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E-mail: xiewei.ccap@pku.edu.cn**Keywords:** global value chains, virtual water trade, agricultureSupplementary material for this article is available [online](#)**Abstract**

Traditional methods of assessing virtual water (VW) trade usually overestimate the foreign VW used by a country as the imported VW can also be re-exported and used by the countries other than the initial importer. Due to its ability to provide better estimates of transboundary resource use, the global value chain (GVC) method can provide more precise guidelines for the global policy debate over sustainable resource use. Here, we use GVC analysis based on multi-regional input-output tables to quantify the embodied trade of virtual blue and green water for China in the major agricultural sectors and agro-based industries. We find that China is a net importer of blue VW (2.9 billion m³) and green VW (57.9 billion m³) through agricultural commodities. Our results reveal that a large portion of imported blue (37%) and green (17%) VW is re-exported by China and consumed in other countries, representing the overestimated parts of China's VW import use. These ratios are even higher for individual commodities, including 44% for blue VW for cotton and 22% for green VW for grains. This work demonstrates the importance of improved accounting in VW trade to achieve the sustainable use of global water resources and equitably share responsibility between producers, intermediates, and end-users.

1. Introduction

A large body of literature has analyzed the transboundary movement of embodied resources through trade in goods and services (Konar *et al* 2012, Lin *et al* 2014, Meier *et al* 2014, Dalin *et al* 2015, Vora *et al* 2017, Zhang *et al* 2017a, Zhao *et al* 2018, Deng *et al* 2020). Due to its scarcity (Mekonnen and Hoekstra 2016, Veldkamp *et al* 2017) and importance for societies through food and agricultural systems (Davis *et al* 2017, D'Odorico *et al* 2018), economies (UNESCO 2016) and ecosystem services (Grizzetti *et al* 2016), water traded as virtual water (VW)⁶ has been widely studied (Fader *et al* 2011, Dalin *et al*

2012, Orlowsky *et al* 2014, Vörösmarty *et al* 2015, Flach *et al* 2016, Salmoral and Yan 2018, Qian *et al* 2019, Zhao *et al* 2019). Agriculture, the largest user of freshwater, has been the main focus of this literature. The traditional 'bottom-up' approach is most commonly used in these studies, employing detailed process data mostly for agricultural products (Chapagain *et al* 2006, Zhang *et al* 2016, Ali *et al* 2017). Despite its utility, this approach fails to account for inputs used at various stages of production. Measuring the trade in gross values through the bottom-up approach, where we hold the last country in the supply chain accountable for the entire value of export, potentially provides an inaccurate picture of international trade relations and may wrongly attribute production and consumption to various geographic locations (Elms and Low 2013).

⁶ The water embodied in traded commodities (Allan 1997).

A ‘top-down’ approach based on the concept of global value chains (GVCs) can eliminate the estimation errors within the ‘bottom-up’ approach (Koopman *et al* 2014, Elms and Low 2013). GVC is based on the concept that goods produced by firms in one part of the world can then be used as inputs by firms in their production process in other places (WTO 2019). Intermediate inputs move between various destinations multiple times; therefore, traditional trade statistics are becoming less reliable in gauging the value contributed by any particular country (Koopman *et al* 2014). In GVC terms, forward-linkages describe a country’s action to sell its exports as inputs for other countries’ exports, and backward linkages describe a country’s action when it buys inputs from other countries for its exports (Greenville *et al* 2019). GVC can thus provide a clearer picture of VW flows associated with imports and exports along the entire global supply chain while maintaining a full system boundary (Feng *et al* 2011)⁷.

China occupies a unique position in global VW trade through agricultural commodities due to its expanding agricultural trade, water scarcity, and increasing role in forward- and backward-linkages of GVCs of agriculture. With the world’s lowest per capita water availability (FAO 2016), China’s domestic water resources are under immense pressure. In addition to several other factors, China’s reliance on foreign agricultural products has been partially driven by the increased stress on its domestic water resources. For example, since joining the World Trade Organization, the country’s total food imports and exports increased from US\$ 15 billion to US\$ 127 billion and US\$ 24 billion to US\$ 92 billion during 2002–2017, respectively. The expanded trade in agro-based commodities was also profound, with, for instance, China’s exports and imports of textiles growing from US\$ 62 billion and US\$ 12 billion in 2002 to US\$ 298 billion and US\$ 24 billion in 2017 (FAOSTAT 2021). Moreover, during 2004–2014, China contributed the highest share (21%) in the global growth of forward-linkages in GVCs of agriculture and food trade (Greenville *et al* 2019).

These factors call for a deeper understanding of the consequences of China’s expansion in GVC networks and its global impact on water and other natural resources. Several existing studies show that China’s trade in VW through agricultural products has been growing (Chapagain and Hoekstra 2004, Liu *et al* 2007, Dalin *et al* 2014, Shi *et al* 2014, Zhuo *et al* 2016, Ali *et al* 2017). Although using different commodity mixes and time scales, most of these studies have employed ‘bottom-up’ analyses to show that China is a net importer of VW through

agricultural commodity trade. For example, China’s net-imports of VW through agriculture trade were reported as 31 billion m³ yr⁻¹ during 1991–2004 (Liu *et al* 2007); 138 billion m³ in 2009 (Shi *et al* 2014); and 120 billion m³ in 2015 (Ali *et al* 2017). However, these analyses may present an incomplete picture of China’s trade in VW through agricultural commodities as they assume that China consumes all the imported VW. While certain studies on VW trade have attempted to use the input-output approach to overcome the overestimation problem of VW imports by China, they have either only covered China’s inter-provincial trade using China’s input/output table or had a coarse representation of agriculture as a single sector (e.g. Zhao *et al* 2010, Wang *et al* 2016, Yang *et al* 2016, Hou *et al* 2018). Therefore, a comprehensive analysis is still needed to assess China’s import, export, and re-export of blue and green VW internationally.

In this study, we construct a multi-region input-output (MRIO) model, integrating direct resource use and monetary flows based on a global economic model for 2011—the latest year for which the data was available. We combine the MRIO model with VW contents (blue and green) of eight major crops to analyze the intermediate and final demand for VW by consumers in China and other countries through primary and processed agricultural commodities. The ultimate objective is to rectify the overestimation problem inherent in the traditional estimation methods by using a more suitable approach for the trade of VW through China’s trade in agricultural commodities to various regions. Using such an approach can lead to more accurate estimates of nations’ virtual resource imports and exports globally. These findings can provide vital information for improving international coordination between China and its trade partners on achieving the sustainable use of freshwater resources.

2. Methods and data

We used a MRIO model to analyze the VW use associated with China’s agricultural trade, integrating direct resource use and monetary flows (see SI figure S2 (available online at stacks.iop.org/ERL/16/045002/mmedia) for MRIO schematic table).

2.1. Measuring embodied water use by GVC decomposition method

We assume a world of G countries and N sectors. These countries are connected through the inter-regional trade of intermediate and final products, and each country’s outputs are used to satisfy intermediate or final demand by domestic and foreign consumers, such that:

⁷ For a detailed description and comparison of ‘bottom-up’ and ‘top-down’ approaches see Feng *et al* (2011).

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \dots & A^{1g} \\ A^{21} & A^{22} & \dots & A^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ A^{g1} & A^{g2} & \dots & A^{gg} \end{bmatrix} \begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} + \begin{bmatrix} \sum_r^G Y^{1r} \\ \sum_r^G Y^{2r} \\ \vdots \\ \sum_r^G Y^{gr} \end{bmatrix} \tag{1}$$

where X^s represents the gross output of country s ($s = 1, \dots, g$), Y^{sr} represents the final demand of country r ($r = 1, \dots, g$) for products from country s , A^{sr} is the input coefficient matrix representing the intermediate use in country r of goods produced

in country s . The elements of the input coefficient matrix satisfy $a_{ij}^{sr} = z_{ij}^{sr}/x_j^r$, where z_{ij}^{sr} ($i, j = 1, \dots, n$) represents the transfer from sector i of country s to sector j of country r . The intermediate input matrix from country s to country r is represented by $z^{sr} = A^{sr}X^r$. Equation (1) can be rearranged as

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} = \begin{bmatrix} I - A^{11} & -A^{12} & \dots & -A^{1g} \\ -A^{21} & I - A^{22} & \dots & -A^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{g1} & -A^{g2} & \dots & I - A^{gg} \end{bmatrix}^{-1} \begin{bmatrix} \sum_r^G Y^{1r} \\ \sum_r^G Y^{2r} \\ \vdots \\ \sum_r^G Y^{gr} \end{bmatrix} = \begin{bmatrix} B^{11} & B^{12} & \dots & B^{1g} \\ B^{21} & B^{22} & \dots & B^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ B^{g1} & B^{g2} & \dots & B^{gg} \end{bmatrix}^{-1} \begin{bmatrix} \sum_r^G Y^{1r} \\ \sum_r^G Y^{2r} \\ \vdots \\ \sum_r^G Y^{gr} \end{bmatrix} \tag{2}$$

where B^{sr} , the Leontief inverse, represents the quantity of the gross output of country s for a one-unit increase in the final demand of country r . From equation (2), the gross output of country r can be given as:

$$X^r = \sum_G^t B^{rt} \sum_G^u Y^{tu}. \tag{3}$$

The intermediate input of country r from country s is $Z^{sr} = A^{sr}X^r$. The exports from country s to country r are $T^{sr} = Y^{sr} + A^{sr}X^r$ and can be divided into three parts (Wang et al 2013) as

$$\begin{aligned} T^{sr} &= Y^{sr} + A^{sr}X^r \\ &= \underbrace{Y^{sr} + A^{sr}B^{rr}Y^{rr} + A^{sr}B^{rs}Y^{sr} + A^{sr} \sum_{t \neq s,r}^G B^{rt}Y^{tr}}_{T_{-f}^r} + \underbrace{A^{sr}B^{rr}Y^{rs} + A^{sr}B^{rs}Y^{ss} + A^{sr} \sum_{t \neq s,r}^G B^{rt}Y^{ts}}_{T_{-f}^s} \\ &\quad + \underbrace{A^{sr}B^{rr} \sum_{t \neq s,r}^G Y^{rt} + A^{sr}B^{rs} \sum_{t \neq s,r}^G Y^{st} + A^{sr} \sum_{t \neq s,r}^G B^{rt} \sum_{u \neq s,r}^G Y^{tu}}_{T_{-f}^{other}}. \end{aligned} \tag{4}$$

$$W^{ps} = F^{ps}X^s. \tag{5}$$

We define sectoral water intensity as $f^{ps} = w^{ps}/x^{ps}$, where w^{ps} represents the water requirement of an agricultural sector p of country s . $F_{ps} = (f_{p1s}, f_{p2s}, \dots, f_{pns}, 0, \dots, 0)'$ is a diagonal matrix composed of f_{ps} . The water consumption of country s is

W^{ps} is the water consumed in the country's agricultural sectors, which we can divide into two parts based on the form it is consumed. The first part is the water embodied in agricultural products that are consumed as final products. The second part is the water embodied in the production that is consumed

as intermediate goods. The water embodied in intermediate goods is

$$W^{nps} = \left[\left(W^{ps} - F^{ps} \text{diag} (A^{ss} X^s) - Y^{ss} - \sum_{r \neq s} T^{sr} \right) C^{ss} \right]^{-1} \tag{6}$$

where $C^{ss} = (Z^{ss} - \text{diag}(Z^{ss})) \times (X^s)^{-1}$, it presents the ratio of the agricultural products consumed in non-agricultural sectors, and the water consumption intensity of the np sector in s country is $f^{nps} = W^{nps} / (Y^{ss} + T^{sr})$. Therefore, the water consumption intensity of all sectors in the country s is

$$F^s = (f^{p1^s}, f^{p2^s}, \dots, f^{px^s}, f^{np1^s}, f^{np2^s}, \dots, f^{np_y^s})'. \tag{7}$$

F^s represents the increase in domestic water caused by an increase of one unit in the country s exports, agricultural sectors x ($x = 1, \dots, x$), and non-agricultural sectors y ($y = 1, \dots, y$). Thus, the domestic water embodied in the exports from country s to country r in equation (6) can be given as:

$$WEX^{sr} = F^s T^{sr} f^r + F^s T^{sr} f^s + F^s T^{sr} f^{\text{other}}. \tag{8}$$

Based on equation (8), the gross domestic water of country s exported to country r is decomposed into three paths. Path 1 ($F^s T^{sr} f^r$) shows the water embodied in products exported from country s to country r , which are directly consumed or used as intermediate products for production in other sectors by country r . Path 2 ($F^s T^{sr} f^s$) is the water embodied in the commodities exported from country s to country r , which are used by country r to produce other commodities and then returned and finally consumed by country s . Path 3 ($F^s T^{sr} f^{\text{other}}$) shows the water embodied in the products exported from country s to country r , which are used by country r to produce other commodities and then re-exported to other countries (excluding countries s and r) and finally consumed by other countries. Each part of equation (8) represents the domestic water embodied in the products produced in the country s .

2.2. Data

2.2.1. Monitory MRIO table

This study uses the latest version of the Global Trade Analysis Project-Water (GTAP-W) database (2011 base-year), which contains 140 countries/regions and 76 sectors (Haqiqi et al 2016). We aggregate the GTAP-W database into 18 sectors while ensuring that all the primary and processed agricultural sectors are present in the most disaggregated form. We also aggregate the GTAP countries into 12 regions while keeping the detailed representation of China's main trading partners (SI tables S1 and S2 contain details of regional and sectoral aggregations) (available online at stacks.iop.org/ERL/16/045002/mmedia).

2.2.2. Agricultural blue water (irrigation) use

We used the following method to estimate the sectoral water intensity ($f^{ps} = w^{ps} / x^{ps}$) for blue VW for all

the sectors and regions in our aggregated database, by dividing the total water requirement of agricultural sector p of country s (w^{ps}) with the gross output of the sector p in country s (x^{ps}).

- (a) Crop water requirement (CWR): this data set is based on the work by Siebert and Döll (2010) and represents worldwide information on water requirements for irrigation for 29 crop categories at a 5 min spatial resolution in 2000. In our study, we assume that the water requirements in 2011 are similar to those in 2000⁸.
- (b) Irrigation water requirement (IWR) by country in 2011: this data set is obtained from the FAO's global water information system (2016). We then use the CWR for each crop to allocate each country's IWR to each crop sector in our aggregated database.

2.2.3. Agricultural use of green water (soil moisture)

Due to data limitations, we rely on the blue water use estimated in the previous subsection and ratios between the blue and green water requirements for crop production to obtain the green water use by crops based on the blue and green water use per unit of the crop, as described in Hanasaki (2016). We then get the green water use through the following equation:

$$GW_{i,r} = (G/B) \text{Ratio}_{i,r} \times BW_{i,r} \tag{9}$$

where $GW_{i,r}$ is the amount of green water embodied in the production of per unit of a crop i in country/region r ; $\frac{G}{B} \text{Ratio}_{i,r}$ is the ratio of green to blue water and $BW_{i,r}$ is the blue water used in per unit production of crop i and country/region r .

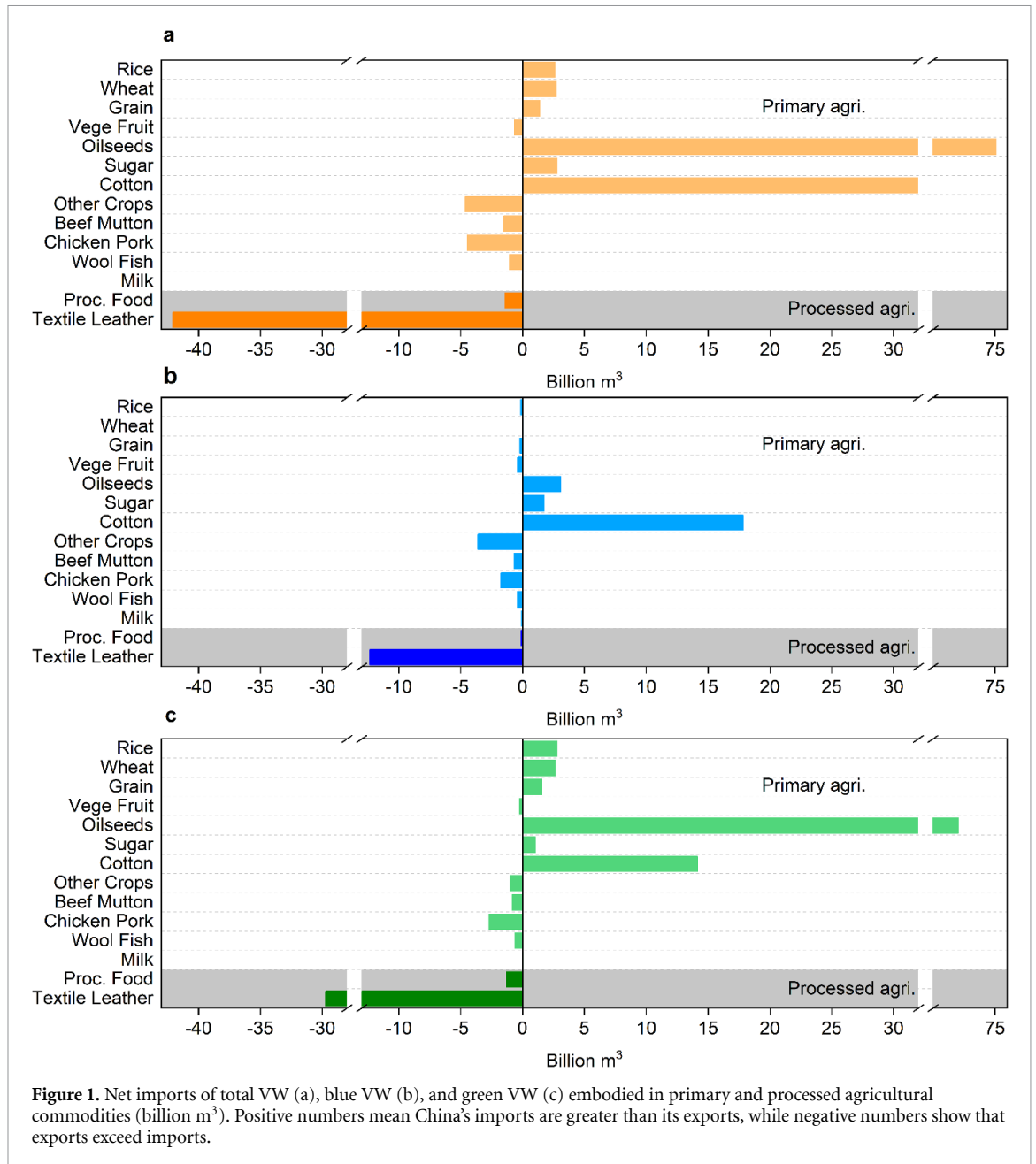
3. Results

Here we present the main net import results of our GVC analysis of China's VW trade associated with primary and processed agricultural commodities in 2011.

3.1. Net VW imports by China through different commodities

The main commodities for total agricultural VW import are soybean (80.9 billion m^3), cotton (32.0 billion m^3), and maize (3.0 billion m^3) from the USA, Brazil, Argentina, India, and Central Asia. The main commodities for export of VW

⁸ For a more accurate representation of water intensities for rice and wheat, we used VWC from Hanasaki (2016) and multiplied them with the total quantity of rice and wheat output in each country to get total water requirement for them. We then subtract the water requirement for rice and wheat from the national IWR. For the rest of the crops, we divided the remaining IWR by using CWR for these crops from Siebert and Döll (2010).

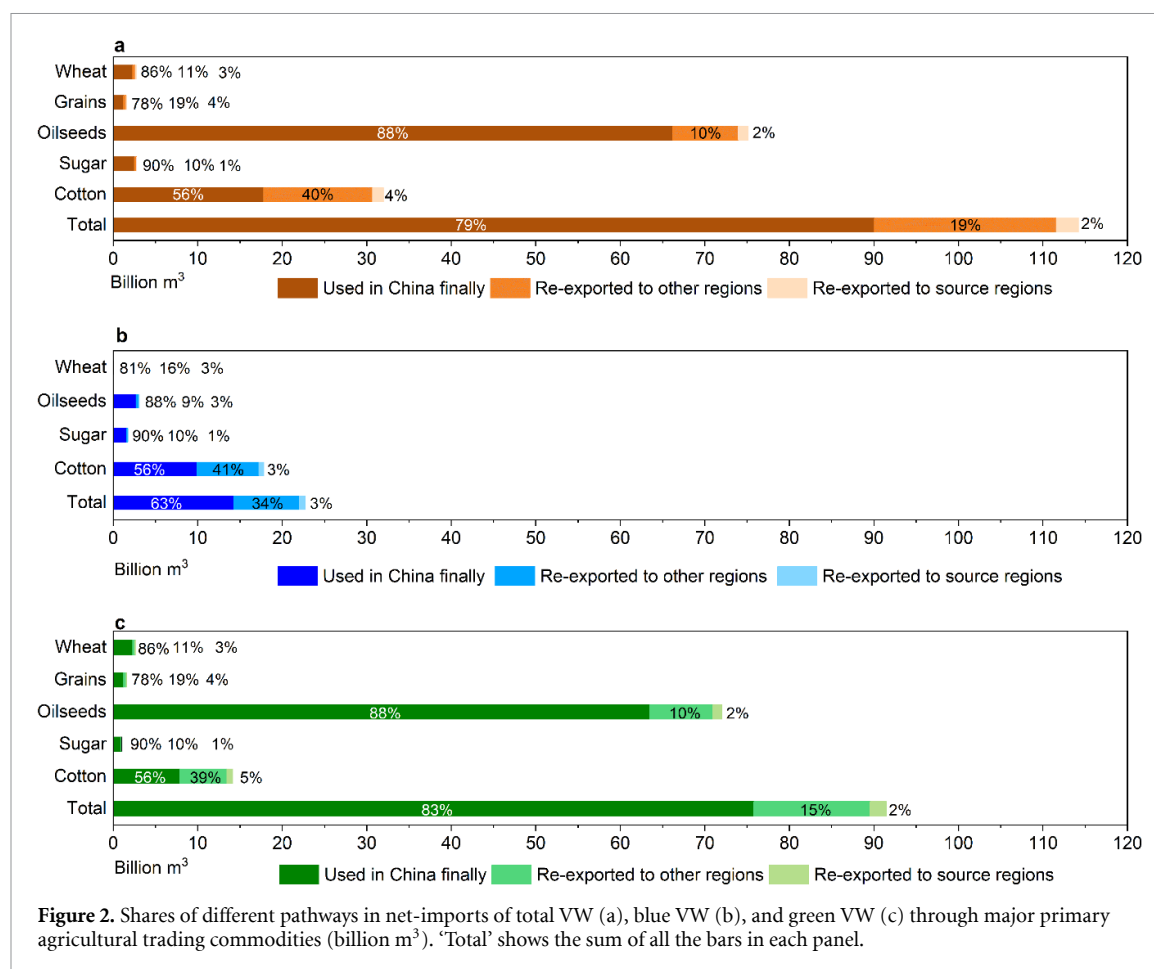


are 'other crops' (including crops like coffee, tea, and spices), processed food, and textile mainly to South Asia, Southeast Asia, European Union, and North America (figure 1(a); see supplementary figure S1 for imports and exports of blue and green VW embodied in primary and processed agricultural commodities).

China is a net importer of blue VW through primary agricultural commodities (15.4 billion m³, the sum of the bars in the upper part of figure 1(b)) but a net exporter of blue VW through processed agricultural commodities (12.4 billion m³, the sum of the bars in the lower part of figure 1(a)). The total effect is a net-import of 2.9 billion m³ of blue VW by China. The highest net import of blue VW is through cotton (17.8 billion m³) and oilseeds (3.1 billion m³, which is mostly soybean). Sectors such as 'other

crops' (including coffee, tea, and spices) are the main primary agricultural commodities responsible for blue VW's net-export, with net-exports of 3.6 billion m³. For the processed agricultural commodities, the net exports are dominated by textile (processed cotton) and leather (12.4 billion m³), followed by processed food sectors (0.1 billion m³).

For green VW, China is a net importer for most agricultural commodities, with a total net-import of 57.9 billion m³ (figure 1(c)). In terms of the primary agricultural commodities, oilseeds (72.0 billion m³) and cotton (14.1 billion m³) dominate green VW's net-import. Chicken and pork (2.7 billion m³) and other crops (1.0 billion m³) are the top primary agricultural commodities responsible for green VW's highest net-exports from China. Among the processed agricultural commodities, textile and



leather (29.7 billion m³) and processed food sectors (1.3 billion m³) show considerable net export of green VW by China (figure 1(c)). The combined net-imports of both blue and green VW through primary agricultural commodities (rice, wheat, other grains⁹, vegetables, fruits, oilseeds, beef, mutton, chicken, and pork) by China stood at 75.3 billion m³, comparable to earlier findings of 76.8 billion m³ by Ali *et al* (2017) for the same period. Shi *et al* (2014) used the traditional 'bottom-up' approach and reported a net import of ~138 billion m³ of VW by China through 27 major primary crops in 2009. Their estimates are higher as they covered more crops and did not report the re-export of VW.

3.2. Net VW imports by China through different pathways

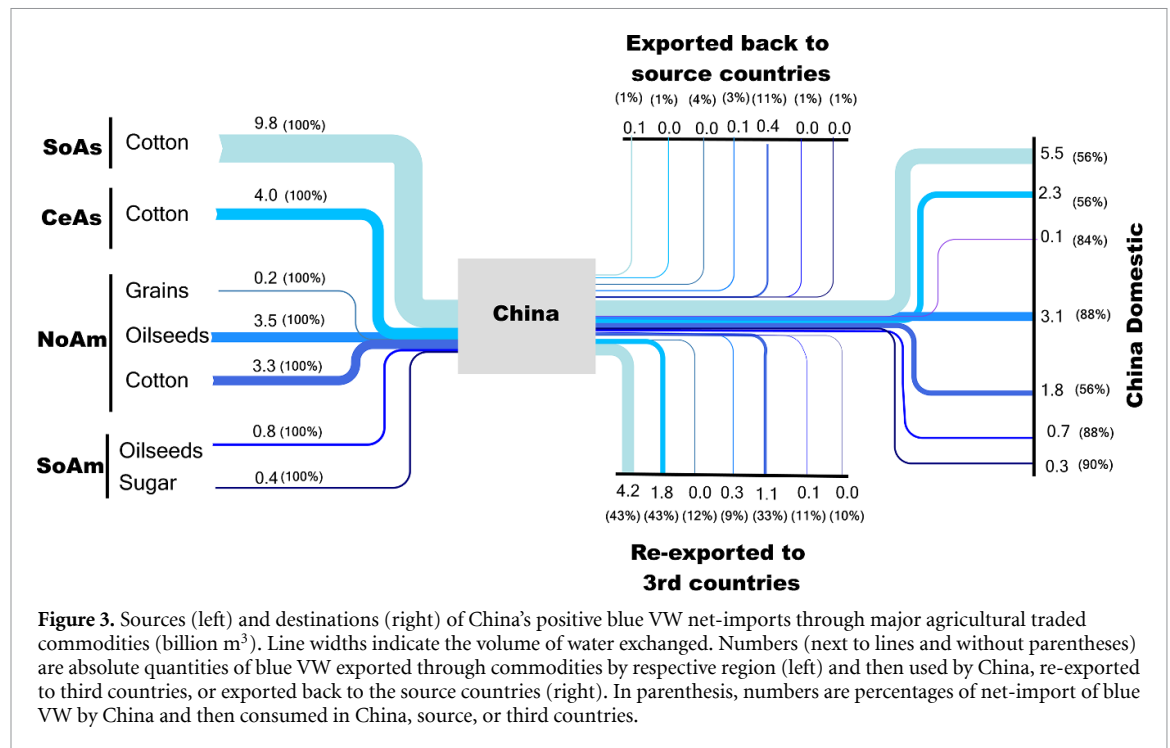
We find that not all of the VW imported by China through agricultural commodities is ultimately consumed within China. Instead, large fractions of this VW are re-exported via primary and processed agricultural commodities, either back to the source country or onward to a third country (figure 2). Although China's combined (positive)

net-imports of blue and green VW through agricultural commodities were 114.2 billion m³, the nation re-exported 24.1 billion m³ (or 21%) of this imported VW to other countries (sum of respective shares in figure 2(a)).

When disaggregated between blue and green VW, we find that China re-exports 37% of imported blue and 17% of imported green VW to other countries for their final consumptive use. For cotton, the biggest net-importing commodity of blue VW for China, we see that about 56% (9.9 billion m³) of blue VW imported by China is used for domestic consumption, while the rest, 7.9 billion m³, is re-exported to the outside world via different trade pathways. About 41% (7.3 billion m³) of blue VW net-import through cotton is re-exported to third countries, while 3% (0.6 billion m³) returns to source countries. For oilseeds (including 'soybean') and sugar crops, the ratios of domestic use of imported blue VW by China are substantially higher (88% and 96%, respectively), showing that most of the blue VW imported through oilseeds and sugar is consumed within China, and the rest (12% and 4%, respectively) is re-exported in the form of intermediate or final goods.

For green VW, we see that China uses a significant portion (88%) of the imported green VW (63.5 billion m³) through the imports of oilseeds for its domestic use, while 10% (7.2 billion m³)

⁹ As maize is the largest part of imports by China among all the grain crops aggregated in the 'Other grains' sector, the results for 'Other grains' closely depict China's VW trade in maize.



and 2% (1.1 billion m³) shares are re-exported to third countries and source countries, respectively (figure 2(b)). We observe that a significant portion (44%) of green VW imported by China through cotton trade is re-exported to other world regions. For wheat (14%), grains (which is mostly maize for China, 23%), and sugar crops (11%), reasonably large ratios of the green VW imported by China are re-exported to other countries.

3.3. Sources and destinations of China's net VW imports

Our findings also show that China's imports of blue VW through cotton are mainly sourced from India (South Asia) and Central Asian countries (72%), followed by the USA (North America, 23%) (figure 3). Interestingly, 43% of the blue VW imported through China's cotton trade is re-exported to third countries, while only 56% is retained for its domestic use. About 11% of the blue VW imported through cotton trade by China from the USA (North America) is returned to the USA, while 33% is re-exported to other countries. China imports about 97% of its blue VW through oilseeds (soybean) from Brazil, Argentina, and the USA (South and North America). However, China consumes 88% of the blue water imported through oilseeds domestically while re-exporting ~12%. Among other major commodities, China re-exports 16% of blue VW imported through other grains from the USA (North America) and 10% of blue VW imported through sugar crops from Brazil (South America).

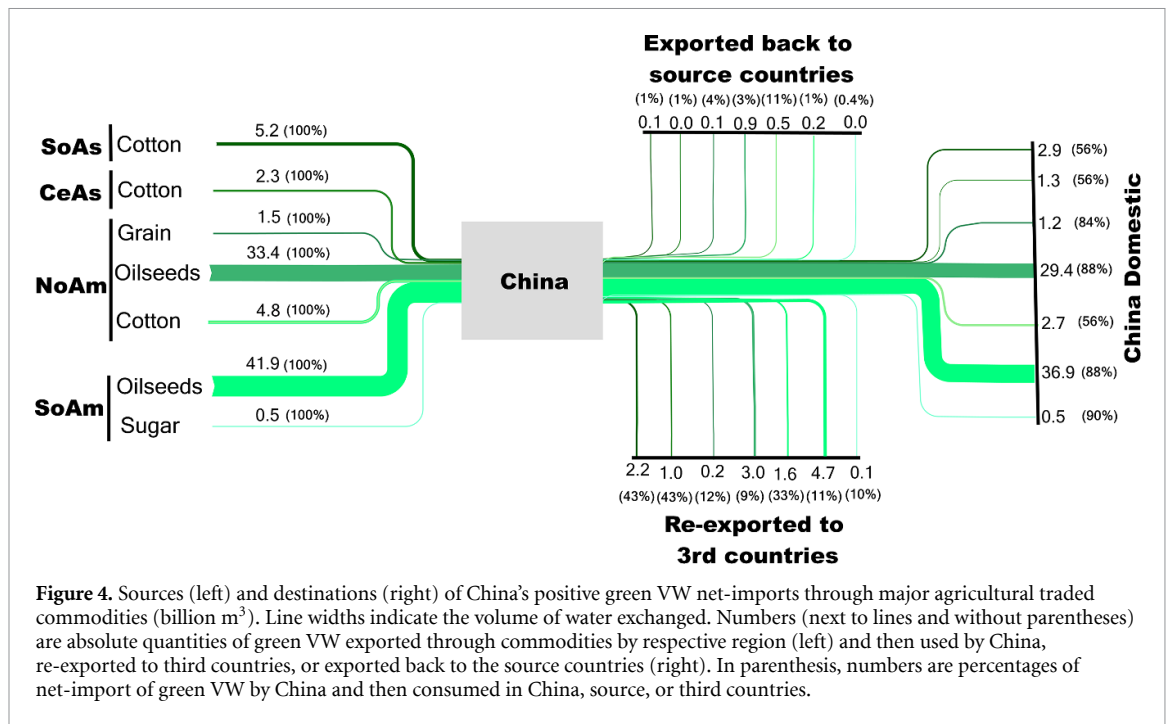
The source countries for green VW trade by China are almost similar to blue VW ones (figure 4).

However, there are considerable differences in quantities. About 44% of green VW embodied in China's oilseeds imports comes from North America and 55% from South America. Out of the 33.4 billion m³ and 41.9 billion m³ of green VW imported from North and South America, 3.0 billion m³ and 4.7 billion m³ are re-exported by China to third countries. With a total share of 71%, the import of green VW through cotton trade by China is dominated by two regions (South Asia (India) and North America (USA)), of which 43% and 33% of green VW is re-exported to third countries. Although the USA is one of the biggest net-exporters of green VW to China through cotton, it imports 11% of the green VW back through the cotton trade.

4. Discussion and conclusion

The sustainable use of water and other natural resources is one of the biggest challenges facing humanity. The interaction between domestic and global solutions to resource sustainability has the potential to furnish novel policy measures. Choosing the most appropriate method for tracing VW flows is essential to draw meaningful conclusions about the sustainable use of water resources, as intermediate trade is of growing importance globally (Kanemoto et al 2012, Jiang and Guan 2017, Zhang et al 2017b, Cadarso et al 2018). In this case, we need a decomposition of intermediate product trade between different countries based on backward industrial linkages.

This study used the GVC method to quantify VW trade measures of China's import, export, and re-export of primary and processed agricultural



commodities. Our approach shows the potential to present a more accurate picture of China's role in global VW trade and allocate final VW consumption to final consumers appropriately. The application of the GVC method to the analysis of both blue and green VW trade can be regarded as an initial effort to understand China's role in managing global water resources and the possibility for the international community to collaborate on developing policy measures based on each region's or country's position in the supply and demand for water resources.

Our results indicate that China is a net importer of blue VW through its agricultural commodity trade. This net-import was mainly associated with large cotton imports from South Asian countries (e.g. India and Pakistan). China's significant exports of textile products to North America, Europe, and East Asian countries are associated with large net-exports of blue VW (12.4 billion m³). The GVC analysis reveals that ~37% of China's blue VW imported via agricultural commodities is ultimately re-exported to other countries. This finding implies that discussions of sustainable water resource use between China and its trading partners should account for the true complexity of global supply chains—including where water is initially used to produce a good and who realizes the benefits of that good as it travels to the end consumer.

For green VW transfers, China is a substantial net importer (57.9 billion m³), mainly through soy imports (72.0 billion m³) from the USA, Brazil, and Argentina and cotton (14.1 billion m³) from India. Notably, the total blue and green VW imports via soy trade are by far the largest among agricultural commodities for China (75.1 billion m³). These results agree with earlier studies that also found

that massive imports of soy are transferring vast VW volumes to China (Dalin et al 2014, Ali et al 2017, Hou et al 2018). Out of the total green VW net-imports, we have shown that China re-exports 17% (15.7 billion m³) of the imported green VW to the rest of the world. Due to China's increasing role in forward-linkages (i.e. supplier of inputs for other countries' export), the country is expected to export higher volumes of VW through its agricultural trade in the coming years. Therefore, China should seek to utilize its local water resources sustainably while also developing mutually beneficial economic ties that ensure the responsible sourcing of VW for China's imports. While our analysis focused on 2011 (the most recent year for which GVC data were available), future analyses that incorporate more detailed and disaggregated crop and livestock sectors and that assess the temporal evolution of China's VW trade can shed light on the extent to which VW re-export is an increasingly important consideration.

Devising policies for sustainable resource use at national and global levels requires accurate estimation methods. As a large fraction of China's imported VW through agricultural trade is ultimately consumed in other countries, global discussions on the sustainable use of water resources should take into consideration the shared responsibility of nations to act with increasingly complex supply chains in mind. Understanding how VW flows through GVCs and who the intermediate users and end consumers are can facilitate informed decision-making related to water sustainability. Countries with higher resource use efficiencies could be incentivized, for instance, while other countries may be encouraged to conserve their water resources.

As China re-exports large proportions of imported VW through agricultural trade, the country can improve its domestic resource use efficiency to supply more resource-efficient products to the world. China (and other major trading countries) should focus on a combination of supply- and demand-side policies and actions for improving the sustainability of global supply chains. Future China-focused research can seek to develop more sophisticated models and more accurate datasets to target policies for specific traded commodities, structural changes of agricultural trade, and their spatial and temporal evolution trends.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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