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Virtual Water Flows in Internal and External Agricultural Product Trade in Central Asia

Xinyao Zhou, Shumin Han, Huilong Li, Dandan Ren, Zhuping Sheng, and Yonghui Yang

Discussions are open until six months from issue publication.

ABSTRACT: Central Asia exports large amounts of virtual water through agricultural trade, a key factor for overexploitation of water resources in the region. Most studies analyze Central Asia's virtual water outflows to the outside world, while ignore the agricultural trade within the region and the varying impacts of virtual water flows on the individual countries. In this study, the changes in virtual water flows embedded in trade with outside regions (external) and Central Asia countries (internal) were analyzed for the period 2000–2018 for wheat, cotton, and livestock. The results show that while Central Asia exported, respectively, 194.3 and 101.8 km^3 of virtual water to the outside world through cotton and wheat trade, it imported 53.7 km^3 of virtual water via livestock trade. Also, while cotton-based virtual water outflows decreased, wheat-based virtual water outflows increased. Total virtual water flows in internal trade reached 71.2 km^3, with flow originating mainly from Kazakhstan and heading to other four countries through wheat trade.Kazakhstan was the largest net exporter of virtual water through wheat trade, Uzbekistan was the second-largest net exporter through cotton trade. Green water (precipitation water used by crops) was dominant in virtual water flow related to wheat and blue water (surface water or groundwater used by crops) was dominant in virtual water flow related to cotton. Uzbekistan and Turkmenistan were most directly influenced by the virtual water trade.

(KEYWORDS: Central Asia; virtual water trade; blue and green water; water resource.)

INTRODUCTION

The concept of "Virtual Water" refers to the amount of water embedded in the process of producing a given commodity or service (Allan 1996). As agricultural commodities account for over 90% of total virtual water (Allan 2013), international trade of agricultural commodities is a critical transboundary exchange of water resources (Oki and Kanae 2004; Hoekstra and Huang 2005; Chapagain and Hoekstra 2006; Hoekstra and Chapagain 2007; Hanasaki et al. 2010; Dalin et al. 2012, 2014, 2017; D'Odorico et al. 2014, 2019; Goswami and Nishad 2015; White et al. 2015; Liu et al. 2019). With globalization in recent decades, virtual water trade has increasingly become an important component of water management. Understanding the flow of virtual water through agricultural product trade can guide the management of regional physical water scarcity, especially in arid regions (Yang and Zehnder 2007).

As an arid continental-climate inland region, Central Asia has experienced the most water loss in the world. This has led to the dry-up of the Aral Sea. There is a general consensus that transboundary trade of water-intensive agricultural products in the region principally contributes to overexploitation of water resources and environmental degradation in

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the Aral Sea basin; The Aral Sea used to be the fourth-largest inland lake in the world (Micklin and Aladin 2008). Historically, water level in the Aral Sea was quite stable because of the balance in water inflow and outflow (Micklin 2010). In the early 1950s, Soviet central began to divert water from the region's two major rivers (Amu Darya and Syr Darya Rivers) to irrigate desert or steppe areas. The end goal was to intensively cultivate cotton in Uzbekistan, Turkmenistan, and Tajikistan (FAO 2013). Until the late 1980s, Central Asia expanded its irrigated area by 1.5 times and produced ~95% of raw cotton and cotton fiber in the Soviet Union (FAO 2013). Until now, Uzbekistan is still the most important cotton exporter globally and it does so by relying on intensive irrigation for sustainable production (Kahriz and Kahriz 2019). As a result of the massive expansion in irrigated land, the Aral Sea has gradually shrunk to a small remnant of its former size since the 1960s. Although the cropping system has greatly changed during the post-Soviet period (Hamidov and Helming 2016), Central Asia is still a net exporter of water-intensive agricultural products; contributing largely to the severe water shortage currently experienced (FAO 2013). Determining the change in virtual water flow in the transboundary trade of agricultural products across Central Asia is critical for understanding the changes in water resources in the region.

Global analyses show that Central Asia is a net exporter of virtual water (Hoekstra and Huang 2005; Chapagain and Hoekstra 2008; Hanasaki et al. 2010; Carr et al. 2013; D'Odorico et al. 2019). However, there are two main inadequacies in these studies — (1) Most of the analyses use the whole of Central Asia and by so doing ignore the differences in the impacts of virtual water flow on water resources in the five countries. It also shows that while eliminating virtual water flow greatly alleviates water scarcity in Uzbekistan, the effect can be much less in other countries (Porkka et al. 2012). (2) Virtual water flow embedded in the trade of agricultural products outside the region (hereafter called external trade) has been intensively analyzed. It shows that a large amount of virtual water flow as agricultural product trade within Central Asia countries (hereafter called internal trade) is ignored. Internal trade in agricultural products is quite large, driven by similar dietary habits and close geographic location (Mogilevskii and Akramov 2014). In this study, three water-intensive agricultural products (wheat, cotton, and livestock products) were used to analyze spatiotemporal trends in virtual water flow in Central Asia in 2000–2018. The objectives of the study were to: (1) Shed light on the changes in virtual water flow embedded in external and internal trade in different countries in Central Asia; and (2) discuss the impact of virtual water flow through trade in agricultural products on regional water resources and the well-being of people in Central Asia.

MATERIALS AND METHODS

Study Area

The five countries covered in Central Asia included Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (Figure 1). Being far away from the ocean, the continental climate is dominant. The average temperature range is 0°C–4°C in January and 29°C–32°C in July, and the mean annual precipitation is ~273 mm (FAO 2013). However, there is a rich diversity of micro-climatic conditions across the region due to the large heterogeneity of the terrains, especially in altitude (range of 0–7,500 m a.s.l.). The annual precipitation ranges are 80–200 mm in the southwestern lowland desert, 300–400 mm in the foothills, and then 600–800 mm in the eastern mountain area (FAO 2013). The Aral Sea lies in the central-western part of the study area.

According to FAO (2013), cultivated land area in the 2000s was estimated at 32 million ha; accounting for ~7% of the total area. Turkmenistan tops the rank, with 100% of the cultivated land irrigated. This is followed by Uzbekistan, Tajikistan, Kyrgyzstan, and Kazakhstan, respectively, with 89%, 85%, 75%, and 9% of the cultivated lands irrigated. The irrigated lands are mainly distributed in the downstream regions of the Amu Darya and Syr Darya Rivers. The irrigated crops are predominantly cotton and wheat, while rice, potato, corn, vegetables, and fodders occupy a relatively small area. Rainfed agriculture is largely in the northern and central Kazakhstan regions, where spring wheat is mainly grown (Gupta et al. 2009).

There have been profound changes in agricultural land cover in Central Asia following the collapse of the Soviet Union in 1991. Kazakhstan was an important breadbasket during the time of the Soviet Union, and the cultivation of legumes has significantly increased following the transition (Kraemer et al. 2015). Kyrgyzstan was specialized in alfalfa, potatoes, and maize before the transition, but wheat area was doubled after the collapse of the Union. Tajikistan, Turkmenistan, and Uzbekistan were specialized in cotton, but bread wheat has rapidly increased in recent decades (Hamidov et al. 2016).

According to the European Parliament (2018), some five main rivers basins exist in Central Asia — Amu Darya, Syr Darya, Balkhash-Alakol, Ob-Irtysh, and Ural River basins. The Amu Darya and Syr

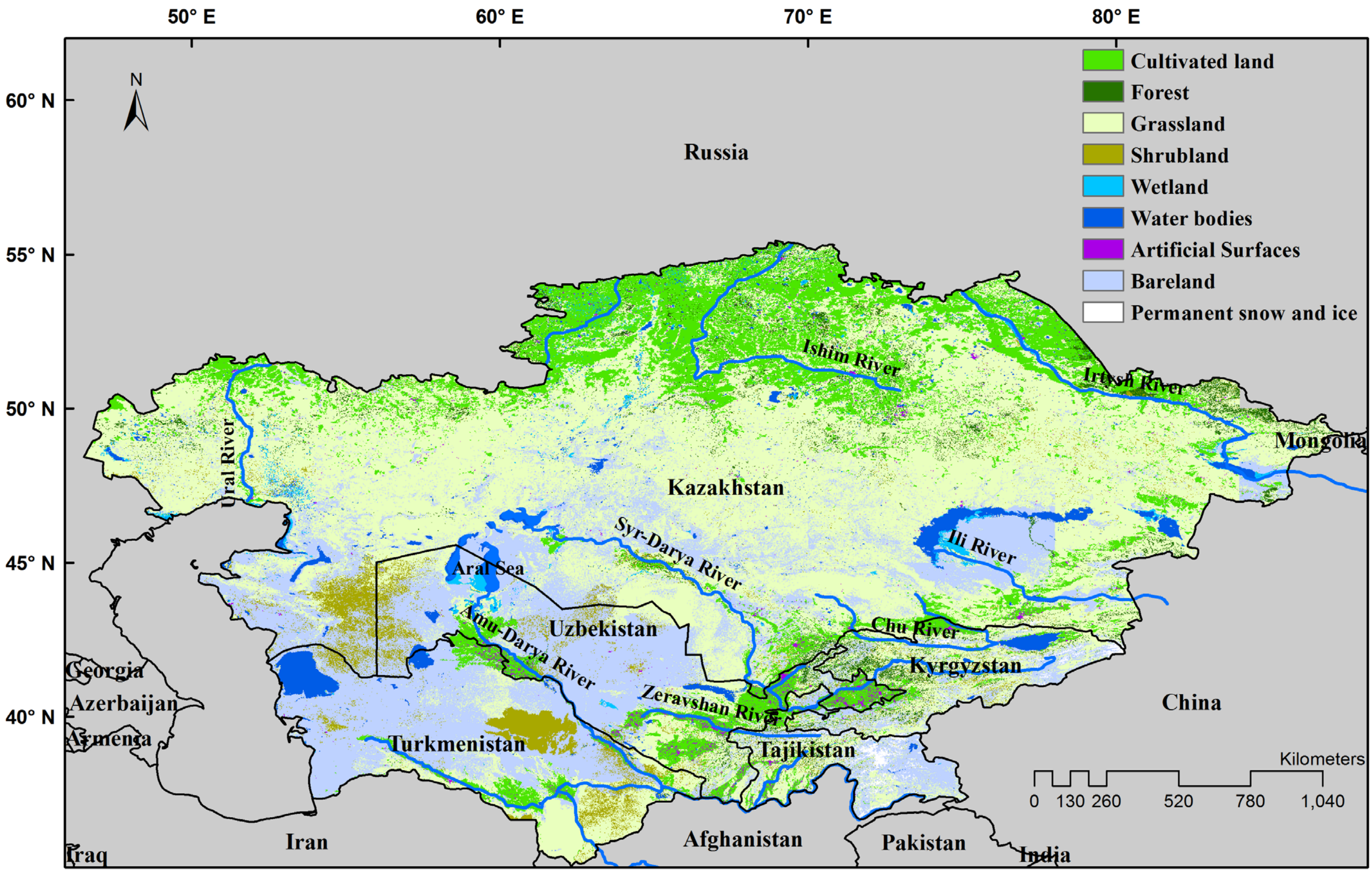

FIGURE 1. A map depicting the geographic location of Central Asia and the types of land use in the study area.

Darya are the two largest rivers which flow into the Aral Sea. Meltwater from Tien Shan, Pamir, and Karakorum Mountains is the main source of river water in the area (Shafeeque et al. 2020). Surface water is the main source of irrigation water in Central Asia, accounting for 82%–99.8% (average of 92.6%) of the sources in the region (FAO 2013).

Data Collection

Data used in this study mainly included exports and imports of wheat, cotton, and livestock products in the five countries in the Central Asia study area. Trade data on agricultural products in Central Asia for 2000–2018 were from the Chatham House Resource Trade Database in the global resource trade web (Chatham House 2018). It contains raw materials, intermediate products, and by-products. In this study, wheat trade data consisted of data on wheat, durum wheat, couscous, wheat gluten, wheat meal, wheat flour, etc. Then, cotton trade data consisted of data on cotton linter, cotton yarn, and cotton sewing thread. Finally, livestock product trade data included data on live animals, meat, dairy, egg, and honey.

Methods

Virtual Water Flow Estimation for Agricultural Products. To calculate the amount of virtual water flow for various agriculture products, the trade volumes (ton/year) of the products were multiplied by their respective virtual water content (VWC, m^3/ton). The VWC is defined as the water requirement in the production of a unit weight of an agricultural product in a country. The VWCs of raw wheat and cotton were taken from previous studies (Hoekstra and Hung 2002). Note that VWC of raw wheat by Hoekstra and Hung (2002) refers to the water used to produce a unit weight of wheat under irrigation. As most wheat is produced under rainfed conditions in Kazakhstan, VWC of rainfed wheat was taken from Martinez-Aldaya and Munoz (2010). For livestock products, VWC was taken from Chapagain and Hoekstra (2003). VWC of livestock products in each country was a blend of live animals (such as bovine, sheep, swine, and poultry) and livestock products including primary products (such as beef, pork, and chicken) and secondary products (such as butter, cheese, and milk powder). All the coefficients of the VWC are widely cited in the estimation of virtual water flow.

Note that cotton and wheat trade in Central Asia are composed of raw materials and processed products with different VWCs. To calculate virtual water flow from processed products, a simple transformation was done. For cotton, the processed product accounts for 17% the weight of the total trade (Chatham House 2018) and all was considered as cotton lint, which was converted into raw seed cotton by dividing by the coefficient 0.37 (Hayat and Bardak 2020). For wheat, the difference in VWC between raw materials and processed products was ignored because the processed products only account for 1.8% of the weight of the total trade (Chatham House 2018).

Due to the varying crop yields and crop water requirements, VWC for the same crop was different for exporting countries and importing countries. To focus on the impact of virtual water flow on water resources in Central Asia, VWC for agricultural products from Central Asian countries was used to estimate virtual water flow in external trade analyses. Further note that although it was balanced in weight, virtual water flow in internal trade was not balanced because of different VWCs between various importers and exporters. Here, VWC of agricultural products in exporting countries was used to show virtual water flow in internal trade. Then, VWC in importing countries was also used to discuss the impact of water used in agricultural production on water resources in two countries of Uzbekistan and Turkmenistan.

Green/Blue Water in Virtual Water Flow. Dividing virtual water into green and blue water can help better evaluate the impact of transboundary trade on water resources because blue water is extracted from surface water/groundwater and has a direct impact on water stress. Note that the concept of green and blue water comes from water footprint, which is a little different from virtual water. While virtual water is about water of production, water footprint is about water of consumption (Velázquez and Madrid 2011). Here, the two terms are used synonymously because most exported/imported crop products are raw materials and water embedded in processing very rare.

Analyses were done only for green and blue water of cotton and wheat because of the large amounts of exports in the trade. The ratios of blue and green water to total water for the production of wheat and cotton in the five Central Asia countries were obtained from previous studies by Martinez-Aldaya et al. (2010). In general, cotton cultivation is mainly in the southern part of the Aral Sea Basin where there is little precipitation. Heavily reliant on irrigation, blue water accounts for 60.3%–97.2% of total water consumption in cotton production (Martinez-Aldaya et al. 2010). On the contrary, green water is dominant in wheat production because spring wheat mainly grows under rainfed conditions in the northern steppe lands of Kazakhstan (Morgounov et al. 2007; Martinez-Aldaya et al. 2010).

Similar to VWC, the ratios of green/blue water in crop production vary for different countries. Therefore, the calculation of green/blue water of virtual water was conducted for exporting countries in the analysis of both external and internal trade. Moreover, in the discussion of the impact of virtual water trade on water resources, the green/blue water of virtual water in importing countries was also estimated for the two most influential countries — Uzbekistan and Turkmenistan.

Water Scarcity Evaluation. Water stress, measured by the ratio of water Withdrawal To Available water resources (WTA), was used to evaluate the impact of virtual water flow on water resources. Note that here, water withdrawal refers to blue water only as it is extracted from surface water/groundwater body and has a direct impact on water stress. According to Vörösmarty's criterion (2000), there is no water stress, moderate water stress, or high water stress in a region if WTA <0.2, 0.2–0.4, or >0.4, respectively.

The calculated blue water in this study, however, actually refers to net water requirement, rather than water withdrawal as mentioned in WTA above. Water withdrawal is much higher than water requirement due to the enormous water loss both at conveyance and field levels. This is particularly the case in Central Asia where infrastructure is outdated and with highly inefficient furrow irrigation (Peyrouse 2013; Bekchanov et al. 2016). Only 30%–35% of the water drawn from the source is used for irrigation of agricultural crops in Central Asia (Ikramov 2007; Dukhovny et al. 2018). To therefore evaluate the impact of virtual water flow on the water resources, water withdrawal was obtained by further dividing blue water by a coefficient of 0.33.

Virtual Water Flow Visualization. Circos, a software package, was used to visualize the directions of virtual water flow in external trade (Krzywinski et al. 2009). The eight external partners are America, Europe, North Asia, East Asia, South Asia, Southeast Asia, Africa, and Oceania. While Sankey diagram was used to show virtual water flow in internal trade. The Sankey diagram is widely used to visualize how water or energy flows from exporting to importing countries (Curmi et al. 2013; Mathis et al. 2019).

Trend Analysis. The trend (slope) was derived using ordinary least square fitting and the significance of the trend (p-value) was tested using a standard t-test.

RESULTS

External/internal Virtual Water Trade Flow in Central Asia

Changes in External Virtual Water Trade Flow. Figure 2a shows the changes in virtual water flows embedded in external trade in Central Asia in the period 2000–2018. A total of 296.1 km^3 of virtual water flowed out of Central Asia in the 19-year period, with 194.3 km^3 embedded in cotton and 101.8 km^3 in wheat export. Meanwhile, Central Asia received 53.7 km^3 of virtual water through livestock import. On average, the region annually exported 15.6 km^3/year of virtual water through cotton (10.2 km^3/year) and wheat (5.4 km^3/year) exports. It then imported 2.8 km^3/year of virtual water through livestock, with a total annual net export of 12.8 km^3/year.

The outflow of virtual water via cotton and wheat exports shows a slight but insignificant decrease in trend, with a slope of −0.17 km^3/year and p-value of 0.23. Separately, virtual water flow via cotton export had a significant decline in trend, with a slope of −0.24 km^3/year and p-value of 0.018. While virtual water flow via wheat export had an insignificant increase in trend, with a slope of 0.07 km^3/year and p-value of 0.39. The inflow of virtual water via livestock import increased significantly, with a slope of 0.24 km^3/year and p-value <0.01.

Figure 2b, 2c, and 2d show how the five Central Asian countries contributed to the changes in virtual water flow via external trade in three agricultural products. For wheat, Kazakhstan contributed the largest amount of virtual water outflow, with a value of 5.3 km^3/year that accounted for 99.6% of the virtual water outflow via wheat trade (Figure 2b). Totally, Turkmenistan and Uzbekistan were net exporters, while Tajikistan and Kyrgyzstan were net importers of virtual water in 2000–2018, with annual trade amount in the four countries <0.1 km^3/year.

For cotton, Uzbekistan was the largest exporter of virtual water in Central Asia (Figure 2c). It annually exported 6.9 km^3/year of virtual water, accounting for 67.3% of virtual water outflow via cotton trade. Turkmenistan ranked the second on the exporter list of virtual water, annually exporting 1.8 km^3/year and accounting for 17.2% of the virtual water outflow. Tajikistan, Kazakhstan, and Kyrgyzstan together exported 1.6 km^3/year (15.5%) of virtual water

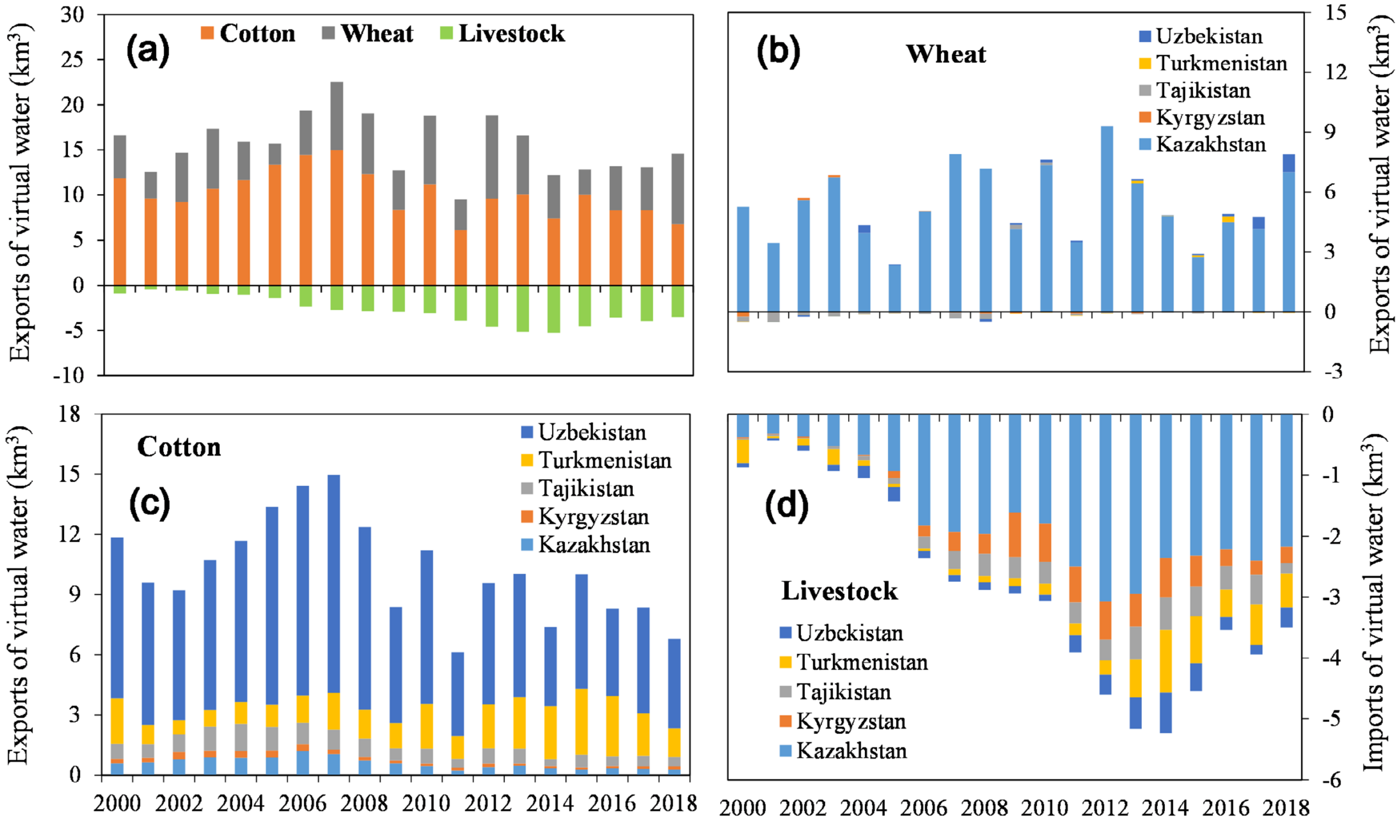

FIGURE 2. Changes and contributions of virtual water flow (a) in Central Asia though wheat (b), cotton (c), and livestock (d) to external trade (positive value is export and negative value is import).

annually via cotton trade. In addition, cotton-based virtual water outflow in Uzbekistan, Tajikistan, Kazakhstan, and Kyrgyzstan increased before 2007 and then significantly decreased, with trend slopes of −0.24, −0.03, −0.04, and −0.01 km^3/year, respectively. Conversely, virtual water outflow in Turkmenistan significantly increased, hitting its peak in 2015 and with a trend slope of 0.08 km^3/year for cotton trade.

For livestock, all the five countries were net importers of virtual water for the study period with imports hitting peak values in 2014 (Figure 2d). Kazakhstan imported the largest amount of virtual water, with a value of 1.7 km^3/year and accounting for ~60% of the total annual virtual water inflow. Kyrgyzstan, Turkmenistan, Tajikistan, and Uzbekistan imported, respectively, 0.32, 0.32, 0.27, and 0.22 km^3/year of virtual water via livestock trade.

External Trade Partners of Central Asia. Figure 3 shows the major trading partners of Central Asia regarding external trade and also the destinations of virtual water outflow originating in Central Asia in 2000–2018. Asia (excluding Central Asia) received the largest amount of virtual water from Central Asia. It received a total of 191.8 km^3 of virtual water, accounting for 64.7% of the total virtual water outflow through wheat and cotton trade. In the region, North Asia was the biggest trading partner of Central Asia, East Asia, and South Asia were almost equal in terms of trade

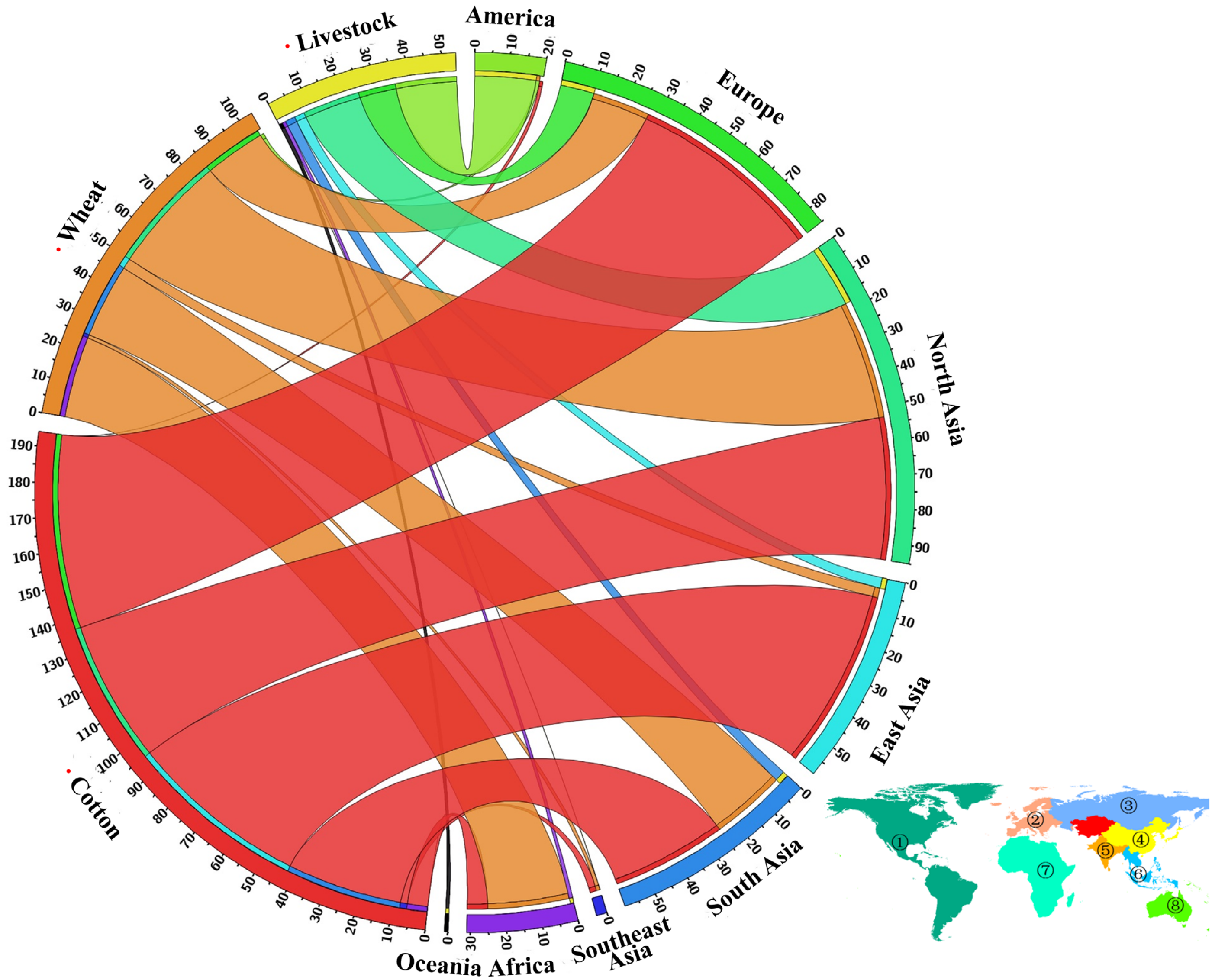

FIGURE 3. The volumes of virtual water flowing to the external regions of Central Asia in 2000–2018. The numbers in the right bottom of the global map represent different partners: ① = America, ② = Europe, ③ = North Asia, ④ = East Asia, ⑤ = South Asia, ⑥ = Southeast Asia, ⑦ = Africa, and ⑧ = Oceania.

amount and Southeast Asia was negligible. Europe and Africa received 25.1% and 10.2% of virtual water from Central Asia, respectively. Then, virtual water trade with America and Oceania was negligible.

During 2000–2018, North Asia, the biggest trading partner of Central Asia, received virtual water of 35.6 and 41.9 km^3 from Central Asia through wheat and cotton trade. It then exported 17.7 km^3 of virtual water to Central Asia through livestock trade. Europe, the second-biggest trading partner, received 17.3 and 57.1 km^3 of the virtual water from Central Asia through wheat and cotton trade. It again exported 10.2 km^3 of virtual water to Central Asia through livestock trade. South Asia received 21.9 and 33.7 km^3 of virtual water from Central Asia through wheat and cotton trade, and then exported 3.1 km^3 of virtual water to Central Asia through livestock trade. East Asia received 53.0 km^3 of the virtual water through cotton trade. Then, Africa received 24.5 km^3 of the virtual water through wheat trade and America exported 18.2 km^3 of virtual water to Central Asia through livestock trade.

Virtual Water Flow in Internal Trade. Figure 4 shows the exchange of virtual water flow embedded in agricultural products in internal trade in Central Asia. During 2000–2018, virtual water flow in internal trade reached 71.2 km^3 (3.7 km^3/year), about a third of net virtual water outflow (12.8 km^3/year) in Central Asia. Virtual water flow in wheat trade accounted for 90.2% of internal virtual water flow, with a total value of 64.2 km^3 or annual 3.4 km^3/year. The flow direction was mainly from Kazakhstan to other Central Asia countries. Uzbekistan received the largest volume of virtual water (35.4 km^3) mainly from Kazakhstan through wheat trade, followed by Tajikistan (20.3 km^3), Kyrgyzstan (8.5 km^3), and then Turkmenistan (2.2 km^3). The virtual water flow embedded in livestock and cotton trade together accounted for 10% of the internal virtual water flow, with 5.4 km^3 of the water via livestock products and 1.6 km^3 via cotton products. Kazakhstan was the major destination country of virtual water flow via livestock and cotton products.

Green/Blue Water Embedded in Cotton/Wheat Trades

Green/Blue Water Outflow in External Trade. Figure 5 shows the green and blue water embedded in cotton and wheat products in external trade with Central Asia in 2000–2018. For the total net exports of virtual water flows in cotton and wheat trades in Central Asia, blue water (180.2 km^3) accounted for 61% of the total outflow (296.1 km^3). For cotton trade, blue water accounted for 92.4% (9.5 km^3/year) of cotton-based virtual water outflow. Then for wheat trade, blue water only accounted for 0.6% (0.03 km^3/year) of wheat-based virtual water outflow (Figure 5). The values in Figure 5 showed a blend of

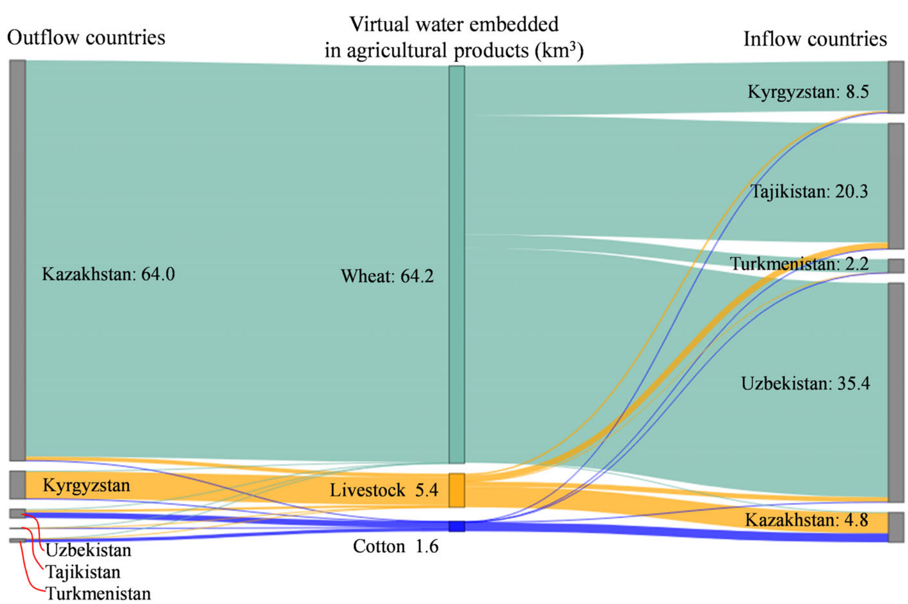

FIGURE 4. Total internal virtual water flow for Central Asia from exporters (left) to importers (right) via three agricultural product trades (middle) in the period 2000–2018. The green, yellow, and blue colors represent, respectively, virtual water volumes for wheat, livestock, and cotton, with the numbers as the corresponding virtual water volumes. For instance, virtual water embedded in wheat is 64.2 km^3, most of it from Kazakhstan (64.0 km^3), total virtual water flows to Kyrgyzstan is 8.5 km^3 via three agricultural product trades.

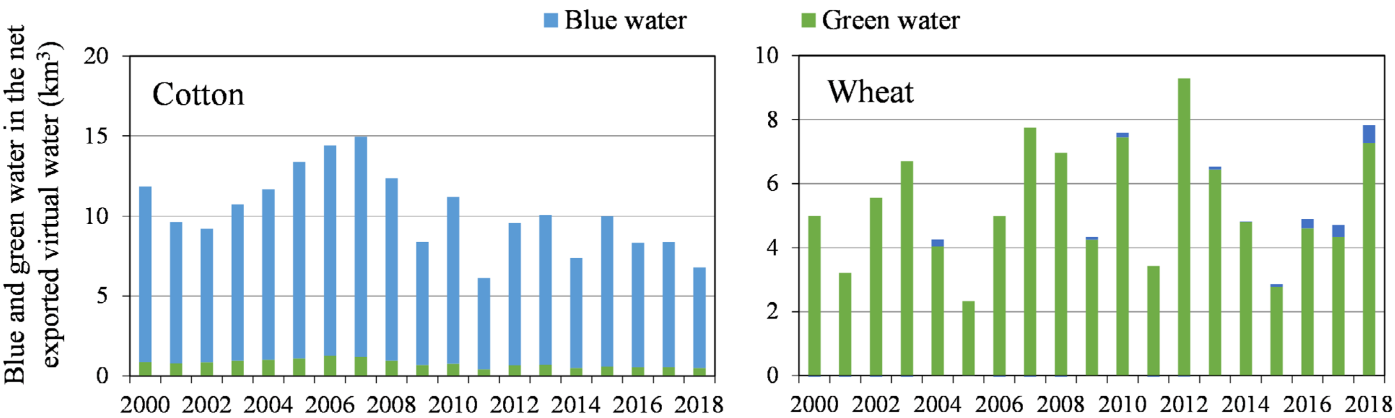

FIGURE 5. Blue and green water as total net export of virtual water embedded in wheat and cotton trades in Central Asia in 2000–2018.

green and blue water for the five countries, ignoring the contributions of different countries and virtual water embedded in internal trade. Concerning the impact of virtual water flow on water resources, it was necessary to estimate green and blue water in both external and internal trades for the different countries.

Green/Blue Water Outflow from Different Countries. Figure 6 shows the blue and green water of cotton and wheat in both external and internal trades in the different countries in Central Asia.

Kazakhstan. Kazakhstan was the largest net exporter of virtual water among the countries in Central Asia, with 176 km^3 virtual water outflow in 2000–2018. Through wheat trade, Kazakhstan exported 101.4 km^3 of virtual water to the outside regions. Also, Kazakhstan exported a total of 64.0 km^3 of virtual water to other countries in Central Asia. All wheat-based virtual water outflow was green water because it was rational to neglect blue water in Kazakhstan (Martinez-Aldaya et al. 2010). For cotton, Kazakhstan exported a total of 11.5 km^3 of virtual water to the outside regions and received 0.83 km^3 from other countries in Central Asia. The green/blue water ratio in terms of virtual water embedded in cotton trade was 0.40 in Kazakhstan.

Uzbekistan and Turkmenistan. Uzbekistan and Turkmenistan were, respectively, the second (103 km^3) and third (31.3 km^3) largest net exporters of virtual water flow in Central Asia. Virtual water outflows due to cotton exports dominated in the two countries, accounting for over 98% of the total virtual water outflow. Uzbekistan and Turkmenistan, respectively, exported 134 and 33.9 km^3 of virtual water in both external and internal trades, with over 99% of the virtual water outflow going via external trade. Blue water accounted for 94% and 97% of the total virtual water outflow via cotton exports, respectively, in Uzbekistan and Turkmenistan. Meanwhile, Uzbekistan and Turkmenistan received, respectively, 31 and 2.6 km^3 of virtual water flow through wheat import from other Central Asia countries. Blue water accounted for 67% and 76% of total virtual water inflows in Uzbekistan and Turkmenistan, respectively.

Tajikistan and Kyrgyzstan. Tajikistan and Kyrgyzstan were two net importers of virtual water in 2000–2018. Tajikistan exported 15.3 km^3 of virtual water via cotton trade and received 57.9 km^3 of virtual water via wheat trade. For cotton trade, virtual water outflow to the outside regions was dominant, accounting for 97% of the total outflow. On the other hand, virtual water inflow from the internal countries was dominant for wheat trade, accounting for 97% of the total virtual water inflow via wheat trade. Blue water accounted for 94% of virtual water outflow via cotton export, accounting for 55% of virtual water inflow via wheat trade.

Kyrgyzstan exported 3.9 km^3 of virtual water via cotton trade with the outside areas and received 15.8 km^3 of virtual water flow via wheat trade with other Central Asia countries. Blue water accounted for 78% of virtual water outflow via cotton trade, accounting for 43% of virtual water inflow via wheat trade.

DISCUSSIONS

Reliability of Virtual Water Calculation

There are some factors that can cause uncertainties in the estimation of virtual water flow in agricultural products. As factors that influence results, VWCs of various agricultural products are critical in the estimation of virtual water flows. In this study, the differences in VWCs of raw materials, intermediate products, and by-products were ignored due to the low

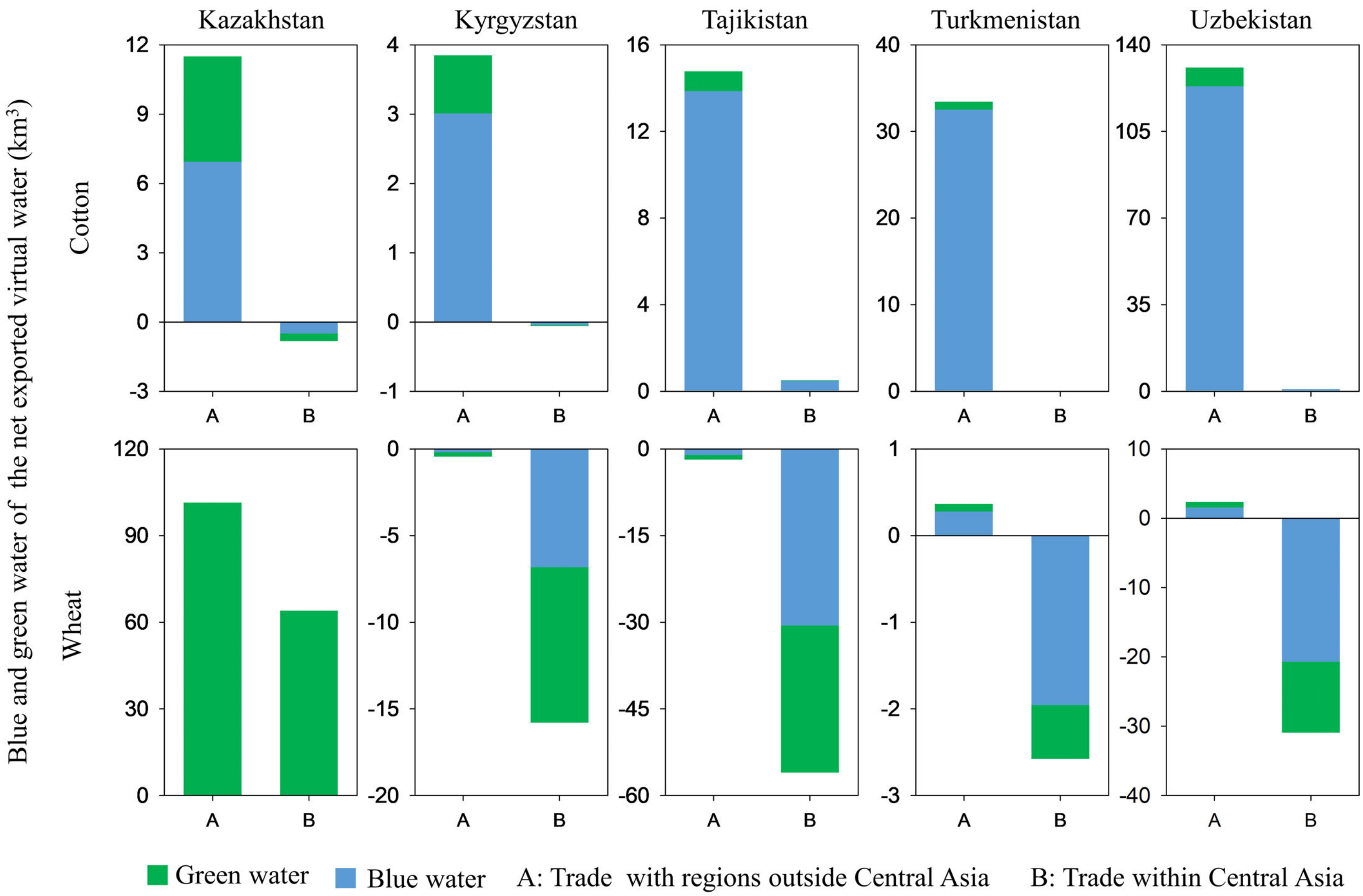

FIGURE 6. Blue and green water as total net export of virtual water embedded in external and internal trade of wheat and cotton in different countries in Central Asia in 2000–2018 (negative values denote net import).

proportions of intermediate and by-products, compared with raw cotton and wheat in international trade. This could have induced a degree of mismatch in the estimation of total virtual water volume.

Second, different methods have different levels of uncertainty in VWC. Using VWC of cotton in Uzbekistan, for example, different methods used in the estimation of cotton water requirements yielded different VWCs. Using satellite remote sensing and crop efficient methods, Thevs et al. (2015) compared the gaps in estimated crop water use in Turkmenistan. Rudenko et al. (2013) considered water used in washing out salts from the soil, delivery water loss, and gray water in the estimation of cotton water requirement during cultivation season. This resulted in high VWC (6,819 m^3/ton) compared with the 3,642 m^3/ton observed by Hoekstra and Hung (2002) when delivery water loss and gray water were not considered.

Third, the use of importer/exporter VWC can result in large differences due to different water use efficiencies of the exporting/importing countries. To concentrate the impact of virtual water trade on local water resources, VWCs of five countries in Central Asia were used to estimate virtual water flow in external trade. For internal trade, exporter VWCs were used in this study. This resulted in an imbalance in virtual water flow between importers and exporters, although trade could have been balanced in weight.

Even with all these uncertainties in the estimated virtual water flows, this study was still reliable. Annually, Central Asia exported 15.6 km^3/year of virtual water to the outside regions in 2000–2018, close to the 16.7 km^3/year of virtual water export reported by Hoekstra and Chapagain (2008). Moreover, Uzbekistan exported 8.0 km^3 of virtual water to external countries via cotton trade in 2000, close to the 7.9 km^3/year export in 1997–2001 reported by Martinez-Aldaya et al. (2010).

Virtual Water Flow Impact on Water Resources

Approximately 24% of the world's agricultural blue water consumption is used in the production of agricultural commodities for international trade (Porkka et al. 2012). In this study, virtual water outflow in cotton and wheat trades was 15.6 km^3/year and the proportion of blue water in that was 9.5 km^3/year. Thus, given 0.33 irrigation water use efficiency in Central Asia, water withdrawal for export reached 28.7 km^3/year. This accounted for 26.5% of total agricultural water withdrawal (108.7 km^3/year) in Central Asia (FAO 2013). Given that only cotton and wheat were considered in this study, the actual amount could be much higher. Compared with the global estimate of 24%, there is a higher impact of virtual water trade on local water resources in Central Asia. Based on FAO (2013), the volume of renewable water resources in Central Asia is 227.6 km^3/year and the annual water withdrawal is 124.6 km^3/year. This means that there is a WTA of 0.55 in the region and a severe water stress. The current export of 28.7 km^3/year blue water, including losses, accounts for 12.6% of total renewable water resources in Central Asia. Based on the result, slashing off 28.7 km^3/year of virtual water outflow can reduce water stress in Central Asia to a moderate level by WTA standard to 0.42 (water withdrawal drops to 95.9 km^3/year).

As noted by Porkka et al. (2012), the elimination of exports could have little impact on water stress in the region. From the case of the three net exporting countries (Kazakhstan, Uzbekistan, and Turkmenistan), however, virtual water export elimination would have different impacts on different countries. For Kazakhstan, green water was dominant in wheat production. Thus, in spite of the large amount of virtual water export, water scarcity was lowest in Kazakhstan in 2000–2018 among the three Central Asian countries. It is worth to note that green water consumption actually has an indirect impact on the hydrologic cycle because: (1) Arable lands may be flattened to retain more rainwater. This increases crop evapotranspiration in the growing season and soil water evaporation in nongrowing season. It also reduces rainwater recharge to the other components of the hydrologic systems such as surface water and groundwater in the region. (2) About 80% of croplands are rainfed globally (Rosa et al. 2018) and once crops are planted, there is no other (forest, grassland, or built-up land) potential use of green water (D'Odorico et al. 2019). Nevertheless, eliminating virtual water export was more meaningful for Uzbekistan and Turkmenistan, which had the highest regional water stress. Uzbekistan and Turkmenistan were the two most affected countries because of the large amount of cotton-based blue virtual water export. While for Uzbekistan the ratio of blue water export (including loss) to renewable water resources was 40.7%, that for Turkmenistan was 21.1%. Under the current trade pattern, water stress in Uzbekistan was 1.15 and that for Turkmenistan 1.13. Eliminating blue water export would reduce water stress from 1.15 to 0.74 in Uzbekistan (water withdrawal drops from 56 to 36.1 km^3/year), and from 1.13 to 0.92 in Turkmenistan (water withdrawal drops from 28.0 to 22.70 km^3/year).

Meanwhile, wheat-based virtual water flow in internal trade from Kazakhstan to Uzbekistan and Turkmenistan also contributed to the reduction in regional water stress. Uzbekistan received 34.5 km^3 and Turkmenistan 2.2 km^3 of virtual water from Kazakhstan for the study period, all from green water. However, this was estimated based on VWC coefficient for Kazakhstan. If the two countries produced their own wheat, Uzbekistan would consume 31.1 km^3 of its water resources with 20.7 km^3 of blue water. Then, Turkmenistan would consume 2.6 km^3 of its water resources with ~2 km^3 of blue water. Given the water loss in irrigation, the required water resources will hit 62.7 and 6 km^3, respectively; further worsening water shortage in the two countries.

Changes and Predictions in Virtual Water Trade

In spite of the benefits for water security and environmental sustainability, reducing the export of raw cotton or cotton products is not feasible because it will harm the revenue of the state and the income of farmers in Uzbekistan and Turkmenistan. Cotton export substantially contributes to the GDP of Uzbekistan, with a share of 13% of the GDP (Djanibekov and Finger 2018) and 30% of rural employment in the country. Similarly, cotton export contributes 8% to the GDP of Turkmenistan and employs almost half of the workforce in the country (Djanibekov et al. 2010). With this reality, cotton production is highly managed by the governments through measures such as state quotas and subsidies in the two countries (MacDonald 2012).

In Uzbekistan, for instance, the increase in cotton export before 2008 was due to low taxation. This reduced economic burden on cotton producers resulted in higher production and export (MacDonald 2012). However, the decline in cotton export after 2008 was caused by high taxation and low food security. In 2008, world grain prices reached a record high (Josling et al. 2010) and Kazakhstan (Uzbekistan's main source of imported wheat) imposed an export ban. In response, Uzbekistan announced an area shift from cotton to grains (MacDonald 2012). In Turkmenistan, the increase in cotton export before 2014 was mainly due to the expansion of irrigated land (Lerman et al. 2012). Then, the decline in cotton export in the post-2014 period was caused by falling cotton prices (Batsaikhan and Dabrowski 2017).

Recently, however, the governments have started to encourage the expansion and intensification of high-value crops such as fruits and vegetables (Lombardozzi 2020). Furthermore, the governments are planning to ban raw cotton exports and push for more investments in value-added production of finished and semi-finished products in textile and fashion (USDA 2020). Also, the governments of Uzbekistan and Turkmenistan have adopted a range of policies to encourage wheat cultivation to promote food self-sufficiency (Svanidze et al. 2019). Due to these polices, raw cotton and wheat exports are expected to drop in the near future in Uzbekistan and Turkmenistan. However, this is by no means equal to the decrease in water consumption because of the following reasons: (1) fruits and vegetables are highly water-intensive and therefore increase water consumption; and (2) value-added processes of raw cotton increase the volume of virtual water that goes as export. Nevertheless, the share of Central Asia in virtual water trade in the world could decline in the long run. Central Asia is predicted to become a virtual water importer by 2100 due to an increase in interregional virtual water trade and unsustainable virtual water flows (Rosa et al. 2019; Graham et al. 2020). There is a need for research in environmentally more sustainable and socially more equitable water governance in Central Asia.

CONCLUSIONS

Virtual water trade is key in managing severe water stress and environmental degradation in Central Asia. Understanding the structure of virtual water flow and its trend can guide the process of averting water crisis in the region. In this study, virtual water flow embedded in main agricultural products (cotton, wheat, and livestock) was estimated for Central Asia. The amounts and directions of the virtual water flow were systematically analyzed for the period 2000–2018 for both internal and external trades. Then, the impact of blue water export on water resources in the different countries was discussed.

Central Asia annually exported 15.6 km^3/year of virtual water to outside regions, 10.2 km^3/year of which was through cotton and 5.4 km^3/year through wheat export. Meanwhile, the region imported 2.8 km^3/year of virtual water from outside regions through livestock trade. Virtual water embedded in internal trade was one-third of that in external trade, with a flow direction coming mainly from Kazakhstan and going to the other four countries as wheat trade. Kazakhstan was the largest net exporter of virtual water in Central Asia, with wheat accounting for 94% of the total trade.Uzbekistan was the second-largest net exporter of virtual water in Central Asia, with cotton export contributing some 98% to the virtual water outflow. Given the different green/blue water ratios for different crops and countries, water resources in Uzbekistan and Turkmenistan were most influenced by agricultural trade because of the large amounts of embedded blue water. Kazakhstan was less directly affected due to a large amount of green water in its wheat production.

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AUTHOR CONTRIBUTIONS

Xinyao Zhou: Methodology; Writing-original draft. **Shumin Han:** Data curation; Formal analysis; Methodology; Validation; Writing-review & editing. **Huilong Li:** Software. **Dandan Ren:** Software. **Zhuping Sheng:** Supervision. **Yonghui Yang:** Conceptualization; Project administration; Supervision.

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