita, and high GDP per capita. Low water scarcity indicates water scarcity index lower than 1; High water scarcity indicates water scarcity index larger than 1 but lower than 2; Extreme water scarcity indicates water scarcity index larger than 2.

When examining income groups, the disparities become even more pronounced. For the lower-middle income group in developed countries, the population with no or low water scarcity increases by 20% (from 133 million to 159 million) as the result of international agricultural trades, whereas in developing countries, the increase is a mere 0.1% (from 913 million to 914 million) for this income group. Among the richest 1% population in developing countries, the population experiencing no or low water scarcity increases by 56% (from 13.5 million to 21 million), compared to just 2% increase (from 47 million to 48 million) for the poorest 1% population. These statistics indicate that wealthier populations, both in developed and developing regions, benefit more from the alleviation of water scarcity due to international trade. In contrast, poorer populations, particularly in developing countries, continue to face significant challenges.

Overall, while international agricultural trade generally reduces water scarcity on a global scale, the benefits are not evenly distributed. Developed countries and the wealthier segments within developing countries experience more significant reductions in water scarcity. In contrast, poorer populations are more likely to suffer from increased water scarcity, highlighting a disparity that exacerbates the water availability and access gap between rich and poor. This disparity underscores the need for targeted policies and interventions to ensure that the benefits of international trade are equitably distributed and do not disproportionately favor wealthier populations. Addressing these challenges requires a concerted effort to improve water management practices, infrastructure, and adaptive capacities in poorer regions to ensure that all populations can benefit from the positive impacts of international trade.

A woman is collecting water from a local source in Rwanda. Photo by Amir Aghakouchak.

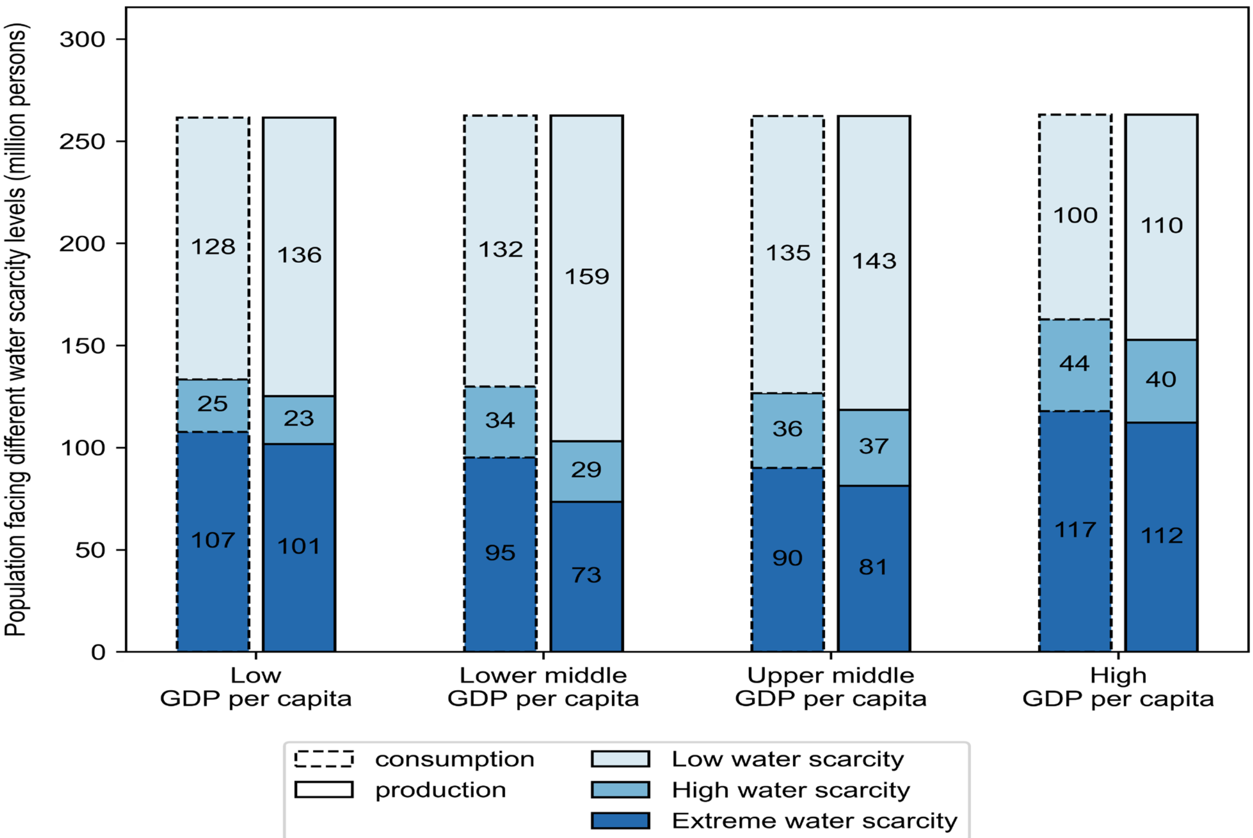

Figure 5**.** Population facing different water scarcity levels under production- and consumption-side accounting for different groups in developed countries. The population in developed countries is categorized into four quartiles according to GDP per capita, namely low GDP per capita, lower-middle GDP per capita, upper-middle GDP per capita, and high GDP per capita. Low water scarcity indicates a water scarcity index lower than 1; High water scarcity indicates a water scarcity index larger than 1 but lower than 2; Extreme water scarcity indicates a water scarcity index larger than 2.

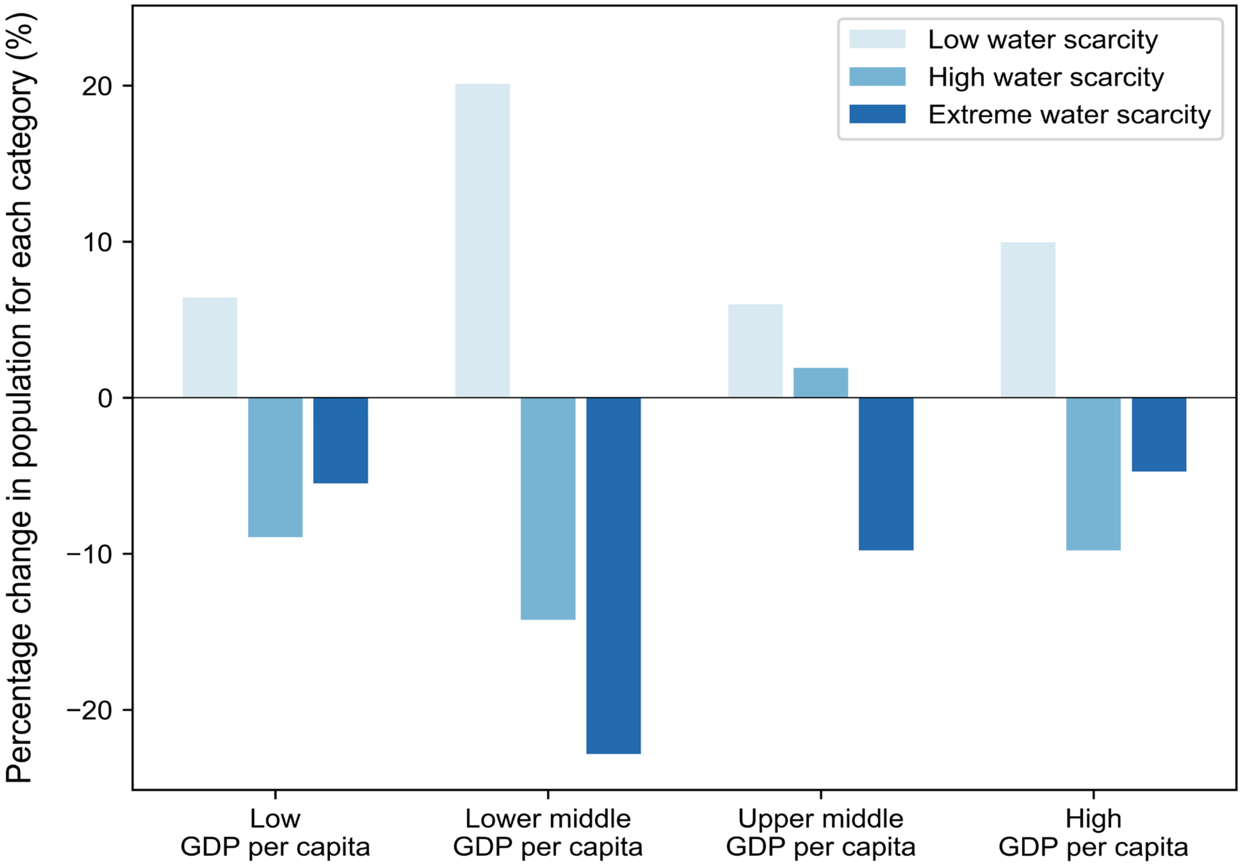

Figure 6. Percentage changes in the population facing different water scarcity levels due to international agricultural trade for different groups in developed countries. The percentage change is calculated as (production-side accounting – consumption-side accounting) / consumption-side accounting. The population in developed countries is categorized into four quartiles according to GDP per capita, namely low GDP per capita, lower-middle GDP per capita, upper-middle GDP per capita, and high GDP per capita. Low water scarcity indicates a water scarcity index lower than 1; High water scarcity indicates a water scarcity index larger than 1 but lower than 2; Extreme water scarcity indicates a water scarcity index larger than 2.

Irrigation field. Photo by PriceM, Adobe Stock.

3. Unequal Impacts of International Agricultural Trade on Global Water Use Inequality and Inequity

Green circular fields created by irrigation in the dry Arabian desert. Photo by JoergSteber, Adobe Stock.

International agricultural trade significantly influences the allocation of water resources, raising concerns about both water use equality and equity. Water use equality refers to equal access to water for all individuals, while equity pertains to the fair allocation of water resources, ideally skewed in favor of the poor. This trade-induced reshaping of water use patterns is evident across various regions, leading to diverse outcomes.

In certain regions, such as northern Africa, particularly Algeria, and Saudi Arabia, international agricultural trade has led to an increase in both inequality and inequity in water use. This means that water resources in these areas may have become more concentrated among wealthier populations, potentially exacerbating existing disparities. Conversely, in some countries like China and parts of Africa, including Ethiopia, trade has had a positive effect, improving both water use equality and equity. These regions have seen a more equitable distribution of water resources, benefiting the poorer population.

Two children drinking sachet water. Photo by ccarlstead, CC BY 2.0. Flickr.

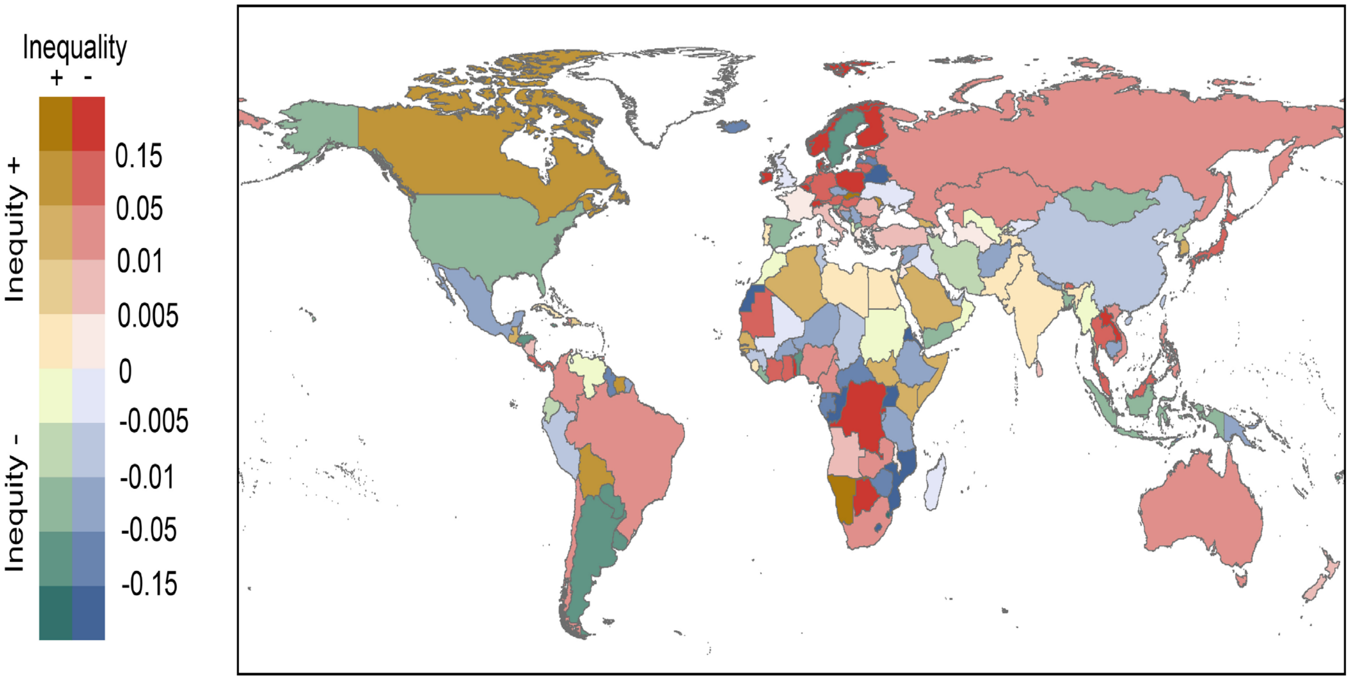

Figure 7. Country-level water use inequality and inequity changes embedded in international agricultural trade. Increases (inequality +, $\Delta|CI| > 0$) and decreases (inequality -, $\Delta|CI| < 0$) of water use inequality are obtained by subtracting the absolute value of consumption-based concentration index ($|CI_{con}|$) from the absolute value of the production-based ($|CI_{pro}|$). The pro-poor (inequity -, $\Delta CI < 0$) and pro-rich (inequity +, $\Delta CI > 0$) denoting changes in water use inequity are obtained by subtracting CI_{con} from CI_{pro} directly.

However, the global picture is more nuanced, with many regions experiencing trade-offs. For instance, in southern Africa, such as the Democratic Republic of the Congo (DR Congo), and in parts of Europe, like Luxembourg, international trade has led to increased inequity but decreased inequality. This indicates that while water resources may be distributed more evenly, they tend to be allocated in favor of wealthier individuals, creating a complex scenario where the overall distribution is fairer, yet still skewed towards the affluent.

The consequences of these trade-induced changes in water use distribution vary significantly. In Algeria, for example, the increase in water use inequity is considered 'unjust' because it results in the loss of minimum water access opportunities for the poorer segments of the population. This lack of access is directly linked to the effects of international trade, making it a severe and critical issue. On the other hand, in Luxembourg, for example, the increased post-trade water inequity is labeled 'regrettable' rather than 'unjust.' This distinction arises because, despite the inequity, water availability remains sufficient both before and after trade, ensuring that basic water needs are met.

When the world is categorized into different continents, African countries exhibit the widest range of changes in inequality or inequity, followed by Europe. In contrast, North America and South America have the smallest range, with fluctuations in inequality and inequity remaining very small (within 0.2). When classifying countries based on the World Bank's income groups, low-income countries experience the most significant variations in water use inequity, indicating that their water use reallocation has been more profoundly affected by global agricultural trade. These changes, however, can be both positive and negative. For instance, DR Congo has witnessed the largest increase in water use inequity globally, whereas Eritrea has experienced the most substantial reduction. This suggests that some low-income countries, such as Eritrea, may benefit from global agricultural trade, enabling vulnerable populations within these countries to access a greater share of water resources. Conversely, other low-income countries, such as DR Congo , need to carefully assess the consequences of trade and explore opportunities to improve water use equity.

The disparity between developed and developing countries in terms of trade-induced water use impacts is stark. In developing countries, 29% of the population is simultaneously exposed to increasing inequality and inequity due to trade. These individuals, who often belong to the lowest income brackets, face significant challenges as the skewed distribution of water resources further limits their access. Among this group, 70% experience what is termed 'unjust' inequity, where the lack of equitable water access severely hampers their quality of life. In contrast, only 9% of the population in developed countries faces the co-occurrence of increasing inequality and inequity due to trade, and within this group, 60% experience 'unjust' inequity.

Despite these challenges, international agricultural trade does offer some benefits. For instance, 34% of the population in the developing regions experiences decreased inequality and improved equity, highlighting that trade can contribute to fairer water distribution under certain conditions. This is a significant contrast to what happens in developed countries, where only 8% of the population benefits from such positive outcomes. This disparity underscores the potential for targeted policies and interventions to harness the positive aspects of trade while mitigating its negative impacts.

The impacts of trade are particularly pronounced among high-income populations in both developing and developed countries. In developing regions like South America and Russia, the wealthiest individuals often face a trade-off: they experience increased inequity but decreased inequality. This means that while water resources are distributed more evenly, they remain disproportionately in favor of the affluent. Conversely, in developed regions such as Europe, the richest populations are exposed to decreased inequity but increased inequality, reflecting a different aspect of trade-induced resource distribution.

Moreover, water use distribution tends to favor higher-income populations in both developing and developed countries. However, the impact on low-income groups varies significantly between these regions. In developing countries, local water consumption already favors the relatively affluent, and international trade intensifies this trend. This results in a 30% increase in both inequality and inequity, further disadvantaging the poorest segments of the population. In contrast, in developed countries, the water allocation starts from a relatively pro-poor stance, with better equity from a consumption perspective. International trade enhances this pro-poor allocation by 65%, though this comes at the cost of greater overall inequality.

These asymmetric patterns underscore the complex and varied impacts of international agricultural trade on water use distribution. They highlight the need for nuanced and targeted approaches to ensure that the benefits of trade are equitably distributed, and that the negative impacts on vulnerable populations are minimized.

Crops in Kansas. Photo by NASA

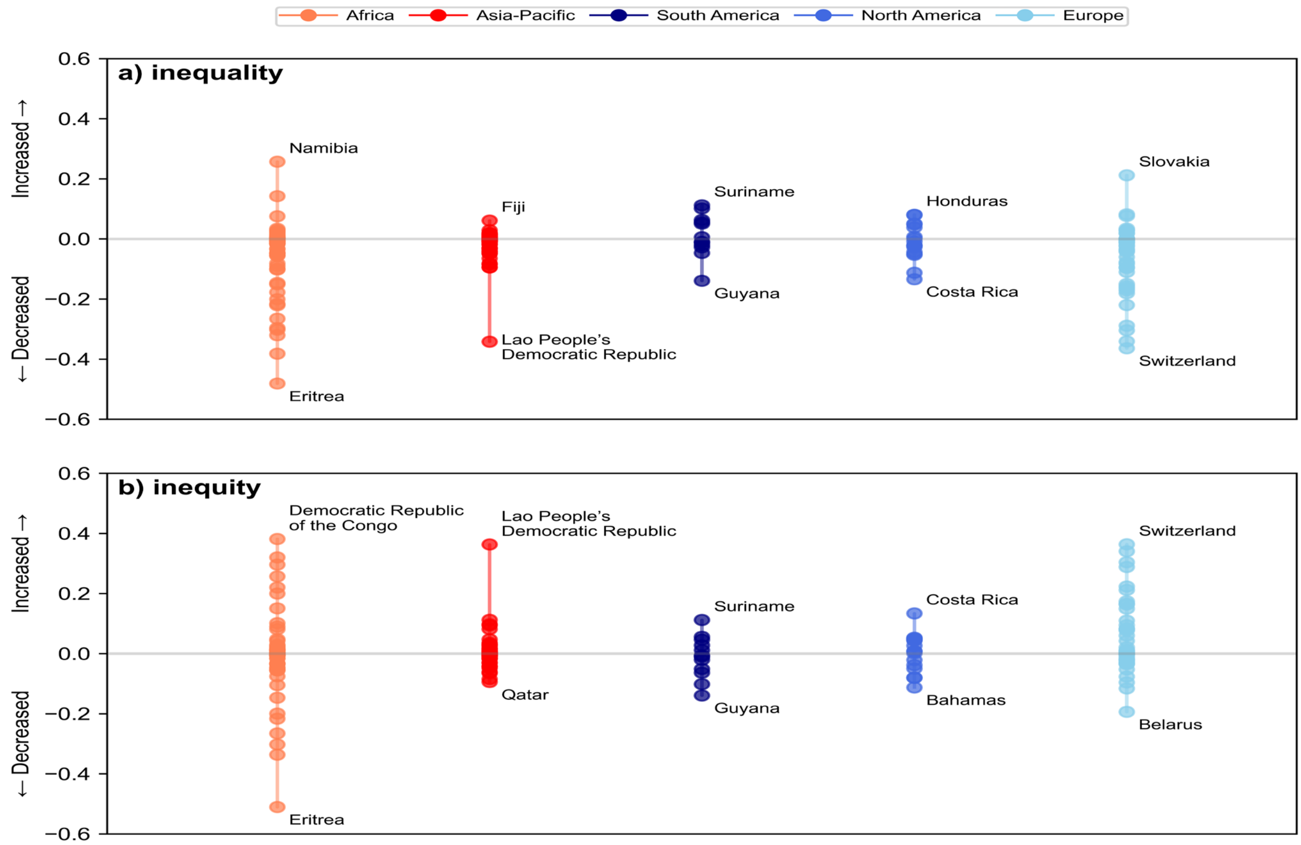

Figure 8. The distribution of country-level water use inequality (a) and inequity (b) changes embedded in international agricultural trade in different continents. Each dot represents one country.

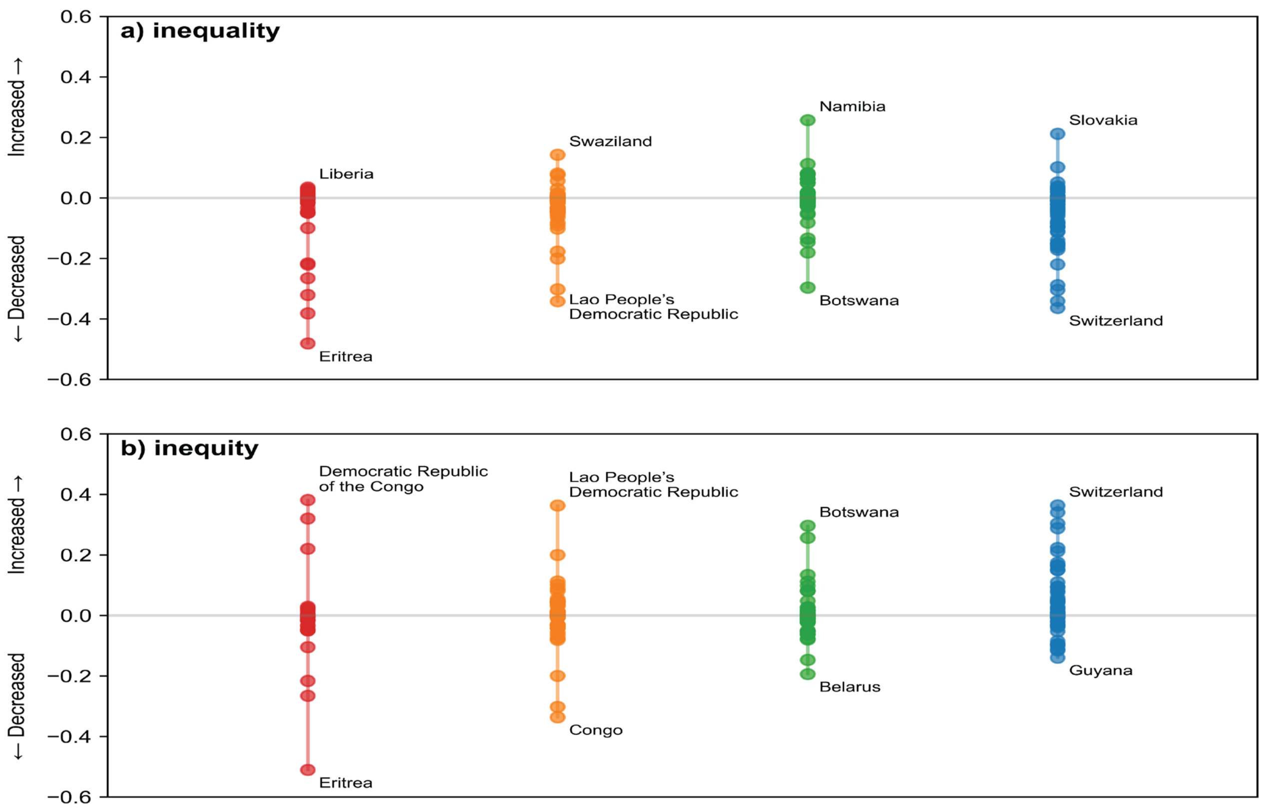

Figure 9. The distribution of country-level water use inequality (a) and inequity (b) changes embedded in international agricultural trade in different income groups. The classification of income groups in this figure is based on the World Bank's income categorization.

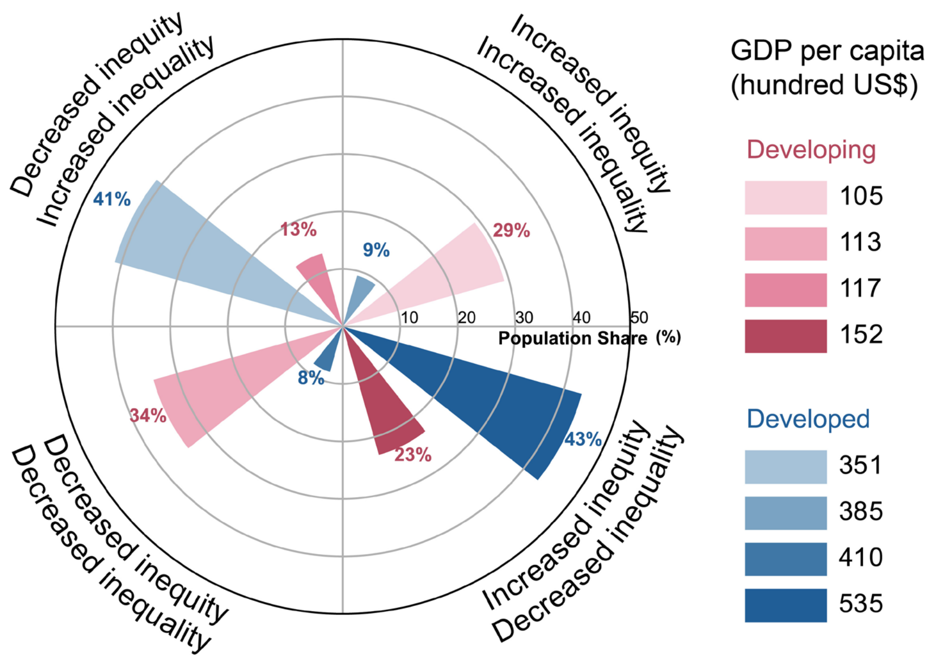

Figure 10. The average GDP per capita and population share for people with increased or decreased water use inequality and inequity in developing and developed countries.

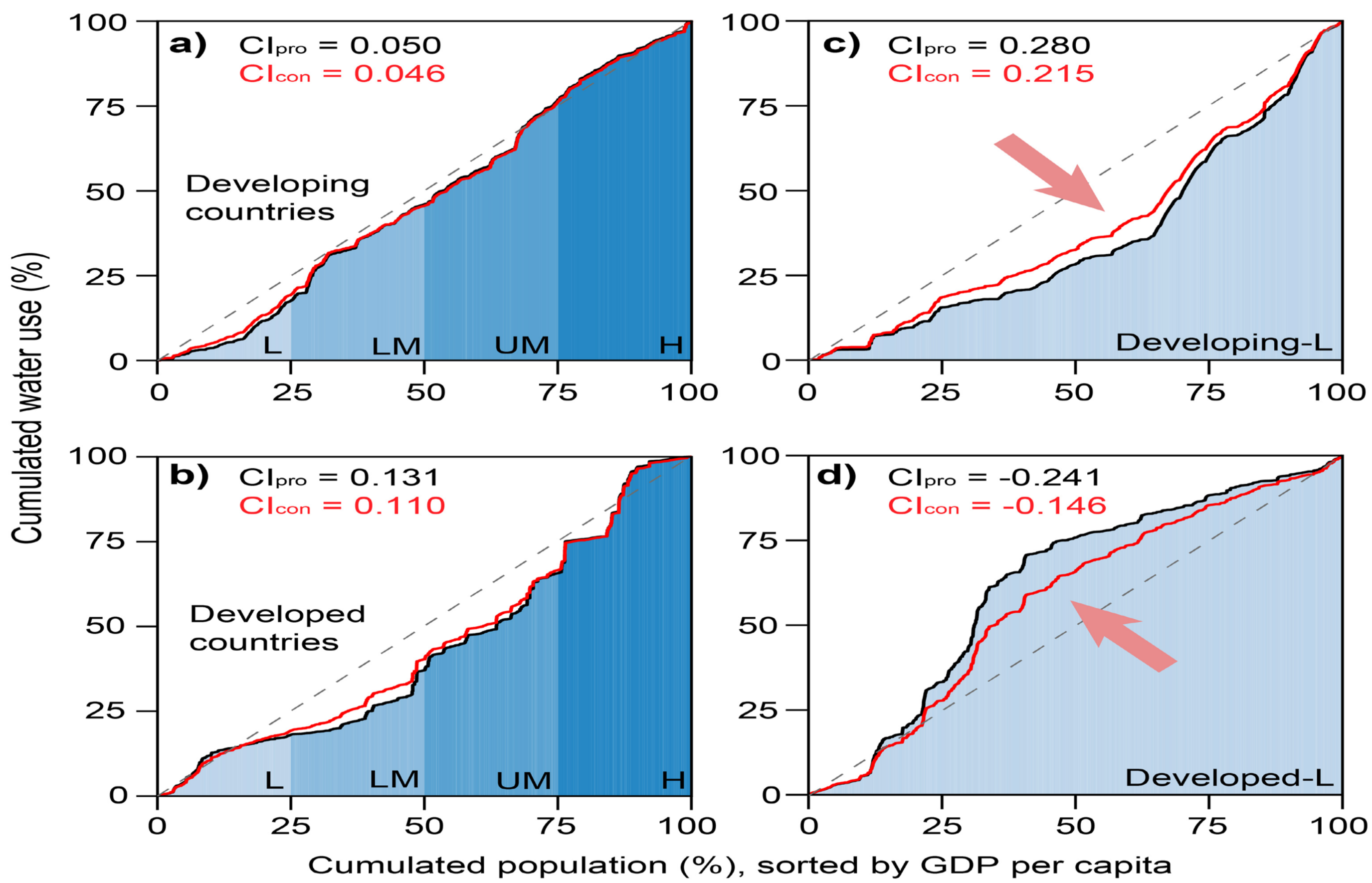

Figure 11. The concentration curve illustrating water use inequality and inequity for developing countries (a), developed countries (b), the low GDP per capita group in developing countries (c), and the low GDP per capita group in developed countries (d). The dashed line denotes the status of absolute equality (CI = 0), i.e. when everyone has equal water consumption. The black solid line denotes production-based concentration curve and the red line denwotes 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 c and d points from consumption-based (before trade) to production-based (after) concentration curve.

4. Synergy and Trade-off of Water Scarcity, Inequality and Inequity

Tractor spraying soybean field at sunset. Photo by Dusan Kostic, Adobe Stock.

International agricultural trade significantly influences global water use by redistributing water resources through the transfer of virtual water, creating complex interplays between water scarcity, inequality, and inequity. These interplays result in both synergies and trade-offs among these metrics across different global economies. Synergies occur when international trade simultaneously alleviates a country's water scarcity (indicated by a reduction in the Water Scarcity Index, WSI), prioritizes water access for the poor (shown by a decrease in the Concentration Index, CI), and moves the distribution of water closer to absolute equality (a reduction in the absolute value of CI). On the other hand, trade-offs arise when improvements in one or two of these aspects come at the expense of the others, leading to a complex array of outcomes that vary significantly between developing and developed countries.

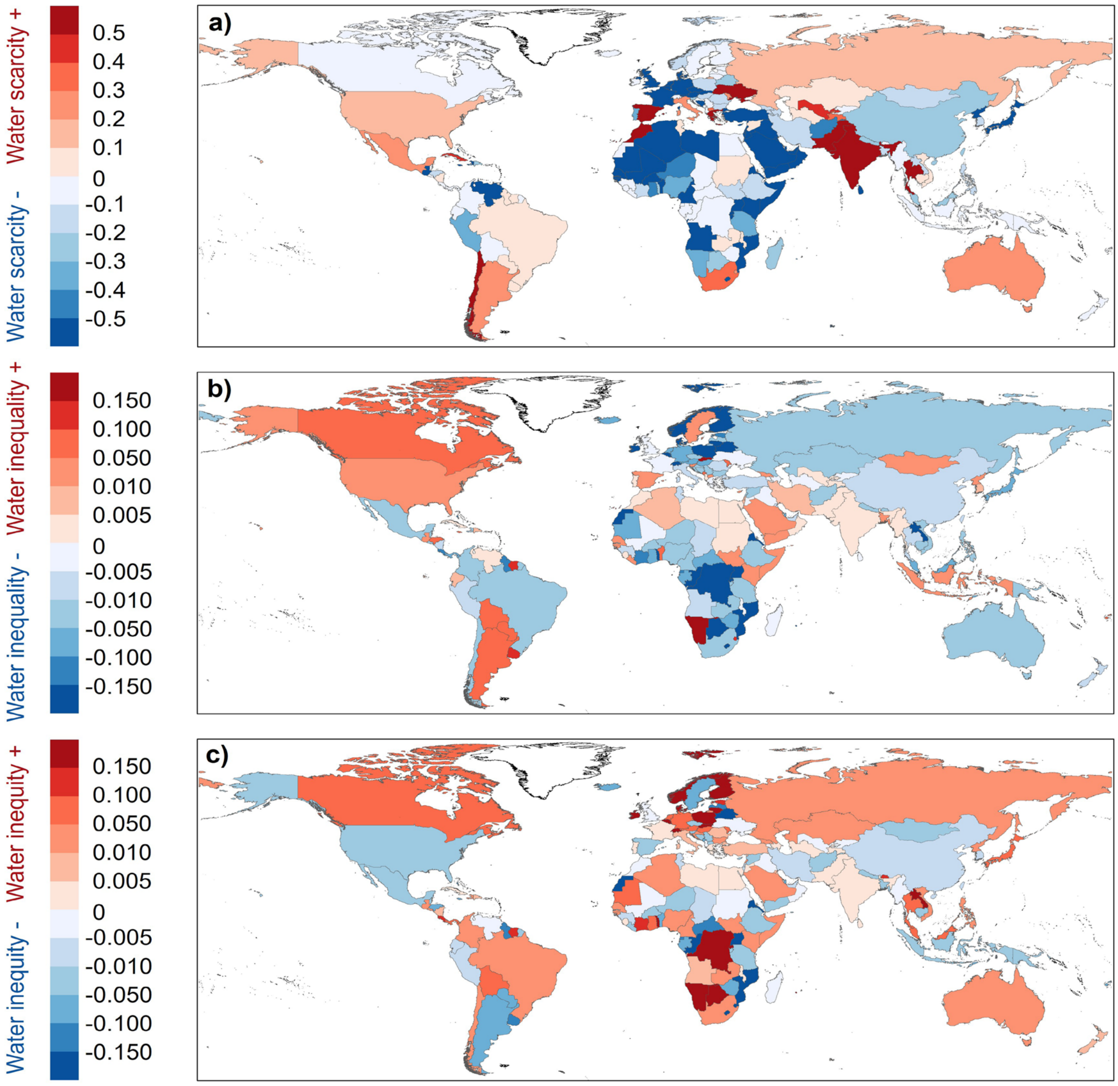

Figure 12. Country-level changes of water use scarcity, inequality, and inequity embedded in international agricultural trade. Country level trade-induced water scarcity changes are measured by population-weighted grid-level water scarcity index changes.

A detailed analysis reveals pronounced differences in how developing and developed countries experience these synergies and trade-offs. In developing countries, a significant 42% of the population benefits from synergies, experiencing both reduced water scarcity and improved equity. These individuals fall into the third quadrant of the quadrant analysis, indicating positive outcomes in both metrics. This implies that for nearly half of the population in these regions, international trade has managed to improve access to water resources and ensure fairer distribution. However, there is a stark contrast for another 35% of the population in developing countries, who suffer from both worsened water scarcity and increased inequity, placing them in the first quadrant, which signifies the most adverse conditions. This segment of the population, which is also the poorest with an average income of $9,114 per capita (16% lower than the overall average), faces compounded challenges. These individuals are already struggling with limited resources, and the adverse effects of international trade further exacerbate their plight. Additionally, 24% of the population in developing countries grapples with intensified water scarcity, inequality, and inequity due to international trade, highlighting the disproportionate impact on the most vulnerable.

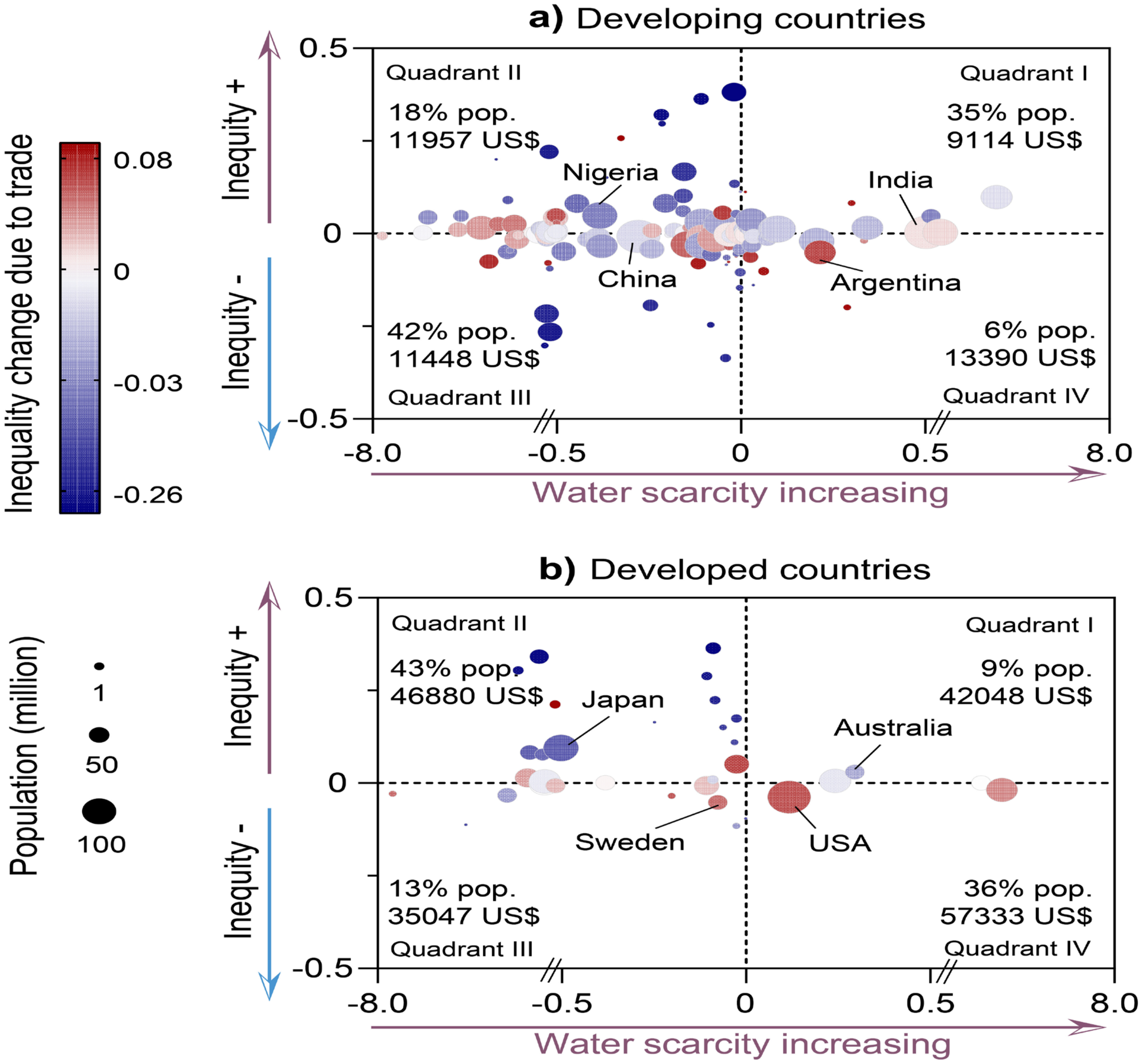

Figure 13. Synergies and trade-offs between water scarcity, inequality, and inequity embedded in international agricultural trade for developing (a) and developed (b) countries. Each circle denotes one country. The size of circles represents the population amount, and the color denotes the increase (red) 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). The countries, whose absolute WSI changes range from 0.5 to 8 (separated by double slashes in x-axis), 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: (tradeoff); III: (tradeoff); and IV: (synergy). Quadrant-specific population share and population-weighted GDP per capita (constant 2015 US$) are denoted in each quadrant.

In stark contrast, the situation in developed countries is markedly different. The population in these regions does not experience the simultaneous exacerbation of water scarcity, inequality, and inequity. Instead, the population in developed countries is primarily divided between those experiencing trade-offs. Specifically, 43% of the population falls into the second quadrant, where they face reduced inequity but increased water scarcity. This represents a trade-off scenario where improvements in the fair distribution of water resources come at the cost of greater overall scarcity. Another 36% of the population experiences reduced water scarcity but increased inequity, placing them in the fourth quadra. Here, the trade-off is reversed, with better overall availability of water but a less equitable distribution. Only 9% of the population in developed countries suffers from both worsened water scarcity and increased inequity. This group, however, has a much higher average income of over $42,000 per capita, suggesting they possess greater financial resources and adaptive capacity to mitigate these adverse effects. The significantly higher income levels in this group imply that even when faced with adverse conditions, they have the means to implement coping strategies and adapt to changing circumstances.

Moreover, the quadrant with the lowest income in developed countries, which benefits from the greatest synergies in both water scarcity and inequity alleviation, highlights an interesting dynamic. This group, despite having lower income levels, experiences significant improvements due to international trade. This indicates that in developed countries, international trade disproportionately benefits the relatively more vulnerable populations, providing them with enhanced access to water resources and fairer distribution. Conversely, in developing countries, international trade often threatens the most vulnerable populations, exacerbating existing inequalities and water scarcity challenges.

These findings underscore the complex and multifaceted impacts of international agricultural trade on water use distribution. In developing countries, the negative impacts are more pronounced, particularly among the poorest segments of the population. The compounded effects of increased water scarcity and inequity highlight the urgent need for targeted policies and interventions to address these disparities. Strategies must be developed to ensure that the benefits of international trade are equitably distributed and that the most vulnerable populations are protected from adverse impacts. This may include investments in infrastructure, improved water management practices, and policies that specifically aim to support poorer communities.

In developed countries, while the impacts of international trade are generally more positive or involve manageable trade-offs, there is still a need for caution. Ensuring that the benefits of trade continue to reach the more vulnerable populations and addressing any emerging inequalities will be crucial. The higher adaptive capacity and financial resources available in these regions provide a strong foundation for implementing such measures, but continuous monitoring and adaptation will be essential to maintain balance and fairness.

Overall, the asymmetric patterns revealed by this analysis highlight the need for a nuanced and targeted approach to managing the impacts of international agricultural trade on water use. Addressing the complex interplay between water scarcity, inequality, and inequity will require a concerted effort from policymakers, researchers, and international organizations. By understanding these dynamics and implementing targeted interventions, it is possible to ensure that the benefits of international trade are realized more equitably, protecting vulnerable populations and promoting sustainable water use globally.

Mist rising above the Katse Dam wall in Lesotho. Photo by Adele De Witte, Adobe Stock.

5. Conclusion

Two individuals are taking their farm products to a market in Rwanda. Photo by Amir Aghakouchak.

This investigation provides one of the first attempts to explore how international agricultural trade affects water use allocation between the poor and the rich, thereby impacting water use inequality and inequity among different income groups. The report reveals a significant asymmetry in water scarcity, inequality, and inequity between developing and developed countries due to international agricultural trade. Generally, more resourceful populations, such as those in developed countries or the wealthier populations within developing countries, benefit significantly more from trade. This dynamic often widens the vulnerability gap between the rich and the poor.

Despite the overall alleviation of water scarcity due to international agricultural trade in both developed and developing countries, the improvements are uneven. In developed countries, the population with no or low water scarcity among the relatively poor increases by 20%, compared to a mere 0.1% in developing countries. Water use inequity decreases by approximately 65% in developed countries, benefiting the poor, while it increases by about 30% in developing countries, favoring the rich. Both regions experience increased water use inequality due to agricultural trade. In developing countries, those suffering from both increased water scarcity and inequity are generally poorer, whereas the relatively poor in developed countries often benefit from trade-induced reductions in water scarcity and inequity.

Developed countries leverage their comparative advantages in economic geography to import crops and meet domestic food demand, thereby alleviating water scarcity and inequity among their relatively poor populations. In contrast, developing countries often rely on their natural resources, such as arable land and water availability, and agricultural production efficiency to export crops. This trade pattern helps them achieve economic gains but often at the cost of increased water scarcity and inequity.

The findings call for an integrated approach to designing water and trade policies that consider multiple Sustainable Development Goals (SDGs). Previous studies on virtual water mainly focus on SDG 6, which emphasize water savings and scarcity alleviation through trade[8,35]. However, this investigation highlights that despite the reduction in water scarcity, many countries, such as Nigeria and Japan, face increased water use inequity. This inequity disproportionately allocates more water resources to the rich, compromising essential water access for the poor and hindering progress towards eradicating extreme poverty (SDG 1)[3,4]. By integrating equity (SDG 10) and water scarcity alleviation (SDG 6), we can also support other SDGs like zero hunger (SDG 2), good health and well-being (SDG 3), gender equality (SDG 5), and quality education (SDG 4).

Water policies should prioritize the needs of low-income groups to reduce inequity and promote sustainable development. For example, developing countries facing increased water scarcity and inequity could implement measures such as providing water subsidies or financial support to poor households[36], capping water prices to make them affordable[37], and investing in accessible water infrustructure and community water points (e.g., public taps or wells) to ensure basic water needs are met[38]. Demand-side practices like drip irrigation[39] (when properly implemented together with strict conservation measures) and crop switching[40] can improve agricultural water use efficiency, enhancing water availability for the poor and supporting agricultural sustainability[41]. Trade policies should aim to diversify staple agricultural trades and trading partners to reduce water scarcity, inequality, and inequity[42]. For example, China could mitigate water use inequity by adjusting its rice imports from Pakistan and Thailand, and Iran could diversify its rice import sources rather than relying heavily on India to reduce its food import risks in the face of future climate and geopolitical uncertainties.

The intensification of the global agricultural trade network has led to increasing interdependence among countries, making it crucial to address sustainability challenges collaboratively. The integrated 'water use scarcity-inequality-inequity' framework in this report sheds light on how international trade transmits and pools these water issues, emphasizing the need to consider the impacts on different population groups, particularly the most vulnerable, in designing water and trade policies. This approach can help achieve sustainable development goals more effectively. As global challenges such as population growth, increased food demand, cross-sector water competition, climate change, and crises like COVID-19 intensify, this framework can guide better-informed water and trade policy design. Future assessments should incorporate more dimensions of inequity and dynamically evolving intra-country and international trading patterns to capture the full impacts of both domestic and international trade flows.

An Indian woman working in the field. Photo by Yogendra, Adobe Stock.

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Appendix I-Methods and Input Data

Crop-specific irrigation water consumption under production-based accounting

The analysis simulated recent year (average of 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[43] with the input of climate variables (e.g., temperature, wind speed, precipitation, etc.), crop-specific planting areas, cropping calendars, etc[44]. Specifically, irrigation water consumption is the amount of crop evapotranspiration that is not compensated by effective precipitation[43-45]. 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)[43-45]. The ET_0 was calculated through Penman-Monteith Equation recommended by FAO[45]:

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

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); and e_a denotes actual water pressure (kPa).

More information about GCWM is available in the literature[43,44]. 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)[46] due to data unavailability for alternative years. Following earlier studies[19,47,48], this analysis further scaled GCWM-simulated results based on country-level area equipped with irrigation from FAO database[49] to factor into the impacts of irrigated area changes on irrigation water use:

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

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. The analysis further aggregated GCWM simulated water consumption to the spatial resolution of 0.25°×0.25° to match water availability data based on runoff from ERA5[50].

Crop-specific irrigation water consumption under consumption-based accounting

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 application of the same method as in the literature18, the investigation used the FAOSTAT bilateral trade data[49] to track the agricultural trade flow and estimate the resulting consumption-based irrigation water consumption. Combining with the production data from FAOSTAT, the study further adjusted the trading matrix following the origin-tracing algorithm[51] to address the re-export issue. Using this algorithm[51], the study obtained 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 was calculated as follows:

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

where, C^r denotes the consumption-based water use in country r; P^r denotes the production-based water use in country r; Tdenotes the transpose of the matrix; and A^{rs} denotes the proportion of production in country r that is ultimately consumed in country s. Following previous studies[52], the study obtained 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.

Water scarcity changes induced by international agricultural trade

Integrating grid-level (0.25°×0.25°) water consumption and water availability (natural runoff minus environmental flow requirement)[53], the study calculated water scarcity index (WSI) in each grid and assume that individuals in the same grid face the same levels of water scarcity. Production-based WSI (WSI_{pro}) and consumption-based WSI (WSI_{con}) were calculated via dividing production-based and consumption-based total water consumption by grid-level water availability excluding environmental flow, respectively[53]. Total water consumption under production-based accounting was estimated by summing up irrigation water consumption for crops production plus industrial and domestic water consumption[54], while consumption-based accounting was calculated by adding consumption-based irrigation water consumption with industrial and domestic water consumption. For this report, the analysis focused on the water impacts due to trade of agricultural products, which account for a dominating share (over 85%[5]) of total water consumption:

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

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; and *R* denotes total runoff, and *EF* denotes the environmental flow required to sustain freshwater ecosystems, which accounts for 80% of the total runoff[24,55,56]. Grid-level annual average runoff data was 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)[50]. Following earlier studies[54,55], the study downscaled country-level industrial and domestic water use according to the downscaled population distribution[57] 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 were estimated by subtracting consumption-based water scarcity index (WSIcon) from production-based WSI_{pro} (WSI_{pro}- WSI_{con}). The analysis divided the water scarcity into three levels ($WSI < 1$; $1 \leq WSI < 2$; $WSI \geq 2$) in ascending order of severity, and compared the number of population changes falling into each of the three categories before and after international agricultural trades[53].

To evaluate the asymmetric impacts on different population groups, the study first categorized global population into developed and developing countries according to International Monetary Fund (IMF)[58]. The study then further equally divided each population group (i.e., developed country and developing country) into four sub-groups based on downscaled grid-level GDP per capita[29], including: low, lower-middle, upper-middle, and high GDP per capita groups. To align with the geographical units of concentration index, the study also calculated the population-weighted country-level water scarcity index for cross-country comparison:

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

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*; and Pop_{tot} denotes the total population of country *c*.

Water use inequality and inequity changes induced by international agricultural trade

The analysis estimated 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[33]. The concentration index (CI) was determined by calculating twice the area bounded by the concentration curve and the line of absolute equality[34]:

$$CI = 1 - 2\int_0^1 L_w\left(p\right)dp = 1 - \sum_{i=0}^{n-1}\left(P_{i+1} - P_i\right)\left(W_{i+1} + W_i\right)$$

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; and P_i denotes the cumulated share of population of the top *i* people. The study assumed 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[30-34].

The study also distinguished inequity from inequality with the aid of concentration index. If $-1 \leq CI < 0$, the concentration curve would 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 would be located below the line of absolute equality, indicating that water use concentrates more on the rich people[33,34]. As water resource is the cornerstone of 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-dependent industries, potentially increasing their capacity to adapt to water shortage and narrowing their economic gap with the rich. For this reason, the study assumed that a pro-poor water use allocation shows more equity than the pro-rich one. The study calculated 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. Figure I-1 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. This analysis 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 were calculated based on the following equations:

$$\Delta Inequality = |CI_{pro}| - |CI_{con}|$$
$$\Delta Inequity = CI_{pro} - CI_{con}$$

where, *ΔInequality* (i.e., Δ|CI|) and *ΔInequity* (i.e., Δ|CI|) denote the effects of agricultural trade on the water use inequality and inequity respectively; and CI_{pro} and CI_{con} denote production-based and consumption-based concentration index.

Loading grain into a sea cargo vessel at Odessa port, photo by Elena, Adobe Stock

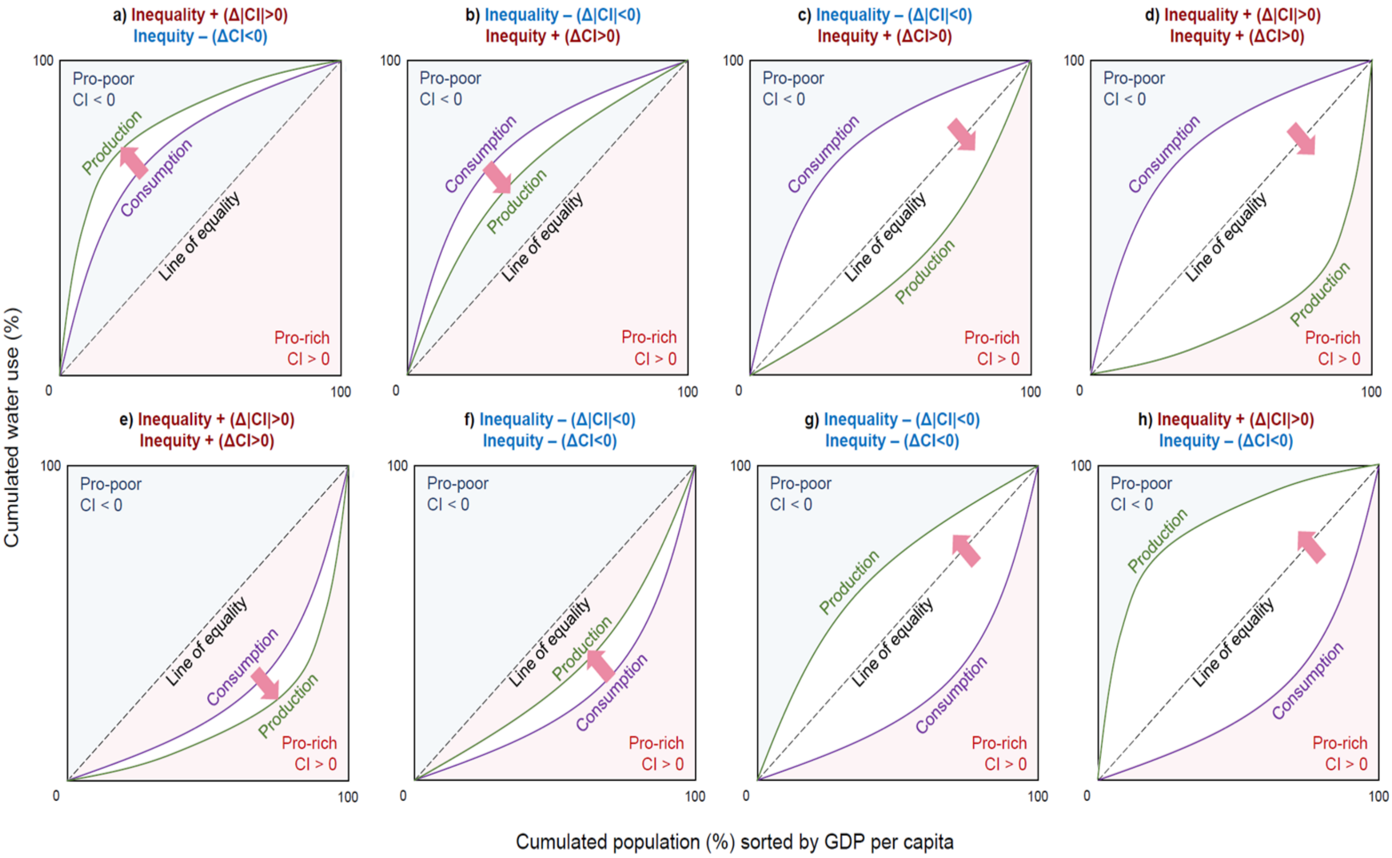

Figure I-1. Schematic figures of changes in water use inequality and inequity due to international agricultural trade. The effects of agricultural trade on changes of inequality and inequity can be captured by shifting the consumption-based concentration curve towards the production-based one. These figures clearly demonstrate the differences between water use inequality and inequity. For example, even if the CI value becomes smaller (i.e., moving towards the pro-poor region and equity increasing) due to international agricultural trade, equality can still decrease if consumption-based concentration curve locates at the pro-poor region originally (Figure I-1a) or the magnitude of movement is too substantial even if the consumption-based curve locates at the pro-rich region originally (Figure I-1h). We focus on both inequality and inequity to simultaneously factor into both whether the water resource is used evenly and whether it is prone to the population who needs it the most, such that to prevent the arbitrary conclusion that water use excessively concentrated on the poor is always deemed positive.

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