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Research article

Water footprint of nations amplified by scarcity in the Belt and Road Initiative

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ABSTRACT

The growing water scarcity due to international trade poses a serious threat to global sustainability. Given the intensified international trade throughout the Belt and Road Initiative (BRI), this paper tracks the virtual water trade and water footprint of BRI countries in 2005–2015. By conducting a multi-model assessment, we observe a substantial increase in BRI's water footprint after taking water scarcity into account. Globally the BRI acts as a net exporter of virtual water, while the export volume experiences a decreasing trend. Noticeable transitions in nations' role (net exporters *vs.* net importers) are found between the BRI and global scales, but also between with and without considering water scarcity. Overall economic and population growth is major drivers of scarcity-weighted water footprint for BRI nations, as opposed to the promotion of water-use efficiency and production structure that can reduce water scarcity. Improving international trade and strengthening cooperation on water resources management deserve priority in alleviating the water scarcity of BRI.

1. Introduction

Geographically, the Belt and Road Initiative (BRI) involves a large number of countries along the land-based "Silk Road Economic Belt" and the oceangoing "Maritime Silk Road", encompassing approximately 64% of the global population and 30% of global GDP [1]. It has now been recognized as an ambitious policy aiming at enhancing regional economic cooperation, with consequences that would

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substantially influence the future of global economy, but also give rise to significant environmental changes [2-4]. The BRI is a major global initiative with profound implications for economies, policies and societies; yet trade-embodied resources throughout the BRI have received little attention [5]. Amongst these, water scarcity probably receives the highest attention due to increasing deforestation and desertification in large parts of the BRI area, particularly in Central Asia and West Asia [6], as is evident from the fact that around 40 BRI countries have renewable internal freshwater resources per capita lower than the world average [7].

The growing scarcity of freshwater due to rising anthropogenic demands and international trade poses a serious threat to global sustainability [8]. Most studies, however, focus primarily on water scarcity associated with trade between developing and developed countries [9,10], neglecting the scarcity associated with the trade between developing countries. The World Bank reports that the trade flows among countries partnering the BRI have increased by 4.1% since its start in 2013 [11]. Therefore, it makes sense to track the virtual water (i.e., the water embodied in trade with other regions to produce goods and services) trade and the water footprint (i.e., the water needed for the production of goods and services consumed by the population) associated with trade between BRI countries. Both indicators have been increasingly considered as powerful accounting tools for mapping the linkages between consumption behaviors, trade activities, anthropogenic water use, and associated water scarcity [12,13].

There are different approaches available for tracking virtual water flows. Normally the footprint accounting can be divided into two categories: the bottom-up approach represented by life cycle assessment (LCA), and the top-down approach represented by multi-regional input–output (MRIO) [14]. While the LCA community and the footprint community have much in common, a footprint analysis is not necessarily based on a LCA [15]. Unlike LCA, the MRIO analysis is a top-down approach aimed at reflecting the interdependence between regional sectors along the whole supply chain [16]. With water extensions, it is a widely used approach to exploring virtual water trade and water footprint [17-19]. A growing number of studies have confirmed that water scarcity has a negative impact on food security, environmental sustainability, and economic growth [9,20,21]. However, the volumetric water footprint has been argued to be misleading without additional information, because in some cases numerically a smaller footprint can induce a larger impact [22]. This brings into focus the scarcity-weighted water footprint, which allows for a quantitative comparison of various products or services across space and time in terms of their potential contributions to water scarcity [23,24].

It has been acknowledged that water scarcity plays a central and often limiting role in the BRI's pursuit of welfare and sustainable development [25]. A better understanding of the impact of water scarcity on international trade by incorporating scarcity into water footprint is needed, as equal volumes of water use can contribute to different degrees of water scarcity in water-rich and water-scarce regions. Moreover, the role of a nation in virtual water trade can vary across scales. While this has been acknowledged in general studies on the virtual water use embodied in worldwide supply chains, a focus on the BRI is lacking. Only Zhang et al. [26] and Qian et al. [27] investigate the virtual water trade in the BRI, but limited to agricultural products with bottom-up approaches. In addition to missing the economy-wide picture that MRIO models provide, they do not take into account the variation and scarcity of water use in BRI. As a result, discussions on this issue are far from settled and thus deserve renewed attention. This paper takes up that challenge.

In addition to accounting for virtual water trade and water footprint, some authors have attempted to further identify the driving forces behind the variations of results. Generally adopted methods include index decomposition analysis (IDA) and structural decomposition analysis (SDA). IDA, in the form of the STIRPAT model and the log-mean Divisia index model has come under criticism for the failure to fully take into account the interconnectedness existing in telecoupled regions and sectors [28,29]. SDA, on the other hand, is easily linked to the MRIO model, which makes it possible to assess the impact of international trade on domestic water resources by pinpointing the drivers of structural change in water footprint in a sound manner [30,31].

The purpose of this study is to analyze the water scarcity among BRI countries by evaluating virtual water trade and water footprint. To that end, we account for the virtual water trade of the 65 BRI countries from both regional and global perspectives by combining MRIO and environmental satellite accounts, compare the water footprint of each country with and without considering nation-specific water scarcity, and explore the driving factors behind the scarcity-weighted water footprint of BRI countries based on SDA. Since the omission of telecoupling of various countries would result in incorrect estimates, this study further explores the impact of water scarcity in BRI through the use of total water footprint distance (i.e., distance between one country and the other countries between which virtual water trade takes place) that delineates the interdependence among nations with respect to scarce water trade and use. By incorporating water scarcity characteristics into water footprint analysis, our paper enables a better understanding of virtual (scarce) water flows and the impact on nations' role in virtual water trade both on the BRI and global scales, all of which yields a first full picture of direct and indirect water use throughout the BRI.

The rest of the paper is structured as follows: Section 2 introduces the methods and data sources. Section 3 presents the empirical results, with a focus on the spatio-temporal variations, the underlying driving factors, and the distinction between the volumetric water footprint and scarcity-weighted water footprint. Discussions on major findings, policy implications, uncertainty analysis and future improvements are assembled in Section 4.

2. Methods

2.1. Water footprint accounting based on multi-regional input–output analysis

Rooted in the undifferentiated input–output (IO) model, the MRIO model has now been globally employed to quantify various environmental footprint indicators embodied in international trade, such as the water footprint [32,33], land footprint [34], and energy footprint [35]. We apply a MRIO model to track both direct and indirect water consumption volume. The MRIO model is able to explicitly show the flows of goods and services by distinguishing production structure, technology, and consumption for each study area. The basic equilibrium of an MRIO with m regions and n sectors can be described as:

$$X = AX + Y \tag{1}$$

From Eq. (1), X is the $mn \times 1$ vector of gross output; $Z = AX$ is the $mn \times mn$ matrix of total intermediate demand; A is the $mn\times mn$ technical coefficient matrix, representing the inputs of each sector per unit of their output; and Y is the $mn \times 1$ vector of final demand, with each region m is classified into five categories, e.g., rural household consumption, urban household consumption, government consumption, gross fixed capital formation, and stock changes.

The above formula can be converted into:

$$X = (I - A)^{-1}Y \tag{2}$$

From Eq. (2), I is the identity matrix, $(I - A)^{-1}$ is the Leontief inverse matrix, expressing both direct and indirect effects from a unit change in the final demand.

Thus, using Eqs. (1) and (2), water use can be included through a satellite vector E of size $1 \times mn$. With this environmental extension, water demand (= water footprint, WF) is can be modelled as Eq. (3):

$$WF = EX = E(I - A)^{-1}Y \tag{3}$$

We will need to study the water demand due to final demand, split by region. The final demand in region r is indicated by Y^r. For instance, the demand by region r for products of sector i produced in region s is $Y^r_{(s-1)n+i}$. According to Eq. (3), the water footprint associated with that can be rewrote as Eq. (4):

$$WF^r = E(I - A)^{-1}Y^r \tag{4}$$

Inferring from Eq. (4), part of WF^r is exerted domestically and part abroad. A disaggregation of the water footprint by region is achieved by Eq. (5):

$$WF^r_s = \sum_{i=1}^{n} E_{(s-1)n+i} \sum_{j=1}^{mn} (I - A)^{-1}_{(s-1)n+i,j} Y^r_j \tag{5}$$

The domestic water footprint to satisfy region's r consumption can be calculated as Eq. (6):

$$WF^r_{dom} = WF^r_r \tag{6}$$

and the imported water footprint from region s to satisfy region's r consumption is Eq. (7):

$$WF^r_{imp,s} = WF^r_s \tag{7}$$

Clearly,

$$WF^r = \sum_{s=1}^{m} WF^r_s = WF^r_{dom} + \sum_{\substack{s=1 \\ s\neq r}}^{m} WF^r_{imp,s} \tag{8}$$

From Eq. (8), the water footprint of region's r final consumption consists of two parts, domestically extracted water and imported as virtual water trade. The virtual trade data represents these terms WF^r_{dom} on the diagonal and $WF^r_{imp,s}$ for the off-diagonal elements, representing the virtual water trade from region s to region r.

A region's total virtual water trade is calculated through Eq. (9):

$$VWT^r = \sum_{\substack{s=1 \\ s\neq r}}^{m} WF^s_{imp,r} - \sum_{\substack{s=1 \\ s\neq r}}^{m} WF^r_{imp,s} \tag{9}$$

When this is positive, the region is a net exporter; otherwise the region is a net importer of virtual water.

2.2. Scarcity-weighted water footprint accounting based on water scarcity index

To explicitly capture the impact of water consumption on global freshwater scarcity [24,36], we make use of scarcity-weighted water footprint to explicitly incorporate the scarcity of water resources that are geographically heterogeneous. Resembling the water scarcity index (WSI) [37], the scarcity-weighted water footprint is able to incorporate water scarcity as a factor into virtual water trade accounting [38]. WSI is employed as a measure of the magnitude of water scarcity, defined as: the ratio of domestic water withdrawal to domestic renewable freshwater resources [39]. Although some of the water withdrawal for human activities mainly comes from water in the environment, studies have proved that in many cases approximately 80% of renewable water must be circulated in the natural system to meet the needs of ecosystems at all levels, and only 20% can be used as potential water supplies for human activities [40,41]. Using this assumption, the water scarcity index of region r (WSI^r, in yr^{-1}) can be expressed as Eq. (10):

$$WSI^r = WW^r / (0.2 \times RFA^r) \tag{10}$$

From Eq. (10), *WW* is its domestic water withdrawal (in m^3/yr), and *RFA* is its renewable freshwater availability (in m^3/yr). On the basis of recent studies on WSI [42,43], we define no water scarcity when a nation's WSI is below 0.2, moderate water scarcity when its WSI ranges between 0.2 and 0.4, severe water scarcity when the WSI is between 0.4 and 1.0, and extreme water scarcity when the WSI is 1.0 or more.

Taking into account the effects of water scarcity in each country, the water footprint of countries is no longer the sum of the domestic and imported water footprints. Each component has to be adjusted using the WSI of the country where the water withdrawal takes place. For the domestic water footprint of countries, we use their domestic WSI: The scarcity weighted water footprint in region *s* due to consumption in region *r* can be calculated as Eq. (11):

$$SWF_s^r = \sum_{i=1}^{n} WSI^s E_{(s-1)n+i} \sum_{j=1}^{nm} (I-A)^{-1}_{(s-1)n+i,j} Y_j^r \tag{11}$$

with SWF, we can calculate scarcity weighted imports, exports and virtual water trade in the same way as above.

2.3. Structural decomposition analysis

Changes over time in a region's scarcity-weighted water footprint are the result of a combination of a variety of factors. Under the SDA framework, five driving factors, i.e., water use efficiency, production structure, economic structure, population, and per capita GDP behind are analyzed to drive the variation in the scarcity-weighted water footprint [44]. As shown in Eqs. (4)–(8), the factors consist of water use intensity or water use efficiency *E*, the Leontief inverse $L = (I-A)^{-1}$ (production structure) and the final demand *Y*. Furthermore, vector Y^r can be further decomposed into economic structure Y_c^r (a vector of length *mn*), population P^r, and per capita GDP Y_p^r, following Eq. (12):

$$Y^r = P^r \times \frac{Y^r}{GDP^r} \times \frac{GDP^r}{P^r} = P^r \times Y_c^r \times Y_p^r \tag{12}$$

The change of scarcity-weighted water footprint of region *r* can be decomposed as Eq. (13):

$$\Delta SWF_s^r = (WSI^r E^r) \times L^r \times Y_c^r \times Y_p^r \times P^r + WSI^r E^r \times L^r \times Y_c^r \times Y_p^r \times P^r + WSI^r E^r \times L^r \times Y_c^r \times Y_p^r \times P^r + WSI^r E^r \times L^r \times Y_c^r \times Y_p^r \times P^r + WSI^r E^r \times L^r \times Y_c^r \times Y_p^r \times P^r \tag{13}$$

$$WF^r = E^r \times L^r \times Y_c^r \times Y_p^r \times P^r + E^r \times L^r \times Y_c^r \times Y_p^r \times P^r + E^r \times L^r \times Y_c^r \times Y_p^r \times P^r + E^r \times L^r \times Y_c^r \times Y_p^r \times P^r + E^r \times L^r \times Y_c^r \times Y_p^r \times P^r \tag{14}$$

From Eqs. (13) and (14), shows the changes in a factor. Each term of Formulas (13)–(14) represents the contribution of each driving force (i.e., water use intensity, production structure, economic structure, per capita GDP and population). In this study, five factors have 5! = 120 first-order decompositions. Finally, we take the average of all possible first-order decompositions as our SDA results.

2.4. Data availability

There is no consensus on the exact number of BRI members. This paper selects 65 countries according to the availability of data and divide them into six regions—Central Asia, CMR, Europe, South Asia, Southeast Asia and West Asia & Africa (Supplementary Table 1). Primarily, data required in this study include global MRIO data, water withdrawal of different sectors, total renewable water resource of each country and the distance between national capitals, as well as population and GDP data for each country.

(1) *MRIO.* Global input–output databases have reached worldwide popularity in the last decade as a basis for environmental footprints accounting, such as World Input–Output Database (WIOD), EXIOBASE, Eora and Global Trade and Analysis Project (GTAP) [34,45–47]. The four MRIO databases have been evaluated with regard to their comparability and consistency [48]. As exemplified by carbon footprint, the disagreement across these four MRIO databases for most major nations is <10% [49]. Of these, the WIOD has time-series water use data for households and sectors during 1995–2009; however, not all the BRI countries have been included. EXIOBASE database is a time series of MRIO tables ranging from 1995 to 2011 for 44 countries and rest five regions of the world, with water use data for limited time points. The GTAP database does not have water use data [50]. At present, the Eora database splits up the global economy in high national resolution and lower sectoral details, covering 189 countries and 26 sectors over a long time span (1990–2015). Note that these data are the latest available MRIO data for the world's 189 economies at the sectoral level and, because of this, a growing number of studies have adopted Eora to study the transfer of flows embodied in international trade [51-53]. Although the data on agriculture in Eora database is highly aggregated, it is still enough to trace virtual water trade throughout the BRI at the sectoral level as the aim of this paper is to provide a full picture of all the industrial sectors throughout the 65 BRI nations, rather than focusing on detailed single agricultural products (e.g., rice, soybean, wheat, corn, plant-based fiber). As such, Eora 26, a simplified version with a harmonized classification of 26 sectors, is chosen for analysis in this paper. To track the changes in results, we choose the year 2005, 2010 and

2015 for comparison. Meanwhile, we acknowledge that the major limitation of our results arises from the robustness and reliability of Eora database. Improvements in input–output data for nations and economic sectors, particularly for BRI countries, would still be needed.

(2) *Water use.* We extend the 189-country and 26-sector Eora MRIO to an environmentally-extended Eora MRIO for 2005, 2010, and 2015, along with a satellite account Q holding information on blue water use.

(3) *Total renewable water resources.* The data on renewable water resource in 2005, 2010 and 2015 come from the AQUASTAT database developed by the Food and Agricultural Organization (FAO). In addition, data on total freshwater withdrawal are derived from water-use environmental satellite account.

(4) *The distance between national capitals.* The straight-line distance between 189 national capitals is calculated by ArcGIS, and the longitude and latitude of each capital city come from Google Earth (https://www.earthol.com/).

(5) *Population and GDP.* The decomposition analysis of driving factors of changes to scarcity-weighted water footprint is conducted for two periods of time, i.e., 2005–2010 and 2010–2015. The population and GDP data for each country in 2005, 2010 and 2015 are derived from the World Bank database.

3. Results

3.1. Virtual water trade and water footprint

3.1.1. Virtual water trade between BRI nations

We track the virtual water trade among 65 BRI countries (Supplementary Table 1) from 2005 to 2015 (Fig. 1a–c). On the BRI scale, the total virtual water exported from the 65 BRI countries increases by 68% between 2005 and 2015. India, Pakistan, Turkmenistan,

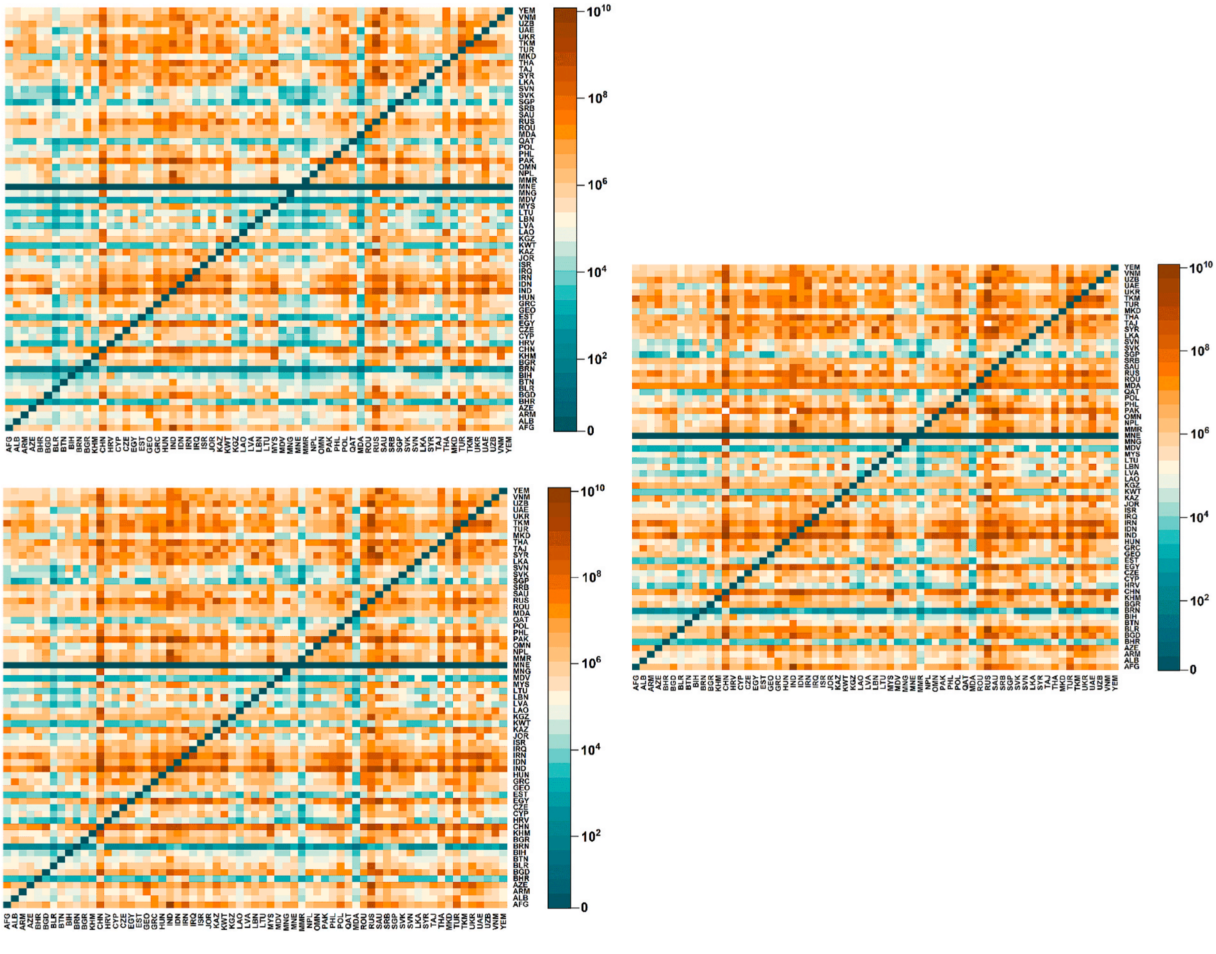
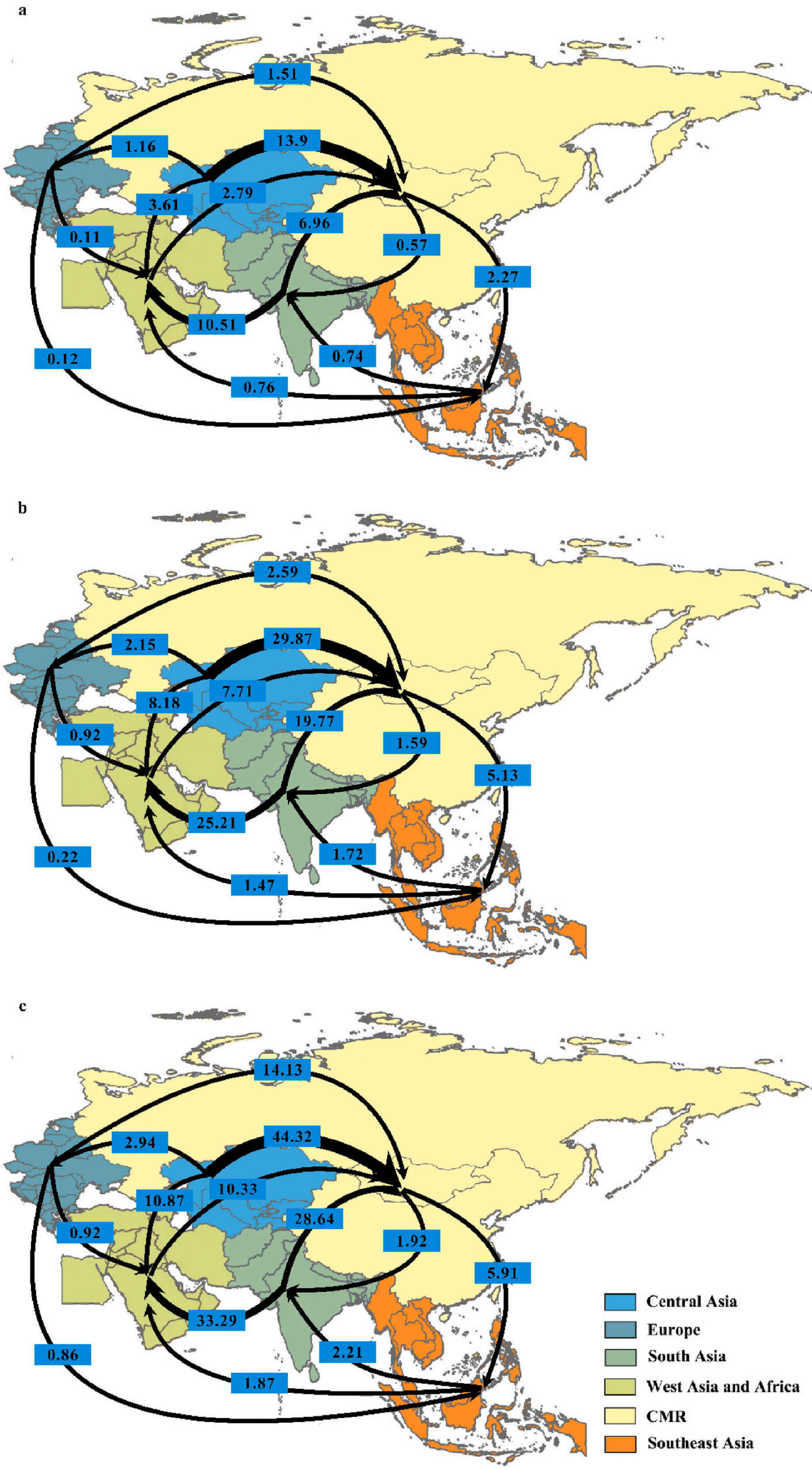


Fig. 1. Virtual water trade between BRI nations in 2005 (a), 2010 (b) and 2015 (c) (Unit: m^3/yr). Cells on the diagonal represent the virtual water to meet domestic demand, while the others represent virtual water trade between two countries. The horizontal axis shows the virtual water importers, and the vertical axis shows the exporters. For each cell, the color depth represents the value of virtual water trade. Country codes are presented in Supplementary Table 1. The same below.



(caption on next page)

Fig. 2. Virtual water trade between six BRI regions in 2005 (a), 2010 (b) and 2015 (c) (Unit: 10^9 m^3/yr). The line width is proportional to the volumes of virtual water flows. Regional classification of BRI is in Supplementary Table 1.

Tajikistan and China are always the top five virtual water exporters, accounting for approximately half of the total export volume of BRI. The top five virtual water importers are Russia, India, China, Saudi Arabia and Turkey, which collectively contribute to large import volume of BRI's virtual water, with a proportion of 60% rising to 65% between 2005 and 2015.

We map the virtual water trade between six regions of BRI in 2005, 2010 and 2015 (Fig. 2a–c). The interregional trade of virtual water within the BRI has been intensified over that period. Virtual water exporters are mainly in South Asia, Central Asia and Southeast Asia. The largest virtual water exporter is observed for South Asia, increasing from 23 trillion m^3/yr in 2005 to 82 trillion m^3/yr in 2015. Meanwhile, CMR, West Asia & Africa and Europe are three importers that receive virtual water from other regions of the BRI in 2005–2015. Of these, CMR's importing water is times larger than that of the other five regions, increasing from 29 trillion m^3/yr in 2005 to 112 trillion m^3/yr in 2015.

By comparing the export and import volumes of each country, we also rank the BRI countries according to their net virtual water trade (Fig. 3a–c). At the BRI level, two opposite trends can be observed for Pakistan and Russia. Pakistan is the largest net exporter of virtual water and continues to increase its export. Most of the major net exporters are in Central Asia, Southeast Asia and South Asia, in which Turkmenistan and Tajikistan are the other major exporters. A prominent change in the ranking of major net exporters can be attributed to India, who rises from the twelfth-largest net exporter in 2005 to the fourth since 2010. When it comes to net virtual water importers, Russia, China and Saudi Arabia are the largest net importers all the time.

3.1.2. Virtual water trade with non-BRI nations

Major economies outside the BRI, primarily including the EU member states, the USA, Canada, Japan and Australia, have been playing crucial roles in international trade (Fig. 4a–c). The virtual water exported from BRI to those countries has increased substantially in volume between 2005 and 2015. India, China, Pakistan, Egypt and Thailand are the top five virtual water exporters for those economies. Saudi Arabia, Qatar, Azerbaijan and Viet Nam are the only four BRI nations whose virtual water export to those five economics decreases in that decade, by 23%, 22%, 7% and 6%, respectively. The volume of virtual water exported from BRI entirely to non-BRI countries experiences an almost parallel trend, increasing from 146 trillion m^3/yr in 2005 to 249 trillion m^3/yr in 2015.

The volume of virtual water exported from EU, USA, Canada, Japan and Australia to BRI increases by 2–3 times in 11 years. In the years considered, the top five virtual water importers are China, Indonesia, Malaysia, Russia and Singapore alternating with India (Fig. 5a–c). All these BRI nations import virtual water primarily from EU, USA and Australia, Canada and Japan playing a minor role. For instance, China's imports of virtual water from EU, USA, Canada, Australia, and Japan in 2015 is 1–2 times larger than that in 2005. Overall, the volume of virtual water imported from non-BRI countries experiences a substantial increase throughout the study period, from 9 trillion m^3/yr in 2005 to 23 trillion m^3/yr in 2015.

By comparing the export and import volumes of virtual water, we see that the BRI overall is a net exporter for non-BRI nations, especially for EU, USA, Canada, Japan and Australia. The export volume to these five economies shows an increasing trend, from 107 trillion m^3/yr in 2005 to 176 trillion m^3/yr in 2015. Specifically, 45 out of the 65 BRI nations are net exporters for EU, USA, Canada, Japan and Australia, and the remaining ones are net importers. The top five net exporters are India, China, Pakistan, Egypt and Thailand between 2005 and 2015 (Fig. 6a–c). Of these, China is the second-largest net exporter of virtual water in 2005, and it is

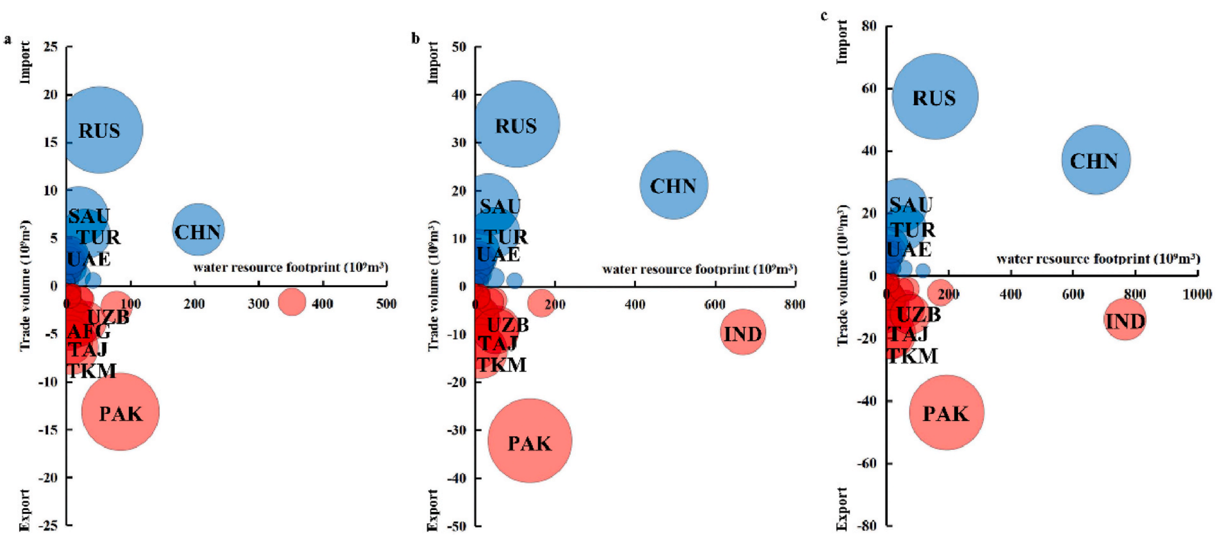


Fig. 3. Net exporters and importers of virtual water in BRI in 2005 (a), 2010 (b) and 2015 (c). Red circles represent the net importing countries, while blue circles represent exporters. The radius of the circles is proportional to the net volumes of importing/exporting virtual water.

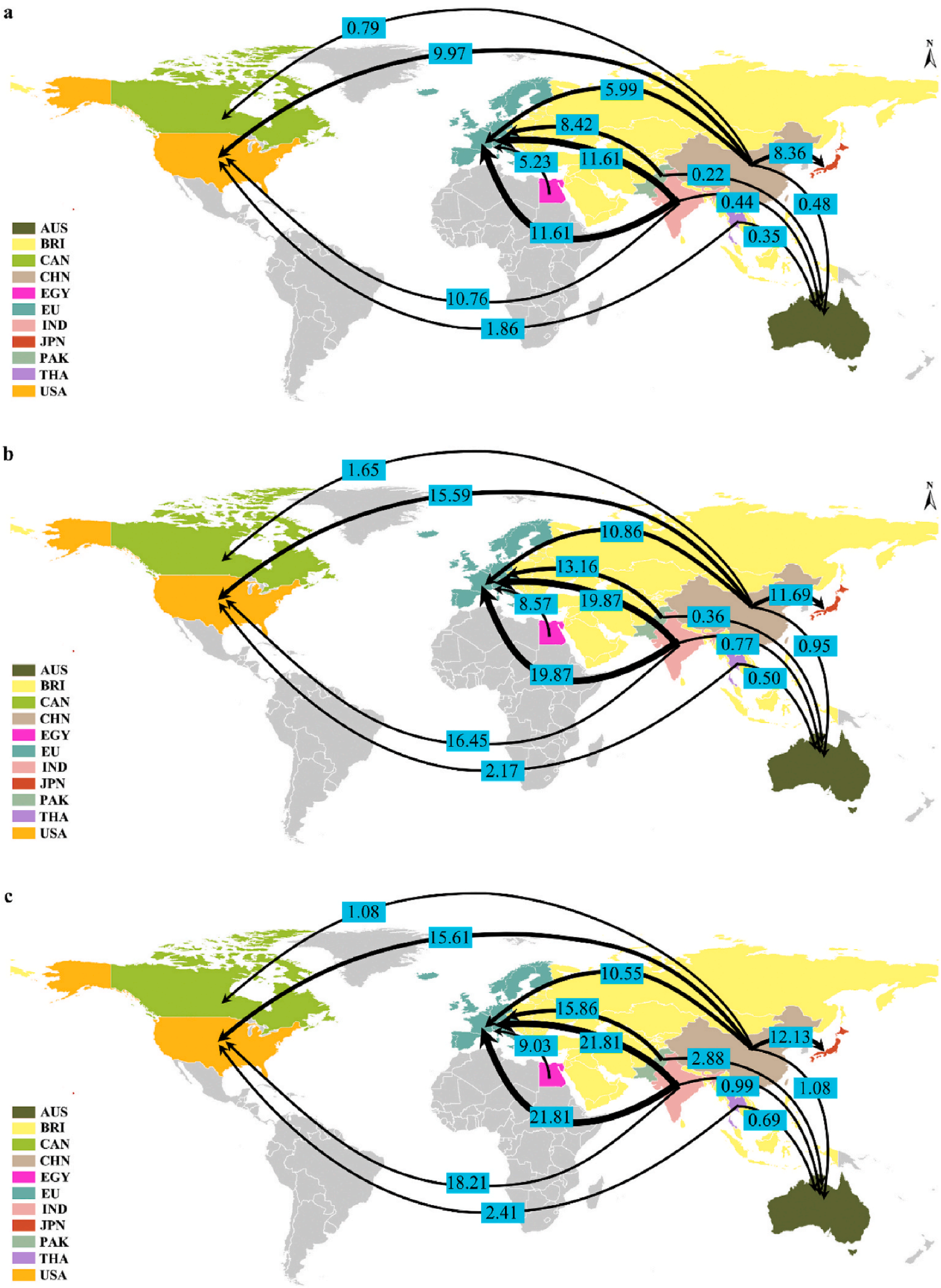


Fig. 4. Virtual water exported from top five BRI nations to EU, USA, Canada, Japan and Australia in 2005 (a), 2010 (b) and 2015 (c) (Unit: 10^9 m^3/yr). The line width is proportional to the volumes of virtual water flows.

replaced by Pakistan since 2010. Meanwhile, China surpasses Saudi Arabia to be the second-largest net importer since 2010 on the BRI scale.

3.1.3. Water footprint of BRI countries

We further measure the water footprint of the 65 BRI nations from a global perspective; that is, the water footprint of each BRI country is calculated by linking the trade of this country with 188 countries over the world, rather than with the other 64 BRI countries (Fig. 7a–c). The total water footprint of 65 countries in the BRI shows an ascending trend over time. The top five countries in terms of water footprint are India, China, Iran, Pakistan and Russia between 2005 and 2015. Specifically, the biggest water footprint is always

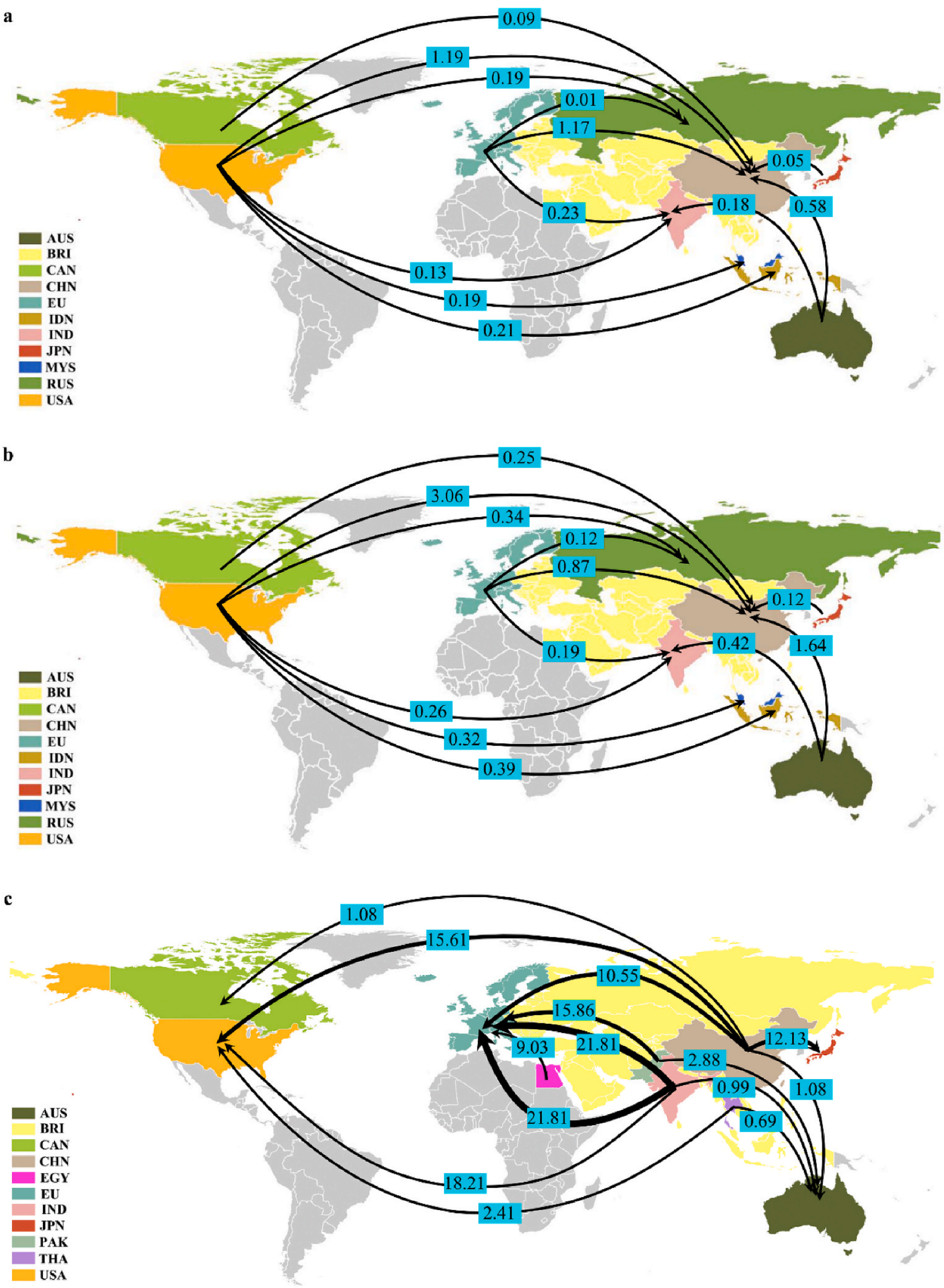


Fig. 5. Virtual water imported from top five BRI nations to EU, USA, Canada, Japan and Australia in 2005 (a), 2010 (b) and 2015 (c) (Unit: 10^9 m^3/yr). The line width is proportional to the volumes of virtual water flows.

observed for India, fluctuating from 353 trillion m^3/yr in 2005 to 771 trillion m^3/yr in 2015. It is followed by China and Iran, whose water footprint increases from 210 trillion m^3/yr in 2005 to 696 trillion m^3/yr in 2015, and from 78 trillion m^3/yr in 2005 to 176 trillion m^3/yr in 2015, respectively. During the study period, India, China and Iran collectively contribute to more than half of the BRI's water footprint.

3.2. Scarcity-weighted water footprint

3.2.1. Water scarcity index of BRI countries

Water scarcity can be categorized into different degrees according to the WSI (Supplementary Table 2). There are five countries

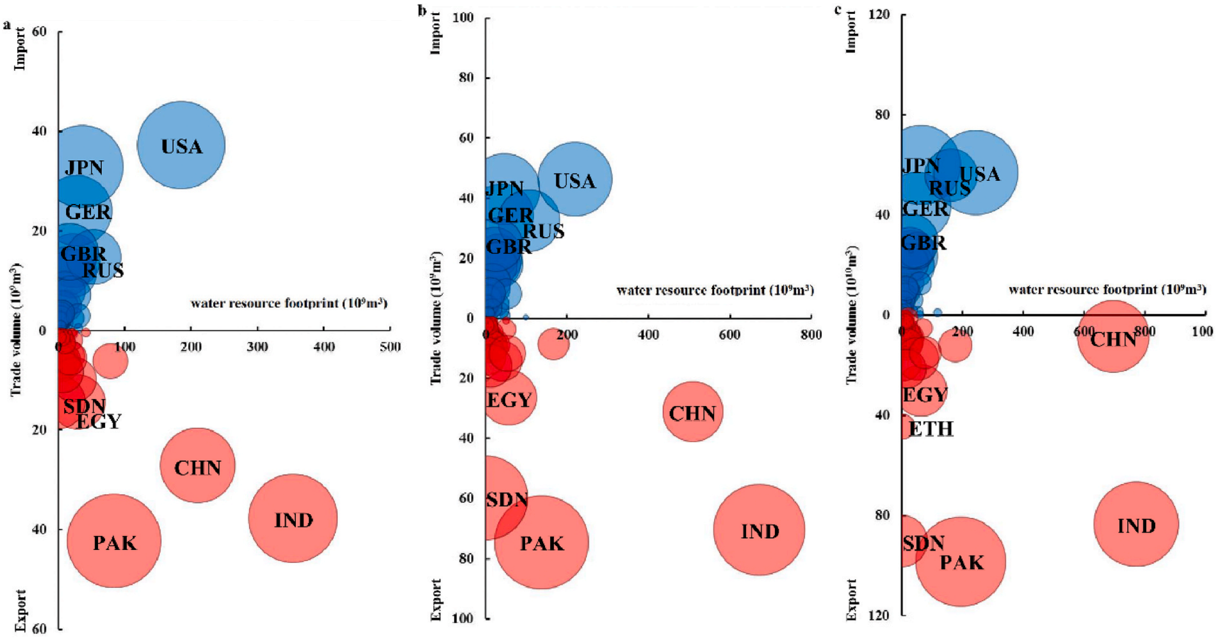


Fig. 6. Net exporters and importers of virtual water in the world in 2005 (a), 2010 (b) and 2015 (c). Red circles represent the net importing countries, while blue circles represent exporters. The larger the circle's size, the greater the net volumes of importing/exporting virtual water.

with no danger of water scarcity, including Bhutan, Brunei, Singapore, Laos and Latvia. Seven BRI countries are classified as suffering from moderate water scarcity, such as Bhutan, Brunei and Myanmar. The remaining 13 countries like Albania, Bangladesh and Belarus have severe water scarcity. Remarkably, 40 BRI countries suffer from extreme water scarcity, many of which are in West Asia, as renewable water resources in these countries are extremely limited. Qatar, in particular, has a tremendously high WSI over the entire period, and its WSI keeps growing with a rate of 35% in 2015. For some countries, such as Qatar, the United Arab Emirates and Kuwait, their WSI in 2015 is much higher than that of the previous years, indicating deterioration in water resources management. In this sense, the shortage of water resources poses a serious threat to the environmental sustainability of many BRI nations with potentially unexpected consequences for their socio-economic development.

3.2.2. Scarcity-weighted water footprint of BRI nations

Our estimates report that between 2005 and 2015, the total scarcity-weighted water footprint of the 65 BRI countries shows an increasing trend (Fig. 8a–c). This is basically due to the fact that an annual increase in scarcity-weighted water footprint is observed for the majority of BRI nations. The top five countries with scarcity-weighted water footprint remain unchanged, including India, China, Saudi Arabia, Iran and Pakistan. All the three countries account for more than half of the total scarcity-weighted water footprint in BRI between 2005 and 2015.

3.2.3. Comparison of volumetric and scarcity-weighted water footprints

We observe that several countries have changed their role between the BRI and global scales, either from a net exporter to a net importer, or the opposite (Fig. 9a and b). Net exporters and importers of virtual scarce water in BRI between 2005 and 2015 are presented in Fig. 10. Specifically, Albania, Bulgaria and China import virtual water from BRI nations while exporting it to the countries outside BRI between 2005 and 2015. From a global perspective, China's total net export volume in 2015 is about one third of that in 2005. The other three countries that change role from net importers on the BRI scale to net exporters on the global scale are Indonesia (in 2005 and 2010), Iraq (in 2005), and Viet Nam (in 2010 and 2015). Opposite situation can be observed for Bhutan in 2005 (Fig. 9a). In addition to the scaling effect on nations' role transitions, we also notice that nine BRI countries undergo a notable role transition after considering water scarcity. Armenia, Bangladesh, Cambodia, Iran and Laos shift roles from net importers of virtual water to net exporters of virtual scarce water from 2005 to 2015, and Bhutan and Viet Nam show the same role transitions in 2005. This finding reveals that many less-developed and water-scarce regions, such as Armenia and Iran, are large net virtual water exporters, highlighting the need to reduce export of water intensive goods, such as agricultural products and processed food. A reverse situation is observed for Bulgaria and the United Arab Emirates, who are large net virtual water importers consuming water resources in other water-scarce countries (Fig. 9b).

By looking deeper into the correlations between the volumetric water footprint and scarcity-weighted water footprint of all the BRI nations during 2005–2015, we observe that the results are by and large aligned (a scatterplot of water footprint versus scarcity-weighted water footprint of BRI nations is in Fig. 11a–c). Nevertheless, there is a substantial increase in the water footprint for most BRI countries after taking water scarcity into account, with the exception of a few nations, such as Albania, Bangladesh and

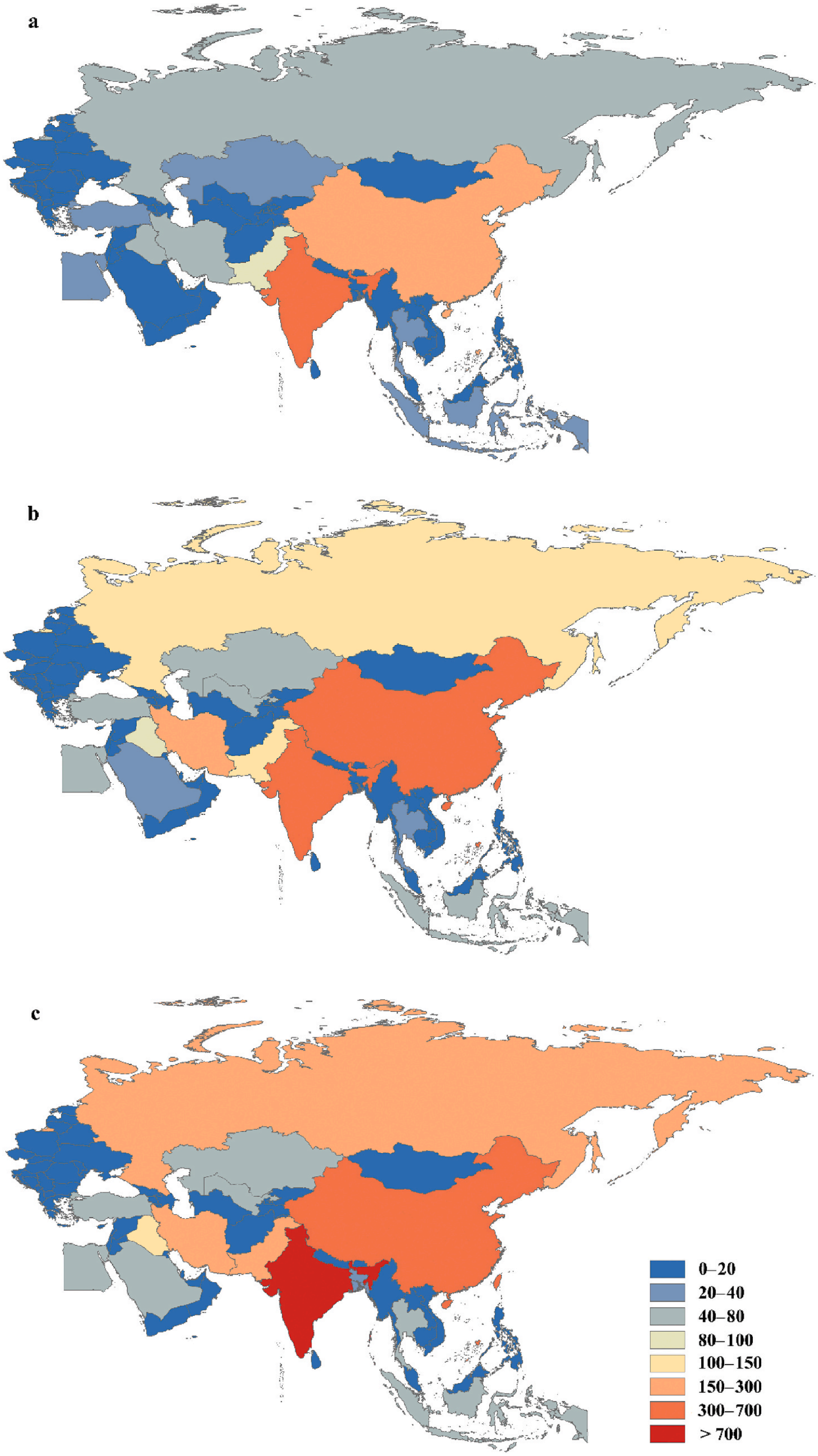


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Fig. 7. The water footprint of BRI nations in 2005 (a), 2010 (b) and 2015 (c) (Unit: 10^9 m^3/yr).

Cambodia. Central Asia, South Asia and West Asia & Africa are the main regions where the water footprint increases significantly by taking into account water scarcity, whereas the water footprint in Europe and Southeast Asia basically decreases after considering water scarcity. The changes to the water footprint in CMR are mixed. In agreement with the ranking of top nations in terms of scarcity-weighted water footprint, the most pronounced increase from volumetric to scarcity-weighted water footprints is found in India, followed by China and Pakistan. On the contrary, however, some nations (e.g., Albania, Bangladesh and Cambodia) experience a decline in their water footprint after considering the scarcity of water resources. A typical example of this is Russia, whose water footprint reduces by 24% on average, thus excluding from the top five countries in terms of scarcity-weighted water footprint.

In addition, when it comes to the sectoral level, the scarcity-weighted water footprint is found to be larger than the water footprint in 82% of all the industrial sectors of BRI nations, reflecting that overall the water footprint in BRI is amplified by taking into account water scarcity. Specifically, there is a substantial increase in the water footprint for 16 out of the 26 sectors when it comes to the scarcity-weighted water footprint. This is particularly true for the *Re-export & Re-import*, *Mining and Quarrying*, and *Metal Products* sectors, whose annual average growth in 2005–2015 is 66%, 44% and 42%, respectively. Moreover, approximately 70% of the water footprint and scarcity-weighted water footprint in BRI can be attributed to the *Agriculture* and *Food & Beverages* sectors (Fig. 12a–c).

3.3. Driving forces of scarcity-weighted water footprint

The drivers of the scarcity-weighted water footprint are decomposed into five factors, including water use efficiency, production structure, economic structure, per capita GDP and population. Our analysis demonstrates that, for most BRI countries, the improvement of water use efficiency over the two five-year periods is the major driving force for the reduction of scarcity-weighted water footprint, as opposed to the growing population and per capita GDP that are identified as prime drivers to the water footprint (Supplementary Tables 3 and 4). In addition, the improvement in production structure acts as a constraint on the scarcity-weighted water footprint for most BRI countries, and this limiting effect has been reinforced to some extent in 2010–2015. This implies that improving production structure can be of benefit to slowing the growth of nations' scarcity-weighted water footprint. Unlike the preceding four factors, the effect of the change to economic structure on the scarcity-weighted water footprint involves too many uncertainties. It, in most cases, appears to be a driver for rising scarcity-weighted water footprint. Overall, the change in the scarcity-weighted water footprint of each BRI nation is the result of a combination of those five factors. Since in many cases the driving forces are likely to outpace the limiting factors, the scarcity-weighted water footprint of most countries continues to grow throughout the study period.

4. Discussion

4.1. Major findings and policy implications

The distribution of virtual water trade in BRI varies across scales and over time. Overall, the BRI acts as a net exporter of virtual water, particularly for EU, USA, Canada, Japan and Australia, and the export volume has been growing. Virtual water exports from non-BRI to BRI countries increase markedly during the same time period. About one-half and one-third of the BRI countries explicitly show an increasing trend in net virtual water trade at the regional and global levels, respectively. This suggests that international trade has become increasingly active after the proposal of the BRI, and the role of BRI as an important exporter of water-intensive products and services in the global market has been reinforced. There are seven BRI countries that undergo a role transition across the BRI and global scales. For example, China, Albania and Bulgaria act as net importers of virtual water at the BRI scale, and become net exporters at the global scale. On the contrary, Bhutan shifts from a net importer on the BRI scale to a net exporter on the global scale. In addition to the scaling effect, we also notice that nine BRI countries experience a notable role transition between with and without considering water scarcity. Countries like Bangladesh, Cambodia and Iran shift their roles from net importers of virtual water to net exporters of virtual scarce water. A reverse transition is observed for Bulgaria and the United Arab Emirates.

For most BRI countries, consideration of water scarcity increases their water footprint. The largest rise in the rankings from water footprint to scarcity-weighted water footprint is witnessed in India, followed by China and Saudi Arabia. On the contrary, Russia is a country with the largest water footprint reduction, thus excluding from the top five countries in terms of scarcity-weighted water footprint. On the sectoral level, a rise from water footprint to scarcity-weighted water footprint is observed in 82% of the industrial sectors in all the BRI countries. As the methodological comparison of the volumetric and scarcity-weighted water footprints has been discussed in a number of studies [6,54,55], this paper is not intended to further this debate. Nevertheless, our research suggests that those studies provide footprint analysis with two complementary paradigms that have different orientation and policy relevance. In contrast to the volumetric water footprint which measures the total volume of water needed to produce goods and services without taking localized scarcity into account, the scarcity-weighted water footprint is appropriate for cross-regional comparison, because consuming the same amount of water in water-rich and water-scarce regions could differ in the impacts on local water scarcity by orders of magnitude [32]. The distinct differences between water footprint and scarcity-weighted water footprint highlight the need of incorporating water scarcity into the MRIO analysis, particularly if the purpose is to identify the stressors on water resources [32].

The improvement of water use efficiency is a major contributor to the reduction of scarcity-weighted water footprint for most BRI nations, which competes with the growing population and per capita GDP that substantially drive the scarcity-weighted water

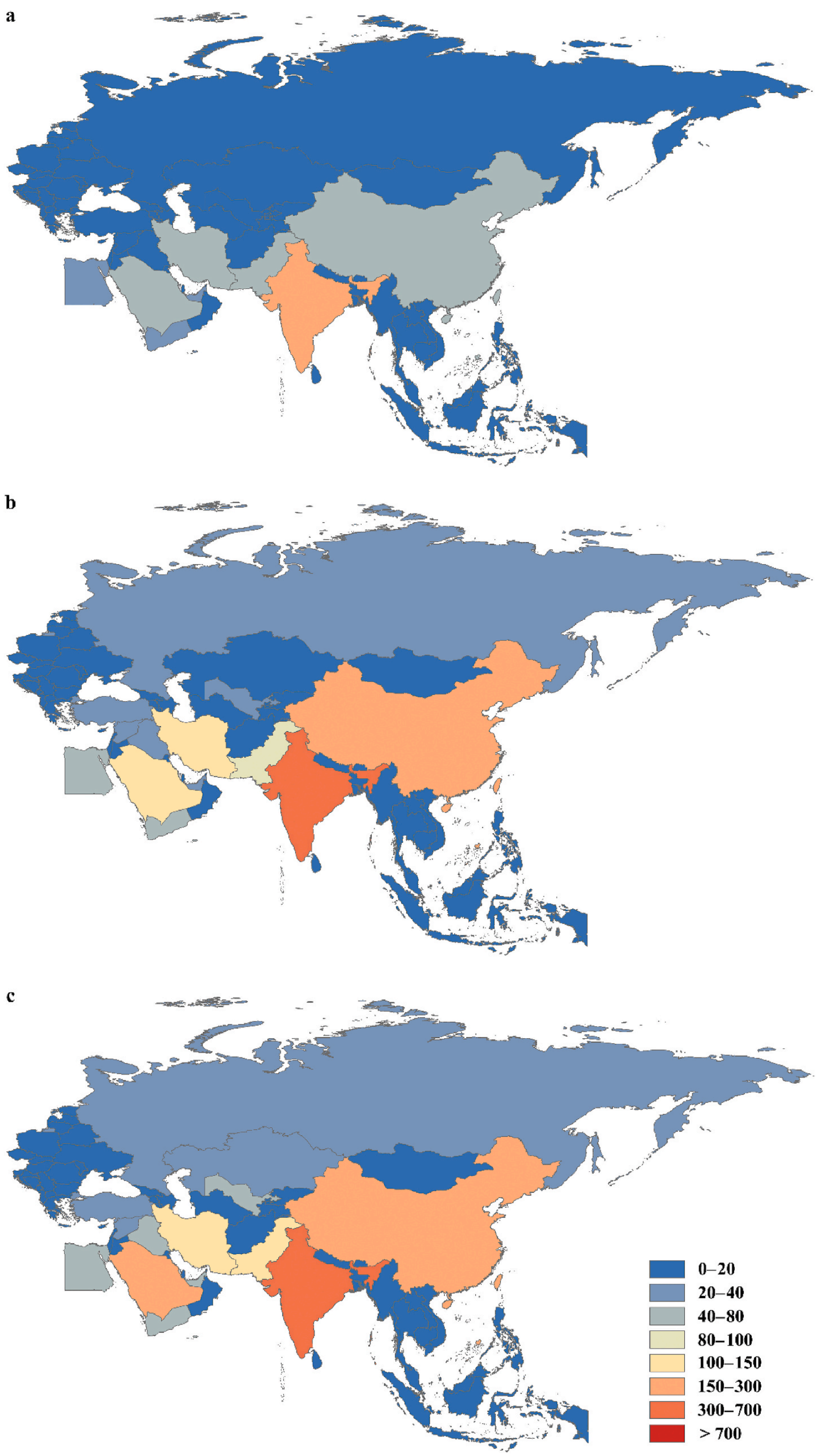

Fig. 8. The scarcity-weighted water footprint of BRI nations in 2005 (a), 2010 (b) and 2015 (c) (Unit: 10^9 m^3/yr).

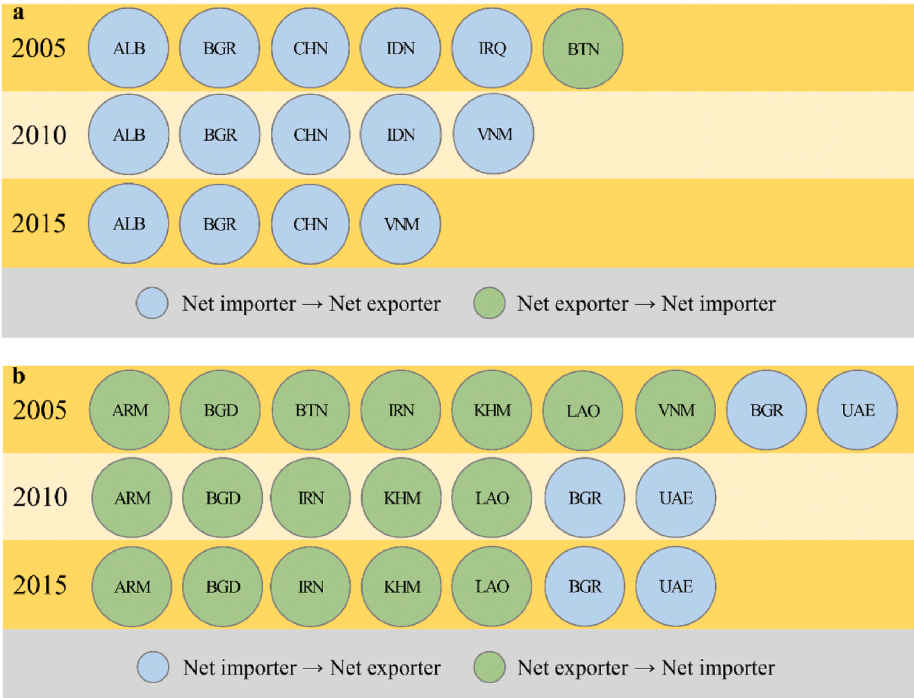

Fig. 9. Role transition of BRI nations between the BRI and global scales (a), and between the net virtual water and net virtual scarce water (b) in 2005, 2010 and 2015.

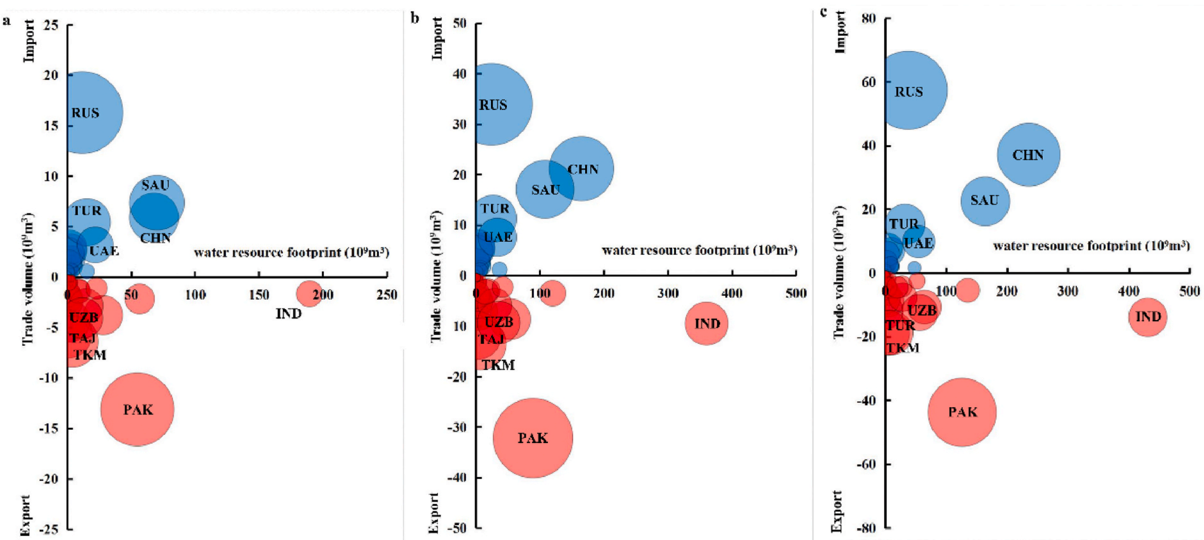

Fig. 10. Net exporters and importers of virtual scarce water in BRI in 2005 (a), 2010 (b) and 2015 (c).

footprint. For those countries who are major exporters with high scarcity-weighted water footprint, it is necessary to take more effective policy actions that encourage reducing their exports of water-intensive products and promoting water-saving technologies. Conversely, for countries acting as importers with high scarcity-weighted water footprint, priorities should be given to changing lifestyles and decelerating consumption for water-intensive products. For instance, the launch of water resources tax has been proved useful in raising the price of water-intensive products and limiting the consumption of these products in China, USA, France, etc. [56-58]. Moreover, countries with low scarcity-weighted water footprint still should speed up technical innovation and enhance international cooperation to avoid potential risks caused by exporting/importing virtual scarce water [59].

Improving production structure represents a critical step for the BRI countries to slow the growth of scarcity-weighted water

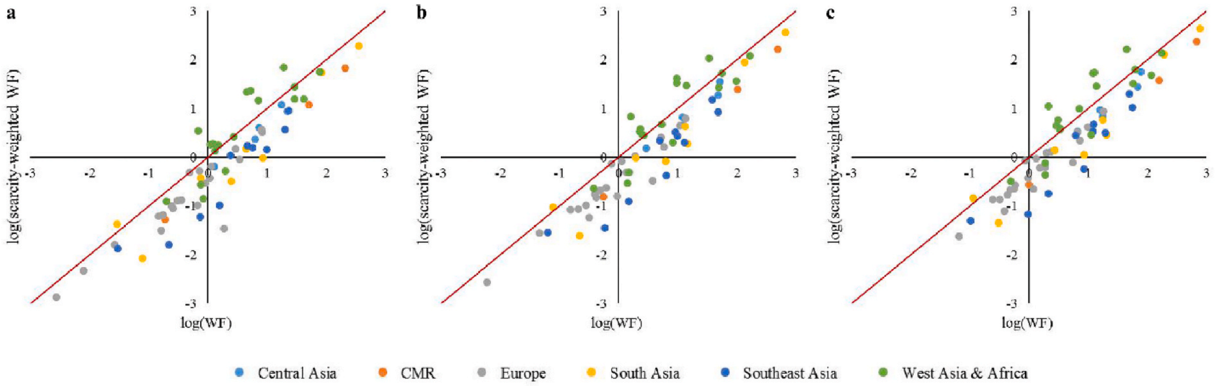

Fig. 11. Logarithmic scatterplot of water footprint versus scarcity-weighted water footprint of BRI nations in 2005 (a), 2010 (b) and 2015 (c).

footprint. Unlike these four factors, the effect of the change to economic structure on the scarcity-weighted water footprint involves too many uncertainties; it may be a driver for increase in scarcity-weighted water footprint normally. The increasing water footprint distance indicates the stronger dependence of economic growth on water resources than ever, providing an opportunity for China and other BRI countries to jointly cope with water scarcity through international cooperation, trade restructuring and technical improvement.

As for China—the first advocate of BRI, it benefits from importing virtual water from other BRI countries, while serving as a net exporter of scarce water for those major economies outside the BRI. Fortunately, China has attached high importance to the green BRI construction in its Ecological and Environmental Cooperation Plan [60], calling for a green transformation of national and regional economies by adopting new clean technologies and higher environmental standards [4], increasing the use of green financing instruments, and expanding international cooperation on water resources management [2]. Although China has taken some policy actions on water consumption, accelerating water scarcity associated with international trade remains a major challenge for the goal of making the BRI environmentally friendly.

As virtual water trade has the potential to improve the uneven spatial allocation of water resources among regions [13,44], the need to boost virtual water flows from water-rich countries to water-scarce countries calls for an important input from experts on water resources management in the decision-making process. In the case of China, for instance, the government needs to promote international alliances and update its trade policies to decline importing water-intensive products from those BRI countries who are severely suffering from water shortage and encourage exports of technology-intensive products [61]. Eco-labelling policies can be implemented for water use of industrial sectors or products to increase the transparency on water use efficiency [62]. Moreover, economic instruments for environmental regulation such as water resources tax and water rights trading can facilitate water saving and enhance water productivity [63,64]. From a broader point of view, in struggling to relieve water scarcity, more attention should be paid to creating policy synergies between green BRI, 2030 Agenda for Sustainable Development as well as China's eco-civilization strategy [65,66].

4.2. *Uncertainty analysis and future improvements*

While the Eora is the best available MRIO database for studies on BRI countries, we acknowledge that the major limitation of our results arises from the robustness and reliability of Eora database. The assessment of virtual water flows based on Eora 26 is subject to sectoral aggregation errors. One example is *Agriculture*—an aggregated sector made up of crop production, fishing, forestry, etc. Moreover, due to the lack of access to official statistics, the Eora database for some small economies in BRI is far from satisfactory [45]. In other global MRIO databases such as WIOD, EXIOBASE and GTAP, these data-scarce countries are usually presented in an aggregated way (as part of the "Rest of world") [67]. To examine the uncertainty in Eora's sectoral aggregation and national disaggregation, we conduct a Monte Carlo simulation of water footprint and scarcity-weighted water footprint of BRI countries by using the above four MRIO databases. First, to make the national classification consistent across databases, we only consider 16 BRI countries covered by all the four databases, and the remaining countries of each database are aggregated as the "Rest of world". Second, we make the sectoral classification consistent by reclassifying the sectors within each MRIO database into 26. Then we account for both the water footprint and scarcity-weighted water footprint of the BRI nations by means of each MRIO model. Finally, by conducting a Monte Carlo simulation (details of the simulation are presented in Fig. 13a and b), we show that overall the results for all the BRI nations disagree by <13% among different databases, showing that despite some divergence, our estimates based on Eora are overall consistent with those based on other MRIO models. Anyhow, we acknowledge that input–output models are inherently fraught with huge uncertainties and hence the findings of this study should be interpreted with caution.

Admittedly, there remain some limitations in our paper that require to be addressed in future analysis. First, as the COVID-19 pandemic has had both positive and negative impacts on the BRI, future research is needed to explore the consequences of the COVID-19 pandemic for natural resources and climate change from a social-ecological system perspective [68-70]. Besides, cross-sectional regression and inter- and intra-BRI econometric analysis should be conducted to make the analysis more

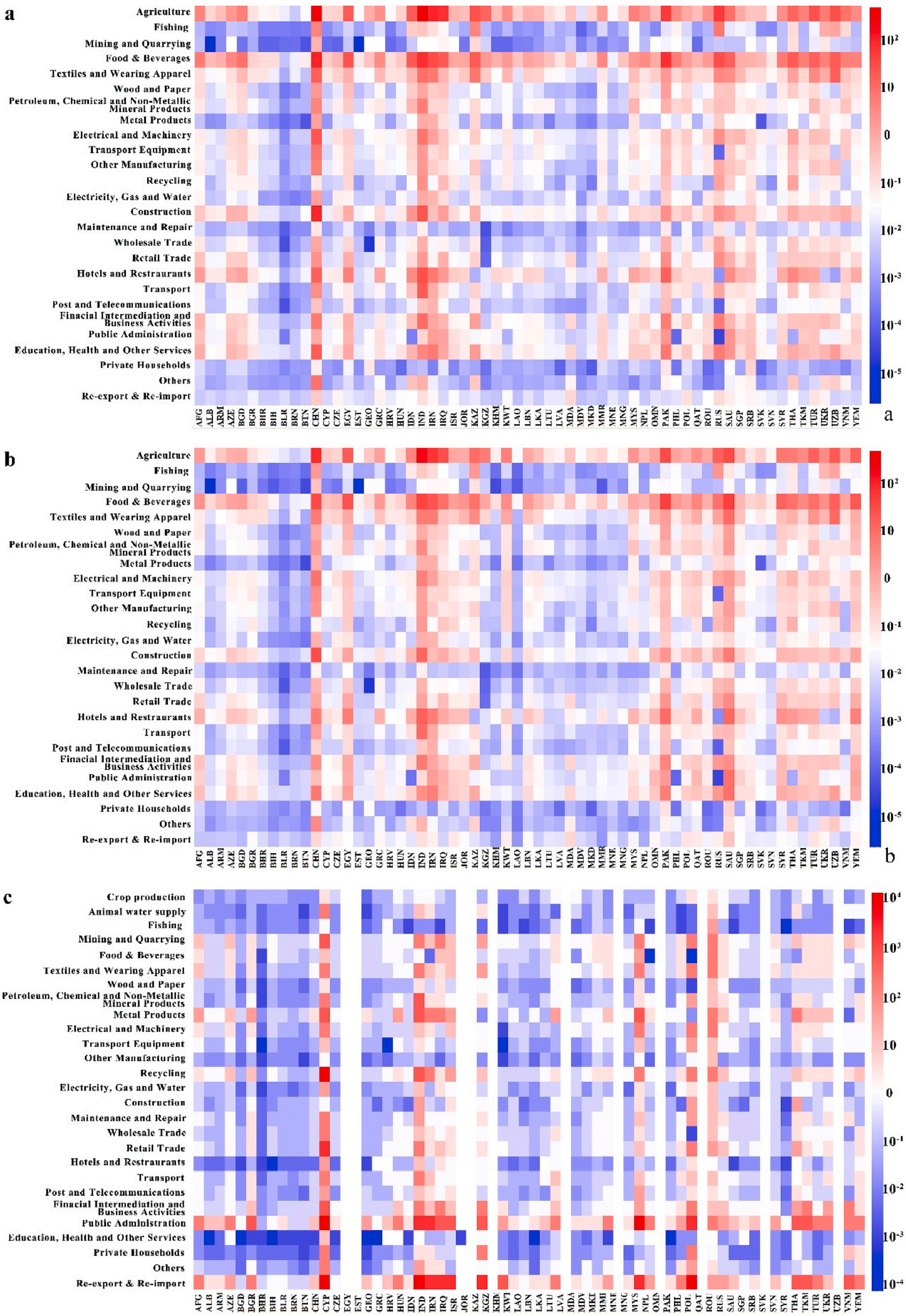

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Fig. 12. The contributions of final demand categories to the water footprint (a), scarcity-weighted water footprint (b) and difference between them (c) by sector in 2015.

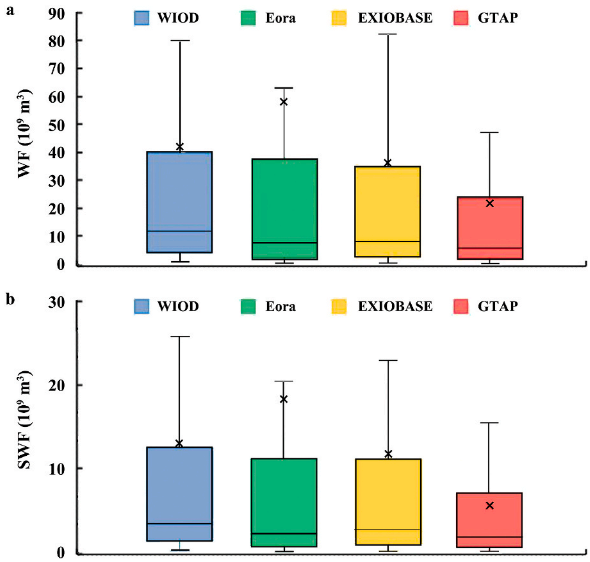

Fig. 13. Monte Carlo analysis of four global MRIO models. The box-plot analysis shows the ranges, the 25 and 75 percentiles, and the medians of the water footprint and scarcity-weighted water footprint of 65 BRI countries based on Eora, EXIOBASE, GTAP and WIOD databases by aggregating sectors and countries. The cross symbol represents the standard deviation. WF: water footprint (a); SWF: scarcity-weighted water footprint (b).

problem-driven and policy-oriented [71]. Additional spatially explicit analysis is also necessary to support place-specific strategies by considering local realities.

Author contribution statement

Kai Fang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Jianjian He: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Qingyan Liu: Performed the experiments; Analyzed and interpreted the data.
Siqi Wang: Analyzed and interpreted the data; Wrote the paper.
Yong Geng: Conceived and designed the experiments; Wrote the paper.
Reinout Heijungs: Analyzed and interpreted the data; Wrote the paper.
Yueyue Du: Analyzed and interpreted the data.
Wenze Yue: Contributed reagents, materials, analysis tools or data.
Anqi Xu: Analyzed and interpreted the data; Wrote the paper.
Chuanglin Fang: Conceived and designed the experiments.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix B. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2023.e12957.

References

[1] Y. Huang, Understanding China's Belt & Road initiative: motivation, framework and assessment, China Econ. Rev. 40 (2016) 314–321.
[2] F. Ascensão, L. Fahrig, A.P. Clevenger, R.T. Corlett, J.A. Jaeger, W.F. Laurance, H.M. Pereira, Environmental challenges for the belt and road initiative, Nat. Sustain. 1 (5) (2018) 206–209.
[3] Q. Lu, K. Fang, R. Heijungs, K. Feng, J. Li, Q. Wen, Y. Li, X. Huang, Imbalance and drivers of carbon emissions embodied in trade along the Belt and Road Initiative, Appl. Energy 280 (2020), 115934.
[4] N. Zhang, Z. Liu, X.M. Zheng, J.J. Xue, Carbon footprint of China's belt and road, Science 357 (6356) (2017) 1107.
[5] K. Fang, S. Wang, J. He, J. Song, C. Fang, X. Jia, Mapping the environmental footprints of nations partnering the Belt and Road Initiative, Resour. Conserv. Recycl. 164 (2021), 105068.
[6] Y. Zhang, K. Huang, B.G. Ridoutt, Y. Yu, Comparing volumetric and impact-oriented water footprint indicators: case study of agricultural production in Lake Dianchi Basin, China, Ecol. Indicat. 87 (2018) 14–21.
[7] World Bank, Renewable internal freshwater resources per capita (cubic meters). http://data.worldbank.org/indicator/ER.H2O.INTR.PC, 2016. (Accessed 4 November 2016). Accessed date:.
[8] X. Chen, Q. Liu, K. Fang, J. He, Y. Chen, T. Wang, C. Fang, Y. Shen, Tracking national sustainability of critical natural capital and the socioeconomic drivers in the context of the Belt and Road Initiative, Ecol. Indicat. 114 (2020), 106315.
[9] A.Y. Hoekstra, Water scarcity challenges to business, Nat. Clim. Change 4 (5) (2014) 318.
[10] L. Zhuo, M.M. Mekonnen, A.Y. Hoekstra, The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: a study for China (1978–2008), Water Res. 94 (2016) 73–85.
[11] S. Baniya, N. Rocha, M. Ruta, Trade Effects of the New Silk Road: A Gravity Analysis, The World Bank, 2019.
[12] A.Y. Hoekstra, A.K. Chapagain, Water footprints of nations: water use by people as a function of their consumption pattern, Water Resour. Manag. 21 (2007) 35–48.
[13] A.Y. Hoekstra, M.M. Mekonnen, A.K. Chapagain, R.E. Mathews, B.D. Richter, Global monthly water scarcity: blue water footprints versus blue water availability, PLoS One 7 (2) (2012), e32688.
[14] K. Feng, A. Chapagain, S. Suh, S. Pfister, K. Hubacek, Comparison of bottom-up and top-down approaches to calculating the water footprints of nations, Econ. Syst. Res. 23 (4) (2011) 371–385.
[15] K. Fang, R. Heijungs, Rethinking the relationship between footprints and LCA, Environ. Sci. Technol. 49 (1) (2015) 10–11.
[16] Y. Long, Y. Yoshida, Q. Liu, H. Zhang, S. Wang, K. Fang, Comparison of city-level carbon footprint evaluation by applying single- and multi-regional input-output tables, J. Environ. Manag. 260 (2020), 110108.
[17] B. Chen, M.Y. Han, K. Peng, S.L. Zhou, L. Shao, X.F. Wu, W.D. Wei, S.Y. Liu, Z. Li, J.S. Li, G.Q. Chen, Global land-water nexus: agricultural land and freshwater use embodied in worldwide supply chains, Sci. Total Environ. 613 (2018) 931–943.
[18] S. Qu, S. Liang, M. Konar, Z.Q. Zhu, A.S. Chiu, X.P. Jia, M. Xu, Virtual water scarcity risk to the global trade system, Environ. Sci. Technol. 52 (2) (2017) 673–683.
[19] X. Tian, J. Sarkis, Y. Geng, Y.Y. Qian, C.X. Gao, R. Bleischwitz, Y. Xu, Evolution of China's water footprint and virtual water trade: a global trade assessment, Environ. Int. 121 (2018) 178–188.
[20] X.C. Cao, M.Y. Wu, X.P. Guo, Y.L. Zheng, Y. Gong, N. Wu, W.G. Wu, Assessing water scarcity in agricultural production system based on the generalized water resources and water footprint framework, Sci. Total Environ. 609 (2017) 587–597.
[21] T. Distefano, S. Kelly, Are we in deep water? Water scarcity and its limits to economic growth, Ecol. Econ. 142 (2017) 130–147.
[22] M. Berger, M. Finkbeiner, Methodological challenges in volumetric and impact−oriented water footprints, J. Ind. Ecol. 17 (1) (2013) 79–89.
[23] K. Fang, R. Heijungs, Investigating the inventory and characterization aspects of footprinting methods: lessons for the classification and integration of footprints, J. Clean. Prod. 108 (2015) 1028–1036.
[24] Y.B. Wang, P.T. Wu, B.A. Engel, S.K. Sun, Comparison of volumetric and stress-weighted water footprint of grain products in China, Ecol. Indicat. 48 (2015) 324–333.
[25] C. Zhang, L.D. Anadon, A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China, Ecol. Econ. 100 (2014) 159–172.
[26] Y. Zhang, J.H. Zhang, Q. Tian, Z.H. Liu, H.L. Zhang, Virtual water trade of agricultural products: a new perspective to explore the Belt and Road, Sci. Total Environ. 622 (2018) 988–996.
[27] Y. Qian, X. Tian, Y. Geng, S. Zhong, X. Cui, X. Zhang, D.A. Moss, R. Bleischwitz, Driving factors of agricultural virtual water trade between China and the Belt and Road countries, Environ. Sci. Technol. 53 (10) (2019) 5877–5886.
[28] C.F. Zhao, B. Chen, T. Hayat, A. Alsaedi, B. Ahmad, Driving force analysis of water footprint change based on extended STIRPAT model: evidence from the Chinese agricultural sector, Ecol. Indicat. 47 (2014) 43–49.
[29] J.F. Kang, J.Y. Lin, X.F. Zhao, S.N. Zhao, L.M. Kou, Decomposition of the urban water footprint of food consumption: a case study of Xiamen City, Sustainability 9 (1) (2017) 135.
[30] B.M. Cai, K. Hubacek, K.S. Feng, W. Zhang, F. Wang, Y. Liu, Tension of agricultural land and water use in China's trade: tele-connections, hidden drivers and potential solutions, Environ. Sci. Technol. 54 (9) (2020) 5365–5375.
[31] J.L. Fan, J.D. Wang, X. Zhang, L.S. Kong, Q.Y. Song, Exploring the changes and driving forces of water footprints in China from 2002 to 2012: a perspective of final demand, Sci. Total Environ. 650 (2019) 1101–1111.
[32] K.S. Feng, K. Hubacek, S. Pfister, Y. Yu, L.X. Sun, Virtual scarce water in China, Environ. Sci. Technol. 48 (14) (2014) 7704–7713.
[33] D.J. White, K. Feng, L. Sun, K. Hubacek, A hydro-economic MRIO analysis of the Haihe River Basin's water footprint and water stress, Ecol. Model. 318 (2015) 157–167.
[34] M.P. Timmer, E. Dietzenbacher, B. Los, R. Stehrer, G.J. De Vries, An illustrated user guide to the world input–output database: the case of global automotive production, Rev. Int. Econ. 23 (3) (2015) 575–605.
[35] B. Liu, D.D. Wang, Y.Q. Xu, C.L. Liu, M. Luther, A multi-regional input–output analysis of energy embodied in international trade of construction goods and services, J. Clean. Prod. 201 (2018) 439–451.

[36] B.G. Ridoutt, S. Pfister, A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity, Global Environ. Change 20 (1) (2010) 113–120.
[37] M. Lenzen, D. Moran, A. Bhaduri, K. Kanemoto, M. Bekchanov, A. Geschke, B. Foran, International trade of scarce water, Ecol. Econ. 94 (2013) 78–85.
[38] S. Pfister, A. Koehler, S. Hellweg, Assessing the environmental impacts of freshwater consumption in LCA, Environ. Sci. Technol. 43 (11) (2009) 4098–4104.
[39] D. Vanham, A.Y. Hoekstra, Y. Wada, F. Bouraoui, A. de Roo, M.M. Mekonnen, W.J. van de Bund, O. Batelaan, P. Pavelic, W.G.M. Bastiaanssen, M. Kummu, Physical water scarcity metrics for monitoring progress towards SDG target 6.4: an evaluation of indicator 6.4.2 "Level of water stress", Sci. Total Environ. 613 (2018) 218–232.
[40] B.D. Richter, M.M. Davis, C. Apse, C. Konrad, A presumptive standard for environmental flow protection, River Res. Appl. 28 (8) (2012) 1312–1321.
[41] D. Vanham, S. Comero, B.M. Gawlik, G. Bidoglio, The water footprint of different diets within European sub-national geographical entities, Nat. Sustain. 1 (9) (2018) 518.
[42] C.J. Vörösmarty, P. Green, J. Salisbury, R.B. Lammers, Global water resources: vulnerability from climate change and population growth, Science 289 (5477) (2000) 284–288.
[43] X. Zhao, J.G. Liu, Q.Y. Liu, M.R. Tillotson, D.B. Guan, K. Hubacek, Physical and virtual water transfers for regional water stress alleviation in China, Proc. Natl. Acad. Sci. USA 112 (4) (2015) 1031–1035.
[44] B.M. Cai, W. Zhang, K. Hubacek, K.S. Feng, Z.L. Li, Y. Liu, Y. Liu, Drivers of virtual water flows on regional water scarcity in China, J. Clean. Prod. 207 (2019) 1112–1122.
[45] A. Tukker, E. Dietzenbacher, Global multiregional input–output frameworks: an introduction and outlook, Econ. Syst. Res. 25 (1) (2013) 1–19.
[46] M. Lenzen, D. Moran, K. Kanemoto, A. Geschke, Building EORA: a global multi-region input–output database at high country and sector resolution, Econ. Syst. Res. 25 (1) (2013) 20–49.
[47] R.M. Andrew, G.P. Peters, A multi-region input–output table based on the global trade analysis project database (GTAP-MRIO), Econ. Syst. Res. 25 (1) (2013) 99–121.
[48] P. Tarne, A. Lehmann, M. Finkbeiner, A comparison of Multi-Regional Input–Output databases regarding transaction structure and supply chain analysis, J. Clean. Prod. 196 (2018) 1486–1500.
[49] D. Moran, R. Wood, Convergence between the Eora, WIOD, EXIOBASE, and Open EU's consumption-based carbon accounts, Econ. Syst. Res. 26 (3) (2014) 245–261.
[50] M. Lenzen, R. Wood, T. Wiedmann, Uncertainty analysis for multi-regional input–output models-A case study of the UK's carbon footprint, Econ. Syst. Res. 22 (1) (2010) 43–63.
[51] A. Oita, A. Malik, K. Kanemoto, A. Geschke, S. Nishijima, M. Lenzen, Substantial nitrogen pollution embedded in international trade, Nat. Geosci. 9 (2016) 111–115.
[52] B.G. Ridoutt, M. Hadjikakou, M. Nolan, B.A. Bryan, From water use to water scarcity footprinting in environmentally extended input–output analysis, Environ. Sci. Technol. 52 (2018) 6761–6770.
[53] M.V. Rocco, R.J.F. Ferrer, E. Colombo, Understanding the energy metabolism of world economies through the joint use of production-and consumption-based energy accountings, Appl. Energy 211 (2018) 590–603.
[54] M. Berger, M. Finkbeiner, Methodological challenges in volumetric and impact−oriented water footprints, J. Ind. Ecol. 17 (1) (2013) 79–89.
[55] K. Fang, S.Y. Song, R. Heijungs, S. de Groot, L. Dong, J.N. Song, E.I. Wiloso, The footprint's fingerprint: on the classification of the footprint family, Curr. Opin. Environ. Sustain. 23 (2016) 54–62.
[56] D. Han, M. Currell, G.L. Cao, Deep challenges for China's war on water pollution, Environ. Pollut. 218 (2016) 1222–1233.
[57] V. Mattheiß, P. Strosser, J. Rodríguez, Notes on financing water resources management, in: Background Report for the OECD Expert Meeting on Water Economics and Financing, 2010, pp. 15–17.
[58] V. Morckel, Why the Flint, Michigan, USA water crisis is an urban planning failure, Cities 62 (2017) 23–27.
[59] A. Pastor, A. Palazzo, P. Havlik, H. Biemans, Y. Wada, M. Obersteiner, P. Kabat, F. Ludwig, The global nexus of food–trade–water sustaining environmental flows by 2050, Nat. Sustain. 2 (6) (2019) 499–507.
[60] The ministry of ecology and environment of the people's Republic of China. The belt and road ecological and environmental cooperation plan. http://eng.yidaiyilu.gov.cn/zchj/qwfb/13392.htm, 2017.
[61] Y. Geng, J. Sarkis, R. Bleischwitz, How to globalize the circular economy, Nature 565 (2019) 155.
[62] T. Dieu-Hang, R.Q. Grafton, R. Martínez-Espiñeira, M. Garcia-Valiñas, Household adoption of energy and water-efficient appliances: an analysis of attitudes, labelling and complementary green behaviours in selected OECD countries, J. Environ. Manag. 197 (2017) 140–150.
[63] P. Gonzales, N.K. Ajami, Goal-based water trading expands and diversifies supplies for enhanced resilience, Nat. Sustain. 2 (2) (2019) 138–147.
[64] H. Li, Z.X. Xiong, Y.T. Xie, Resource tax reform and economic structure transition of resource-based economies, Resour. Conserv. Recycl. 136 (2018) 389–398.
[65] K. Fang, M. Mao, C. Tian, J. Chen, W. Wang, R. Tan, Exploring the impact of emissions trading schemes on income inequality between urban and rural areas, J. Environ. Manag. 329 (2023), 117067.
[66] Z.C. Xu, S.N. Chau, X.Z. Chen, J. Zhang, Y.J. Li, T. Dietz, J.J. Wang, J.A. Winkler, F. Fan, B.R. Huang, S.X. Li, S.H. Wu, A. Herzberger, Y. Tang, D.Q. Hong, Y. K. Li, J.G. Liu, Assessing progress towards sustainable development over space and time, Nature 577 (2020) 74–78.
[67] H.R. Zhang, K.B. He, X.J. Wang, E.G. Hertwich, Tracing the uncertain Chinese mercury footprint within the global supply chain using a stochastic, nested input–output model, Environ. Sci. Technol. 53 (12) (2019) 6814–6823.
[68] A. Facciolà, P. Laganà, G. Caruso, The COVID-19 pandemic and its implications on the environment, Environ. Res. 201 (2021), 111648.
[69] S. Muhammad, X. Long, M. Salman, COVID-19 pandemic and environmental pollution: a blessing in disguise? Sci. Total Environ. 728 (2020), 138820.
[70] A.K. Verma, S. Prakash, Impact of Covid-19 on environment and society, J. Glob. Biosci. 9 (5) (2020) 7352–7363.
[71] K. Fang, T. Wang, J. He, T. Wang, X. Xie, Y. Tang, Y. Shen, A. Xu, The distribution and drivers of $PM_{2.5}$ in a rapidly urbanizing region: the Belt and Road Initiative in focus, Sci. Total Environ. 716 (2020), 137010.