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Assessing virtual water flows from small-scale and large-scale agriculture in global trade

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Abstract

Non-technical Summary. Water is a shared global resource, yet its movement is often invisible. When a country imports products, it also imports 'virtual water', the water used to produce those products. While agriculture accounts for 85% of global water transfers, we have lacked a clear understanding of who is actually moving this water: large industrial farms or small-scale farmers? Our study shows that small-scale agriculture plays a disproportionately large role in global virtual water flows, compared to its volume of crop production involved in trade.

Technical Summary. Most global virtual water flows come from agri-food sectors, describing how commodity demand in one country drives water use in others. Despite their significance, virtual water flow assessments have largely overlooked the distinct roles of small-scale versus large-scale agriculture, hindering the development of targeted water and food security policies in both producing and consuming countries. To address this gap, we estimate the contributions of small-scale and large-scale agriculture to crop production and virtual water embedded in trade (export) using detailed hybrid multiregional input–output tables spanning 55 countries. We reveal that, although small-scale agriculture accounts for only 17% of the total crop production involved in trade (in tonnes), its role in virtual water flows is disproportionately large, accounting for 22% of blue and 30% of green virtual water flows. In 13 of the 55 countries, small-scale agriculture accounts for more than 50% of green virtual water exports. Furthermore, virtual water exports from small-scale agriculture exhibit distinct spatial patterns and are driven primarily by demand for labor-intensive crops rather than animal-sourced human food and nonfood products. Our results suggest that explicitly accounting for farmers' roles in virtual water flows is critical for the design of context-specific, effective, and equitable policy interventions.

Social Media Summary. Check out the unique role of small-scale agriculture in global crop trade and virtual water flows.

1. Introduction

When countries import products from abroad, they also import 'virtual water', defined as the water embedded in traded products (Allan, 1998, 2003). Virtual water flows describe how nations rely on water resources in other countries to meet domestic consumption needs (Hoekstra & Mekonnen, 2012). This concept links localized basin-level water demand to transboundary activities and is thus critical for global water resource management (Hoff, 2013; Liu et al., 2013; Vörösmarty et al., 2015). Virtual water flows account for 20% of global water consumption (Hoekstra & Mekonnen, 2012), including green (the consumptive use of precipitation embodied in international trade) and blue virtual water flows (the consumptive use of surface water and groundwater embodied in international trade). When virtual water flows originate from water-scarce regions, they raise sustainability concerns (Hoekstra, 2020; Vörösmarty et al., 2015). About 30–50% of virtual water flows originate in physically or economically water-scarce regions (Lenzen et al., 2013; Mekonnen & Hoekstra 2020; Rosa et al., 2019; Taherzadeh et al., 2021; Vallino et al., 2020, 2021), which calls for further action to manage virtual water flows.

Understanding the characteristics of the stakeholders involved in virtual water flows is essential for designing effective interventions. This means that not only should we understand the quantity of virtual water flows, but also from whom (farmers and producers), via whom (traders and distributors), and to whom (retailers and consumers) the virtual water is traded internationally. Since around 85% of the international green/blue virtual water flows are crop-related (Hoekstra & Mekonnen, 2012), most studies focus on the agricultural system. Current studies have shown that large multinational agri-food corporations have significant impacts on existing virtual water flows (Baronchelli et al., 2024; De Petrillo et al., 2023; Sojamo et al., 2012). A single large corporation may trade more virtual water than a major importing country, particularly in cash-crop-related virtual water flows (Baronchelli et al., 2024; De Petrillo et al., 2023).

The role of farmers in virtual water flows, who directly consume water and supply crops to agri-food corporations, remains poorly understood (Hoekstra et al., 2011; Sun et al., 2019). Small-scale agriculture, which contributes substantially to food security (Ricciardi et al., 2018a; Taherzadeh et al., 2026), has distinguishing characteristics compared to large-scale agriculture. For example, small-scale agriculture generally has different crop structures than large-scale agriculture (Herrero et al., 2017; Ricciardi et al., 2018a). Small-scale agriculture is largely located in water-scarce regions, but uses less irrigation compared with large-scale agriculture (Ricciardi et al., 2020; Su et al., 2022) and might be inefficient in terms of green water use because of low agricultural input (Su et al., 2025b). Consequently, small-scale farming might play a different role in international trade and virtual water flows than large-scale agriculture (Giller et al., 2021). Failing to distinguish the farmers behind virtual water flows may undermine the design of effective water and food security policies (Trottier & Perrier, 2017).

Distinguishing between small-scale and large-scale agriculture in global virtual water flows poses methodological challenges. Most international virtual water flow studies focus on the national level. Distinguishing between small-scale and large-scale agriculture requires subnational farm-size-specific production, water consumption, and export information for each crop, which is not always readily available. Though a few studies have estimated farm-size-specific crop production through the allocation of national data (Herrero et al., 2017; Ricciardi et al., 2018b), to our best knowledge, only a recent dataset developed by Su et al. (2025b) using a gridded crop model provides consistent farm-size-specific production and water consumption data. It covers 171 crops in 55 countries for the period 2008–2012, where the farm-size-specific harvested area is from the subnational agricultural census (Su et al., 2022). Compared to crop production and water consumption, subnational export data is even more scarce. Instead of collecting subnational data, it can be estimated by combining various datasets and making certain assumptions, for example, allocating exports based on production (Sun et al., 2019).

In this study, we estimate the contributions of small-scale and large-scale farming to crop production involved in trade and virtual water flows (export-based) for 55 countries, using the baseline 2008–2012 due to data availability. We combined multiregional input–output (MRIO) databases, food and agriculture biomass input–output (FABIO, v1.2; Bruckner et al., 2019), and global resource input–output assessment (GLORIA, v059; Lenzen et al., 2022) to obtain the national crop production involved in trade at high sectoral resolution, and farm-size-specific crop production and water consumption data (Su et al., 2025b). We allocated the national crop production involved in trade to small-scale and large-scale agriculture based on two assumptions: a production-based assumption (export proportional to production) (Sun et al., 2019) and a farming system-based assumption (export proportional to the production of irrigated and high-input farming systems) (Hoang et al., 2023). Based on the above datasets and models, we estimate the contribution of small-scale and large-scale agriculture to the crop production involved in trade, green and blue virtual water export, and the associated sectors that drive them. Here, crop production involved in trade refers to the crop traded, directly or indirectly. The latter means the crop is used as input for exported products. We identify the crops in which small-scale agriculture makes a significant contribution to trade. Furthermore, we reveal the different roles of small-scale and large-scale agriculture in blue and green virtual water flows.

2. Method

We first used the MRIO databases, FABIO (v1.2; Bruckner et al., 2019), and GLORIA (v059; Lenzen et al., 2022) to estimate the crop production involved in international trade for each crop at the national level. Then, we allocated the crop production involved in trade to small-scale and large-scale agriculture based on their production (production-based assumption) or farming systems (farming system-based assumption). Here, crop production involved in international trade refers not only to the crop production traded directly but also to that traded indirectly, where a crop is used as an input for an exported product. MRIO describes the inputs and outputs of each sector and trade among all the countries. Since the crop production differentiating small-scale and large-scale agriculture by Su et al. (2025b) is available for 55 countries for the period of 2008–2012, with the main purpose of establishing the baseline estimates, the virtual water flow analysis focuses on the same geographic and temporal scope. These 55 countries are representative across continents and collectively account for more than half of the global cropland.

2.1. Crop production involved in international trade

To describe crop-related international trade with high sector-level detail and less uncertainty, we leveraged a physical MRIO designed for food and agriculture, FABIO (v1.2; Bruckner et al., 2019). FABIO covers 192 global countries/areas and 123 agricultural sectors (61 crop sectors). Because FABIO does not track the nonfood uses of crops along the supply chain, we linked it to the GLORIA (v059) MRIO model (Lenzen et al., 2022) for further traceability of virtual water flows within the wider resource economy. GLORIA represents the monetary flow of 120 sectors within and between 160 countries and four aggregated regions, including 36 agricultural and 84 nonagricultural sectors.

We connected FABIO and GLORIA using a linking table. To construct the linking table Z_{link}, for each region r, we have

$$T^r = \phi V^r_{\text{GLORIA}} \circ \Theta, \tag{1}$$

where ϕ is the supply filter matrix defining the GLORIA sectors supplying the FABIO product; Θ is the use filter matrix defining the potential sectors in GLORIA using the FABIO product; $^\circ$ is the Hadamard product. $V^{\text{r}}_{\text{GLORIA}}$ is an aggregation of the GLORIA transaction matrix Z_{GLORIA}. It first selects the corresponding columns for regions r in Z_{GLORIA} and then enumerate along the rows over regions for each sector. T^r was further divided by its row sums, resulting T^r_{share}. Then for region r, we have

$$Z^r_{\text{link}} = \begin{pmatrix} T^r_{\text{share}} \\ \vdots \\ T^r_{\text{share}} \end{pmatrix} * Y^r_{\text{otheruse}}, \tag{2}$$

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where Y^r_{otheruse} is the crop production used for nonfood uses in FABIO. The Z_{link} is constructed as

$$Z_{\text{link}} = \begin{pmatrix} Z^1_{\text{link}} & \ldots & Z^R_{\text{link}} \end{pmatrix}. \tag{3}$$

Here, Z_{link} has 192*123 rows (FABIO) and 164*120 columns (GLORIA). A more detailed description can be found in Bruckner and Kuschnig (2020).

The Leontief inverse B^{-1} of the linking table (Bruckner & Kuschnig, 2020):

$$B^{-1} = -A^{-1}BD^{-1}, \tag{4}$$

$$B = (0 - A_{\text{link}}), \tag{5}$$

$$A = (I - A_{\text{FABIO}}), \tag{6}$$

$$D = (I - A_{\text{GLORIA}}). \tag{7}$$

Here, A is the direct requirement matrix, $A = Z\hat{X}^{-1}$ and X is the total output for the linking table, FABIO, and GLORIA, respectively. For all the food uses, the crop production involved in international trade (X_{ctf}) was calculated by

$$X_{cpt,\,food} = (I - A_{FABIO})^{-1} Y_{FABIO} \tag{8}$$

Here, $(I - A_{\text{FABIO}})^{-1}$ is the Leontief inverse of FABIO. Y_{FABIO} is the final demand matrix, with one column per country in FABIO, excluding the nonfood uses and 'balancing' columns. Crop production involved in trade was derived by isolating the final demand originating from other countries. Similarly, for nonfood uses, the crop production involved in international trade (X_{ctnf}) was calculated by

$$X_{cpt,\,nonfood} = B^{-1} Y_{GLORIA} \tag{9}$$

Here, Y_{GLORIA} is the final demand matrix in GLORIA. We further distinguish the final demand Y_{FABIO} into three types of food products (crops as food, crop food products, and animal-sourced human food, Supplementary Materials S.2 for details). In addition to nonfood uses, we have four types of final demand. The sum of $X_{cpt,\,food}$ and $X_{cpt,\,nonfood}$ provides the crop production involved in international trade for each country for each of the 61 crop sectors.

2.2. Link the crop production involved in trade to small-scale and large-scale agriculture and virtual water flow calculations

Distinguishing between small-scale and large-scale agriculture in international trade and virtual water flow is challenging due to limited subnational trade data. Although market access to small-scale and large-scale agriculture could be retrieved from household surveys, it is only available for a few countries (FAO, 2021). Small-scale farmers in particular may experience limited access to formal markets, especially international markets (Giller et al., 2021). We allocate the total production involved in international trade per crop sector per country to small-scale and large-scale agriculture using two commonly used assumptions in the literature: the production-based assumption (Sun et al., 2019) and the farming system-based assumption (Hoang et al., 2023). The production-based assumption allocates crop production (domestic or export) to small-scale and large-scale agriculture solely on their production, regardless of any other factors. The farming system-based assumption suggests that irrigated and high-input farming systems have significantly better access to export markets than the low-input farming system. This assumption allocates the export first to irrigated and high-input farming systems, and then to the low-input farming system. Since the low-input farming system could still be export-oriented, this assumption may overestimate the contribution of irrigated and high-input farming systems to international trade. Using both assumptions provides upper and lower bounds for estimating the contribution of different farming systems to virtual water flows.

Under the production-based assumption, the crop production involved in trade is allocated to small-scale and large-scale agriculture proportionally based on their crop production:

$$cpt_{s,ih} = cp_{s,ih} * \frac{cpt_{total}}{cp_{total}}, \tag{10}$$

$$cpt_{s,low} = cp_{s,low} * \frac{cpt_{total}}{cp_{total}}, \tag{11}$$

$$cpt_{l,ih} = cp_{l,ih} * \frac{cpt_{total}}{cp_{total}}, \tag{12}$$

$$cpt_{l,low} = cp_{l,lows} * \frac{cpt_{total}}{cp_{total}}. \tag{13}$$

where cp and cpt are crop production and the crop production involved in trade, respectively. The subscript s indicates small-scale agriculture; l indicates large-scale agriculture; ih indicates irrigated and high-input farming system; low indicates the low-input farming system. Thus, $\text{cpt}_{s,ih}$ indicates the crop production involved in trade from small-scale agriculture and from irrigated and high-input farming systems.

Under the farming system-based assumption, we first allocate the crop production involved in trade to the irrigated and high-input rain-fed farming systems and then distribute it proportionately between small-scale and large-scale agriculture, based on their respective production in irrigated and high-input rain-fed farming systems. If the volume of crop production involved in trade exceeds the combined production from irrigated and high-input farming systems, the surplus is allocated to small-scale and large-scale agriculture according to their respective production in the low-input farming system. When $\text{cpt}_{\text{total}} < \text{cp}_{s,ih} + \text{cp}_{l,ih}$,

$$cpt_{s,ih} = cp_{s,ih} * \frac{cpt_{total}}{cp_{s,ih} + cp_{l,ih}}, \tag{14}$$

$$cpt_{s,low} = 0, \tag{15}$$

$$cpt_{l,ih} = cp_{l,ih} * \frac{cpt_{total}}{cp_{s,ih} + cp_{l,ih}}, \tag{16}$$

$$cpt_{l,low} = 0. \tag{17}$$

Otherwise:

$$cpt_{s,ih} = cp_{s,ih}, \tag{18}$$

$$cpt_{s,low} = cp_{s,low} * \frac{cpt_{total} - cp_{s,ih} - cp_{l,ih}}{cp_{total} - cp_{s,ih} - cp_{l,ih}} = cp_{s,low} * \frac{cpt_{total} - cp_{s,ih} - cp_{l,ih}}{cp_{s,low} + cp_{l,low}}, \tag{19}$$

$$cpt_{l,ih} = cp_{l,ih}, \tag{20}$$

$$cpt_{l,low} = cp_{l,lows} * \frac{cpt_{total} - cp_{s,ih} - cp_{l,ih}}{cp_{total} - cp_{s,ih} - cp_{l,ih}} = cp_{l,lows} * \frac{cpt_{total} - cp_{s,ih} - cp_{l,ih}}{cp_{s,low} + cp_{l,low}}. \tag{21}$$

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Table 1. The crop production involved in trade by small-scale and large-scale agriculture from 55 countries, based on the farming system assumption

	Crop production involved in trade, million tonnes			
Crop groups	Total	From large-scale agriculture	From small-scale agriculture	The share of small-scale agriculture in total
Cereals	325.9	239.8	86.1	26%
Coffee, tea, cocoa	4.7	2.5	2.3	49%
Fiber crops	1.2	0.3	0.9	75%
Fodder crops	246.5	237.2	9.3	4%
Oil crops	160.1	121.9	38.2	24%
Roots and tubers	36.1	23.2	12.9	36%
Sugar crops	383.6	346.5	37.1	10%
Tobacco, rubber	2.3	1.3	1.0	43%
Vegetables, fruit, nuts, pulses, spices	92.3	69.5	22.8	25%

The virtual water flow was calculated using unit blue and green water consumption for small-scale and large-scale agriculture, per farming system, and crop. Crop production and water consumption data for small-scale and large-scale agriculture were retrieved from Su et al. (2025b). This dataset covers 171 crops from 55 countries between 2008 and 2012 (Supplementary Materials S.1), which were aggregated into FABIO 61 crop sectors (Supplementary Materials S.3). While other datasets provide a more extensive global coverage than this dataset in terms of crop production, e.g., Herrero et al. (2017) and Mehrabi et al. (2020), they were developed for the year 2000 cropland and, more importantly, do not provide corresponding water consumption and farming system data. The farming system-based assumption requires distinguishing between low-input and high-input farming systems in the crop map dataset. SPAM2010 is the latest version containing this information and is covered by the dataset of Su et al. (2025b). The dataset of Su et al. (2025b) provides the estimated crop production and water consumption per grid cell, farming system, and crop for both small-scale and large-scale agriculture, based on underlying regional agricultural census data. In this dataset, small-scale agriculture was identified by the combination of three definitions: a 2-ha threshold (below 2 ha farm size), a subsistence farming system, and the SDG 2.3.2 definition (the smallest farms that contribute 40% of national cropland and 40% of agriculture revenue). The remaining part is classified as large-scale agriculture, which includes both medium- and large-scale agriculture (Su et al., 2025b). Virtual water flow was calculated by multiplying unit water consumption by the crop production involved in trade for small-scale and large-scale agriculture, respectively.

3. Results

3.1. The contribution of small-scale agriculture to crop production involved in trade

Overall, small-scale agriculture contributes only about 17% of the total crop production involved in trade (in tonnes), among the 55 countries analyzed. However, its contribution is significantly higher for several cash crops (Table 1). For example, based on the farming system assumption, small-scale agriculture accounts for 75% of fiber crop production involved in global trade. In addition, small-scale agriculture also contributes significantly to coffee, tea, and cocoa (49%); tobacco and rubber (43%); roots and tubers (36%); cereals (26%); vegetables, fruit, nuts, pulses, and spices (25%); and oil crops (24%). Many of these crops are labor-intensive and less well-suited to mechanized agriculture. In contrast, small-scale agriculture contributes substantially less to the production of fodder crops and sugar crops involved in trade, which are dominated by large-scale agriculture.

The production-based assumption provides similar results. By comparing the two assumptions, there are minor differences in the allocation of crop production involved in trade between small-scale and large-scale agriculture at the national level (Supplementary Materials S.4). Specifically, for the crop production of large-scale agriculture involved in trade, the two assumptions produce nearly identical national-level estimates. In contrast, the differences are more pronounced for small-scale agriculture, particularly in developing countries where the export volume is low. The farming system-based assumption generally allocates slightly less crop production involved in trade to small-scale agriculture (typically $<4\%$ for each crop group).

3.2. The contribution of small-scale agriculture to virtual water flows

Under both assumptions, small-scale agriculture accounts for approximately 22% of blue and 30% of green virtual water flows, which is higher than its contribution to the crop production involved in trade. The relatively lower blue water contribution reflects the lower blue water consumption of small-scale agriculture on the production side. The contribution varies substantially among countries (Figure 1). In many countries, small-scale agriculture accounts for a large share of virtual water exports. It accounts for more than 90% of blue virtual water exports in Costa Rica and more than half in Peru, South Africa, Uganda, Ethiopia, and Timor-Leste. In terms of green water, small-scale agriculture contributes over 90% in Peru and over half in Costa Rica, South Africa, Uganda, Ethiopia, Timor-Leste, Mongolia, Romania, Colombia, Mexico, Malawi, Russia, and Greece, across low-income, middle-income, and high-income countries. For Greece, about 40% of small-scale agriculture's contribution to green virtual water export comes from olive production (Su et al., 2025a).

The larger contribution of small-scale agriculture to virtual water flows can be explained by the type of crops it supplies to international trade. For example, fodder crops generally consume less blue and green water per unit of crop production. Large-scale agriculture is more involved in fodder crops; thus, its relative

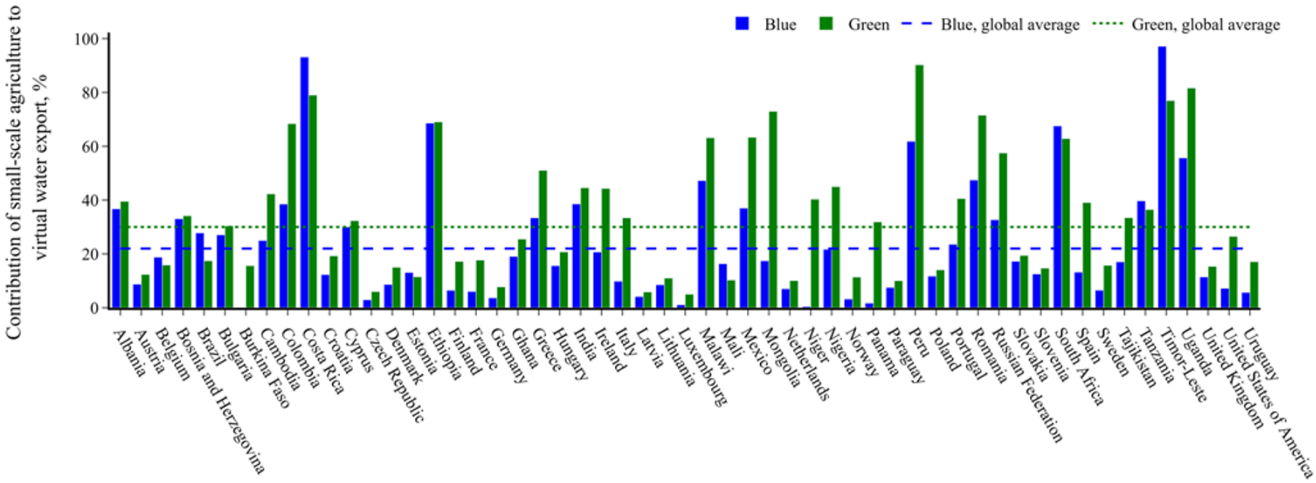

Figure 1. The contribution of small-scale agriculture to blue and green virtual water exports at the country level according to the farming system-based assumption. The production-based assumption provides similar spatial patterns.

contribution to virtual water flows is lower. At the same time, many cash crops are water-intensive, increasing the relative contribution of small-scale agriculture to virtual water flows.

Differences between blue and green virtual water contributions are influenced by several factors in our estimates, e.g., crop type and farming system. For example, if small-scale agriculture does not consume blue water, e.g., no irrigation, then it may contribute significantly to green virtual water export compared to blue. In addition, small-scale agriculture generally consumes more green water per unit of crop production because of lower inputs to agriculture. This pattern is evident in many African countries. At the same time, though many cash crops do not consume much blue water, they consume a substantial amount of green water per unit of production. This also results in the difference between blue and green virtual water flows.

The contribution of small-scale agriculture to virtual water flows does not necessarily correlate with its contribution to domestic water consumption. In Nigeria, small-scale agriculture consumes about 52% of crop-related domestic blue water; however, it contributes only 22% of blue virtual water exports. At the same time, small-scale agriculture contributes 23% of (crop-related) domestic blue water consumption in Russia, but 33% of blue virtual water flows.

Our results indicate that the spatial pattern of virtual water export differs significantly between small-scale and large-scale agriculture. For example, in Brazil, the green virtual water exports from small-scale agriculture are estimated to largely originate in the Northeast and Southwest Brazil; at the same time, for large-scale agriculture, the green virtual water exports are estimated to originate from middle Brazil (Figure 2). This highlights the importance of distinguishing between small-scale and large-scale agriculture in virtual water flow analysis. Agricultural policies informed by virtual water flow analysis may not only have different impacts on small-scale and large-scale agriculture but also uneven spatial impacts, as shown in the case of Brazil.

The farming system-based assumption often results in higher blue virtual water exports and lower green virtual water exports (Supplementary Materials S.4). This is the consequence of the fact that irrigated and high-input farming systems consume more blue water but less green water due to the high water use efficiency. Since the farming system-based assumption allocates slightly less export to small-scale agriculture, the contribution of small-scale agriculture to blue and green virtual water flows is also slightly lower than that under the production-based assumption.

3.3. Sectoral drivers of virtual water trade

At the global level, the largest final demand driving small-scale agriculture's blue and green virtual water export is crops used directly as food (Figure 3, Supplementary Materials S.5), as cereals are generally more traded than other crops. The second largest final demand associated with small-scale agriculture's virtual water export is nonfood uses for blue and animal-sourced human food for green. The nonfood uses primarily refer to fiber crops for textiles, crops for biofuels, and crops as feed for livestock, which ultimately produce nonfood products, for example, leather. These two final demands drive about 70% of small-scale agriculture's contribution to blue/green virtual water flows. The two dominant final demand categories driving small-scale agriculture's virtual water exports may differ across countries. For example, final demand for crop food products is the largest driver of small-scale agriculture's blue virtual water exports in Costa Rica and Italy; in Mali, almost all of small-scale agriculture's blue virtual water exports are driven by nonfood uses.

The final demand sectors driving virtual water exports differ between small-scale and large-scale agriculture (Figure 3, Supplementary Materials S.5). Demand for crops as food is generally a stronger driver for blue and green virtual water export for small-scale agriculture than for large-scale agriculture. Where this is not the case, demand for crop food products shows a stronger driver in small-scale agriculture than in large-scale agriculture. Although demand for crops as food and crop food products still accounts for a significant share, demand for animal-sourced human food and nonfood uses represents a higher proportion in large-scale agriculture than in small-scale agriculture, both at the global level and across the majority of the 55 countries. Nonfood uses and animal-sourced human foods are generally associated with higher-value products than crops used directly as food. This suggests that small-scale agriculture may benefit less from high-value products, and that its contribution might be driven primarily by demand for labor-intensive crops.

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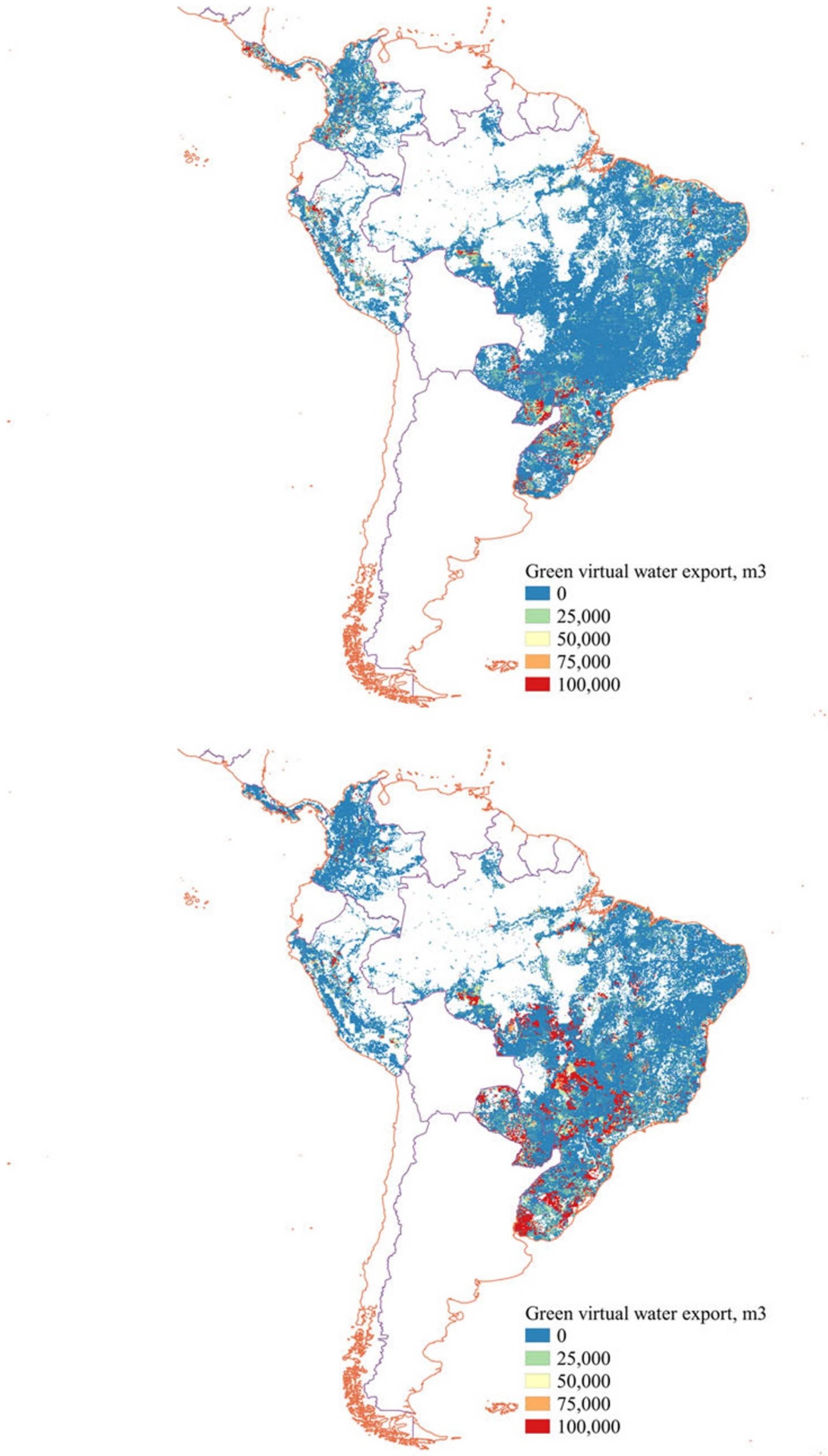

Figure 2. The green virtual water exports from small-scale (a) and large-scale agriculture (b) according to the farming system-based assumption in Latin America.

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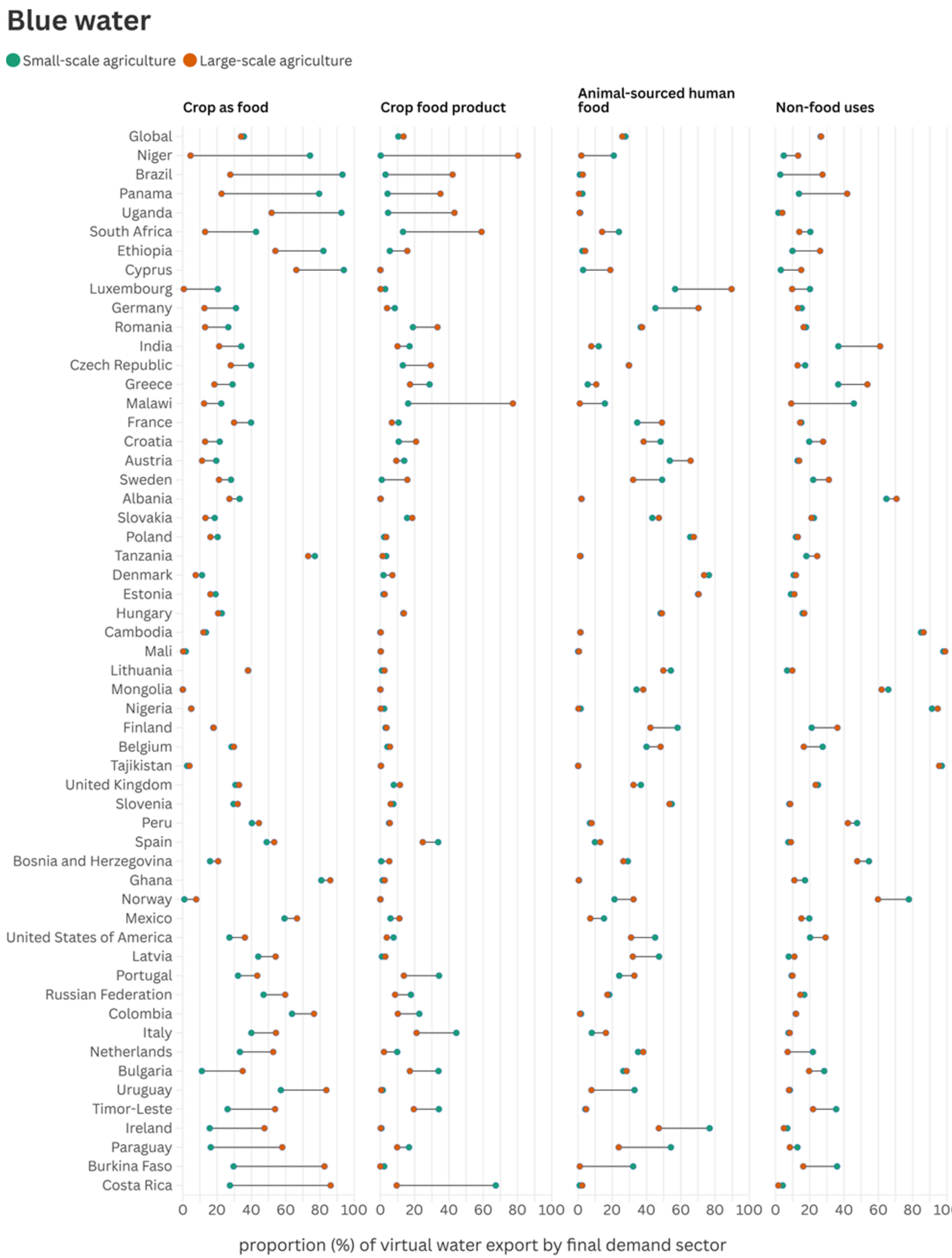

Figure 3. Share of the four final demand sectors associated with the blue virtual water export of small-scale and large-scale agriculture according to the farming system-based assumption, sorted by the difference between small-scale and large-scale agriculture in crops as food share. The production-based assumption provides similar patterns. The four final demand values sum to 100% for small-scale and large-scale agriculture, respectively. The corresponding figure in green water can be found in Supplementary Materials S.5.

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4. Discussion

4.1. Policy implications

Understanding the involvement of small-scale and large-scale agriculture in trade helps design more context-specific policies. For example, our results show that small-scale agriculture's contribution is prominent in many cash crop-related virtual water flows, where large corporations are more prominent as well (Baronchelli et al., 2024). This makes policy interventions involving both farmers and corporations more challenging, given the unequal power dynamics. This inequality is further compounded by the type of water resource controlled. Smallholders are more likely to rely on rain-fed systems and green water. Because green water is not easily managed through traditional economic instruments like water pricing, smallholders face unique vulnerabilities that corporate-centric policies often overlook. Interventions must therefore account for these distinct water-use profiles to avoid placing undue burdens on the small-scale producers.

This economic marginalization is mirrored in market pricing. Water scarcity, which disproportionately affects small-scale agriculture (Ricciardi et al., 2020; Su et al., 2022), is less embedded in the crop price for cash crops (Falsetti et al., 2020). This indicates that the value of water is substantially underestimated for these crops. Unlike large-scale farms, small-scale farms are generally not specialized (Fan & Rue, 2020; Frelat et al., 2016; Ricciardi et al., 2021). They often rely on a more diverse mix of on-farm (e.g., multiple crops or crop-livestock systems rather than a single crop) and off-farm income sources (Frelat et al., 2016). This implies that they may have fewer incentives to improve water use efficiency compared to large-scale farmers, which means that policy interventions may not only focus on crop production, but also on other activities that small-scale farmers are involved in.

Our results also highlight the limitations of the current virtual water flow assessment, which overlooks interactions between small-scale and large-scale agriculture. For example, countries may want to reduce their external water consumption by improving the water use efficiency of imported products (Hoekstra & Mekonnen, 2016). Such a supply-chain-oriented policy could, in light of our findings, encourage greater investment in already-efficient large-scale agriculture. These efficient large-scale farming systems may expand based on the assumption that they can save global water use via transboundary food trade, but this expansion, driven by foreign investment, may compete with the water availability of small-scale farmers (Chiarelli et al., 2022; Dalin et al., 2012; Hoekstra, 2020) and lead to greater consolidation of food production. Distinguishing the farms involved in virtual water flows can help guide policies that balance poverty reduction, food security, and water sustainability.

4.2. Uncertainties and limitations

Many factors influence the relative contribution of small-scale and large-scale agriculture to international trade and virtual water flows. The difference in virtual water flows in our study mainly comes from crop structure and farming systems in small-scale and large-scale agriculture, and the crop water footprint of different farming systems. If small-scale and large-scale farms produce the same crop with the same farming system, our method cannot distinguish between them without additional information, e.g., export market access.

Based on the assumption that irrigated and high-input farming systems are more export-oriented than low-input and subsistence farming systems, we estimated that small-scale agriculture makes a significant contribution to virtual water flows. This represents a substantial share of blue and green water consumption, and our estimates do not conflict with current household surveys, showing the majority of small-scale agricultural crop production was sold (FAO, 2023a; Malek & Verburg, 2020; Rapsomanikis, 2015).

The countries studied cover around half of global cropland (Su et al., 2022). The virtual water flows from crops in 55 countries account for roughly 30% of global blue virtual water and 50% of global green virtual water (Graham et al., 2020; Hoekstra & Mekonnen, 2012; Mekonnen & Hoekstra 2020). Our analysis is based on harvested areas, crop production, and water consumption in small-scale and large-scale agriculture instead of the number of farms and farmers. We do not include livestock or industrial sectors, which account for a considerable amount of virtual water flows but are outside the scope of this study. We included the virtual water flows of crops as feed in livestock exports.

The reliability of virtual water flow estimates depends on the reliability of the input–output table (FABIO) and the crop water footprint. FABIO was established using FAOSTAT data (FAO, 2023b) for food products (Bruckner et al., 2019). The water footprints of crops were retrieved from and validated by Su et al. (2025b). Our estimates of blue virtual water flows from soybean and sugar crops in Brazil, based on the two assumptions, could cover the estimates from the previous study (59 million and 850 million m^3) that incorporated subnational international trade information. Compared to the studies incorporating local information and using more sophisticated models to estimate the trade direction, e.g., Flach et al. (2016) and Pandit et al. (2023), we do not differentiate export destinations from subnational regions; our method requires less detailed information but covers more countries.

While our dual-assumption approach (production-based and farming system-based) provides a robust range for current estimates, precisely distinguishing farm-level contributions in complex global supply chains remains a methodological frontier. Future research could overcome these challenges by integrating emerging technologies such as satellite-based crop monitoring and blockchain-verified supply chain data. These tools could eventually allow for the direct tracking of commodities from specific farm sizes to final consumers, reducing the need for proxy-based allocations.

5. Conclusion

Small-scale agriculture plays an important role in international trade and exports virtual water through the production of many crops, except fodder crops and sugar crops. Across all crops, small-scale agriculture accounts for 22% of blue and 30% of green virtual water flows, which is higher than its share of crop production involved in trade. Although the estimates at the country and sector levels involve certain uncertainties, they show consistent patterns at the global level, as demonstrated by the comparison of our two assumptions. Nevertheless, our findings provide valuable insights into how virtual water flow assessment can help to identify the role of small-scale agriculture in global food and water security. The findings also underscore the importance of considering the agricultural heterogeneity in virtual water flow assessments to improve the targeting of interventions.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/sus.2026.10066.

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Competing interests. The authors have no competing interests to declare.

Code and data availability. The country- and crop-level estimates of crop production involved in trade and virtual water flows estimated by this study are freely available via a Creative Commons Attribution 4.0 International license at the DOI: https://doi.org/10.4121/4d32300f-28cf-45f8-8e9d-77759bf6e9ce (Su et al., 2025a). All code, input data, and output data required to reproduce the results in this study will be archived for at least 10 years after publication within the University of Twente, Multidisciplinary Water Management (MWM) group. The MWM group will make the code and data available upon request.

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