Paddy Water Environ
DOI 10.1007/s10333-016-0569-4

ARTICLE

Evaluation of external virtual water export and dependency through crop trade: an Asian case study

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Received: 28 November 2015 / Revised: 10 November 2016 / Accepted: 25 November 2016

Abstract The aim of this study was to evaluate virtual water export through five crops (barley, rice, maize, soybeans, and wheat) in terms of the external virtual water rate, within and outside of Asia from 2000 to 2012, and in comparison with that within and outside the European Union (EU). The external virtual water rate indicates the proportion of virtual water export outside of a boundary. Approximately 46.9% of the green water exports and 40.9% of the blue water exports were discharged from Asia to non-Asian countries. For example, Thailand, which is the main exporter in Asia, exported 55.5% of the total virtual water exported to non-Asian countries, and Kazakhstan exported 63.8% of the total virtual water exported to European countries. In comparison, the external virtual water rate for the EU was 30.2% (green water) and 25.2% (blue water). The virtual water trade is also important to the main importers in Asia. We evaluated the virtual water dependency on exporters in East Asia of Japan, Korea, and Taiwan. These three countries have a high dependency on virtual water imported from only a few exporters; thus, they should extend their virtual water trade boundary to include additional exporters. These results provide information necessary for the development of an integrated water strategy in Asia, and could convince the main Asian importers of the risks of serious dependency on foreign water resources.

Keywords Virtual water trade · External virtual water rate · Water dependency · Asia

Introduction

Agriculture consumes the largest share of global freshwater resources, making water scarcity a local phenomenon that is sensitive to global food production (Molden 2007; Biewald et al. 2014). The water demand for agricultural production increases with population growth (Rosegrant and Sombilla 1997; Pingali 2006). Since most water demand derives from agriculture, crop trade can be regarded as the primary source of water demand, because the water used by crops includes the water embedded in traded products (Aldaya et al. 2010). The water used in production is called "virtual water" (Allan 1996). The method of trading water in this way is referred to as the virtual water trade (Hoekstra 2003).

The water used to produce export commodities for the global market contributes significantly to changes in regional water systems (Chapagain and Hoekstra 2008). In the past, national water strategies have considered the quantification of actual water use and the allocation of water resources, such as surface water or ground water, in the context of their neighboring countries. However, the virtual water trade concept suggests an expanded perspective of the watershed boundary, from a real watershed to a virtual area that includes the importer and its exporters.

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Published online: 03 December 2016

Countries also share water resources indirectly through virtual water trade, even though they may not directly share water resources. As a result, the virtual water trade has been suggested as a relevant tool to analyze the water policy of a nation (Schyns and Hoekstra 2014). Falkenmark and Lannerstad (2010) estimate that in order to compensate for agricultural water deficits, it will be necessary to double the virtual water trade by 2050. Also, the International Water Management Institute (IWMI) and the Government Office for Science have both stated that virtual water flows will offer the possibility of relieving water stress and the development of a more efficient use of global water (Government Office for Science 2011).

The national water savings achieved by virtual water trade are equal to the import volume multiplied by the volume of water required to domestically produce the commodity. However, the virtual water trade not only generates water savings for importing countries, but also causes water "losses" for the exporting countries (Chapagain et al. 2006). The global net effect of the virtual water trade between two nations depends on the actual water volume used in the exporting country (Chapagain et al. 2006). For example, countries for which the major industry is agriculture spend their water resources for food trade in terms of water discharge. In particular, in terms of virtual water trade, Asian countries are the main sources of global water consumption for food supply. In addition, the available amount of global freshwater is decreasing due to climate change, suggesting that water needs to be considered as a precious natural resource.

It is therefore important to understand the amount of water that is discharged within and outside of nations in terms of water security, yet applying virtual water trade to integrated water management has remained a challenging task. Several researchers have studied the virtual water trade balance of nations and regions. Virtual water trade, and its respective savings through the trade of agricultural goods, has been quantified in a number of studies (Hoekstra and Hung 2005; Yang et al. 2006; Fader et al. 2011; Hanasaki et al. 2010). However, these studies have focused on the quantification of virtual water in terms of global water savings. Recently, studies have been performed on local virtual water flow. Biewald et al. (2014) evaluated the impact of the international food crop trade on local blue water resources, in order to determine the trade-related value of blue water usage. Bulsink et al. (2010) quantified interprovincial virtual water flows related to crop trade in Indonesian provinces, and found that Java, the most water-scarce island, had the most significant external water footprint. Van Oel et al. (2009) quantified the external water footprint of the Netherlands by partner country, and found that Dutch consumption implied the consumption of water resources throughout the world, with significant impacts in water-scarce regions. Schyns and Hoekstra (2014) assessed the value of water footprint with a case study for Morocco, and found that most of the virtual water exported from Morocco was derived from low economic water productivity, and that blue water scarcity was severe in all river basins. As a case study for China, Wang et al. (2013) applied a modified input–output model to quantify the agricultural and industrial water footprint of Beijing, taking into consideration the virtual water flows and national gross water savings as a result of trade. Zhang and Anadon (2014) used a multi-regional input–output model to analyze the domestic virtual water trade and provincial water footprint in China.

In terms of virtual water trade, Asian countries are the primary sources of global water use for crop supplies. However, this indicates that virtual water trade also discharges water resources to other areas, which is an important issue in Asia, because it is dominated by external water resources. In this study, we evaluated the virtual water export within and outside of Asia from 2000 to 2012, and compared the result to that of the EU, by considering the virtual water traded through wheat, rice, barley, maize, and soybeans. In addition, we focused on virtual water imports by the main importers (Korea, Japan, and Taiwan), and evaluated their virtual water dependency on exporters. These results provide information for an integrated water strategy in Asia, and illustrate the risks of serious dependency by countries on foreign water resources.

Materials and methods

Virtual water contents

Virtual water content (VWC, m^3/ton) is the volume of water needed to produce one ton of crops in the region where the product is actually produced (Chapagain and Hoekstra 2004). The VWC of a crop is calculated by dividing the crop water requirement (m^3/ha) by the yield (kg/ha). The VWCs of crops were estimated using Eq. (1) as follows:

$$\mathrm{VWC}[c] = \frac{\mathrm{CWR}[c]}{\mathrm{Production}} \quad (1)$$

where VWC (m^3/ton) is the water required for the production of one ton of a given crop c, the crop water requirement (CWR) is the quantity of water required for the amount of crop produced, and the Production is the quantity harvested per year.

The concept of virtual water has been expanded to include water footprints that consider the water source. The water footprint has been proposed to include green and blue water resources (Hoekstra and Chapagain 2008). The green water footprint is the volume of consumption of green water, which is stored in the soil, or stays temporarily on top of the soil in vegetation, eventually transpiring through plants. The blue water footprint is the volume of consumption of blue water, which refers to the water in freshwater lakes, rivers, and aquifers. The water footprints within the agricultural sector have been extensively studied, with the primary focus on the water footprint of crop production at various scales from sub-national regions (Aldaya and Llamas 2008; Zeng et al. 2012), to country/national levels (Ma et al. 2006; Bulsink et al. 2010), and to the global level (Hoekstra et al. 2012).

The water footprint within a nation is defined as the total freshwater volume consumed within a territory of that nation as a result of economic activities. Mekonnen and Hoekstra (2011) quantified the green and blue water footprints of crops and crop products. Chapagain and Hoekstra (2011) estimated the green and blue water footprints of rice from production and consumption perspectives. The water footprint of a nation is increasingly used as a means of synthesizing a nation's water needs (Orlowsky et al. 2014). In the present study, the Mekonnen and Hoekstra (2011) method for the footprint of a nation is used to analyze the virtual water trade.

Virtual water trade and external virtual water

Virtual water trade between or within nations can be seen as an alternative to actual water transfer. The virtual water export from a nation is the sum of the virtual water export from domestic water resources and the re-exported virtual water of foreign origin. When calculating the virtual water trade in recent years, the distinction between green and blue water has been considered, and blue and green water exports have been estimated for all agricultural goods and crop types (Fader et al. 2011; Hanasaki et al. 2010; Mekonnen and Hoekstra 2011). The virtual water trade is calculated by multiplying the volume of trade by the water footprint per ton of product in the exporting nation. The virtual water trade is calculated as follows:

$$\mathrm{VWT}[n_e, n_i, c, t] = \mathrm{CT}[n_e, n_i, c, t] \times \mathrm{WFP}\ [n_e, c], \quad (2)$$

where VWT denotes the VWT from the exporting country n_e to the importing country n_i in year t as a result of the trade in crop c; CT represents the crop trade from the exporting country n_e to the importing country n_i in year t as a result of the trade in crop c; and WFP represents the water footprint of crop c in the exporting country.

The virtual water export without a boundary could be regarded as the water resource discharge. In this study, we set the boundary as either Asia or the EU, and analyzed the external virtual water rate using the total virtual water export with and without a boundary. Accordingly, the external virtual water rate is considered as a proper indicator of the virtual water discharge, which is described as:

$$\text{External virtual water rate} = \frac{\text{External virtual water export}}{\text{Total virtual water export}} \times 100(\%) \quad (3)$$

where the external virtual water export indicates the amount of virtual water export outside a boundary, i.e., in Asia or the EU.

The distance between an importer and exporter could affect the trade situation, and it could be applied as the fraction factor of the relationship in trade network analysis. However, we focused on the quantification of virtual water exported from importer to exporter; thus, we only considered the amount of trade and water footprint in each exporter.

International crop trade and water footprint data

Although we analyzed the internal and external virtual water trade in Asia and the EU, respectively, the global virtual water trade could also be computed. Therefore, we considered global virtual water trade with the trade data of 185 countries, and extracted the results of virtual water export in 47 Asian countries and 28 EU countries. Table 1 lists the results for the Asian and the EU countries. The country-scale import and export data of agricultural crops for the years 2000–2012 was obtained from the Food and Agriculture Organization Corporate Statistical database (FAOSTAT) (see: http://faostat3.fao.org/download/T/*/E) from the Food and Agriculture Organization of the United Nations Statistics Division. In addition, the data on the water footprints of crop production in Asia and the EU were taken from Mekonnen and Hoekstra (2011).

Results and discussion

Internal and external virtual water trade in Asia and the EU

The virtual water export of several crops, including wheat, rice, barley, maize, and soybeans, was evaluated for Asia from 2000 to 2012, and we defined the virtual water export to non-Asian countries as the external virtual water rate in Asia (Table 2). Approximately 663.9 Gm^3 of green water and 191.9 Gm^3 of blue water were exported from Asia from 2000 to 2012 via the international trade of the grain crops of barley, maize, rice, soybeans, and wheat. Approximately 46.9% of the total green water exports and

Table 1 Estimates of Asian and EU countries' virtual water export through crop trade

Asian countries (47)				EU countries (28)	
Afghanistan	Israel	North Korea	Turkmenistan	Austria	Italy
Armenia	Japan	Oman	UAE	Belgium	Latvia
Azerbaijan	Jordan	Pakistan	Uzbekistan	Bulgaria	Lithuania
Bahrain	Kazakhstan	Philippines	Viet Nam	Croatia	Luxembourg
Bangladesh	Kuwait	Qatar	Yemen	Cyprus	Malta
Bhutan	Kyrgyzstan	Saudi Arabia		Czech Republic	Netherlands
Brunei Darussalam	Lao	Singapore		Denmark	Poland
Cambodia	Lebanon	South Korea		Estonia	Portugal
China	Libya	Sri Lanka		Finland	Romania
Cyprus	Malaysia	Syria		France	Slovakia
Georgia	Maldives	Taiwan		Germany	Slovenia
India	Mongolia	Tajikistan		Greece	Spain
Indonesia	Myanmar	Thailand		Hungary	Sweden
Iran	Nepal	Turkey		Ireland	UK

Table 2 Internal and external virtual water trade in Asia and the EU from 2000 to 2012

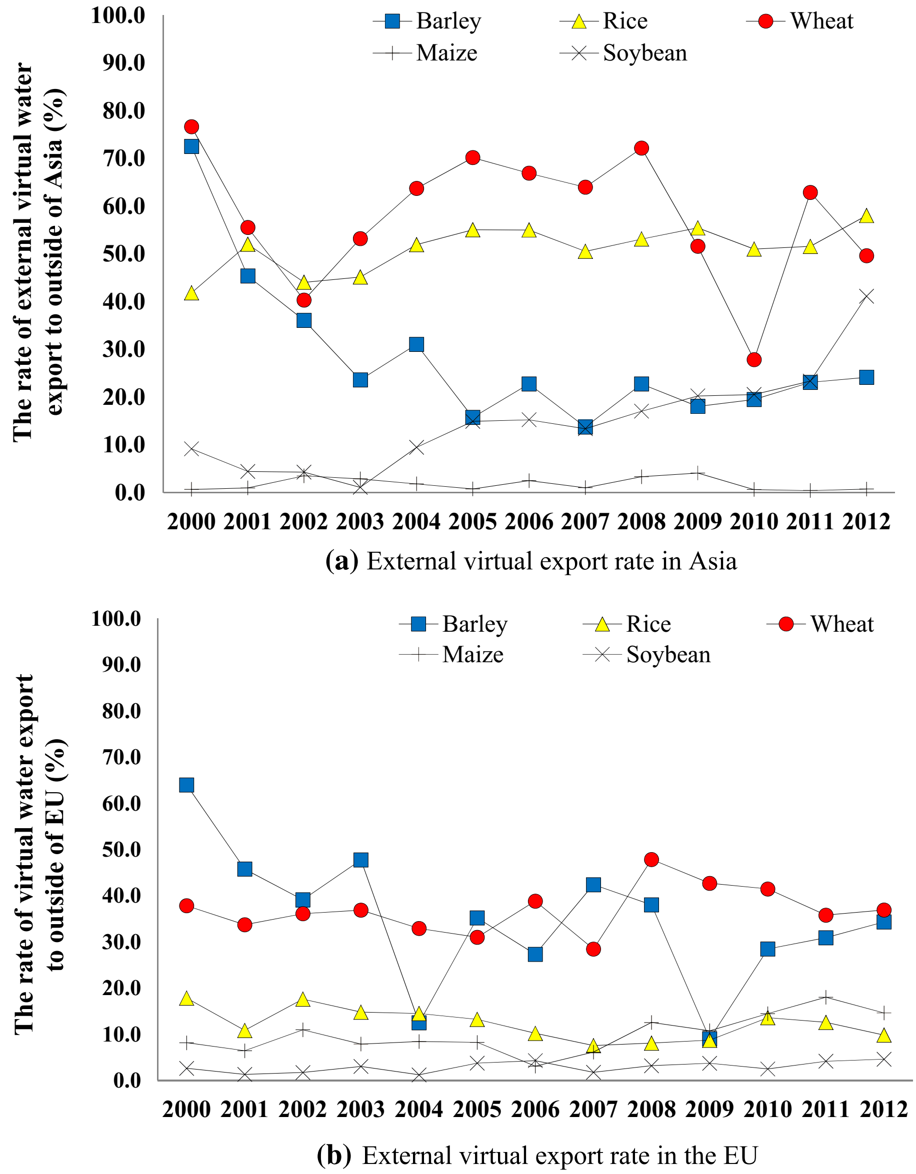
Crops	Internal virtual water trade (Gm^3)			External virtual water trade (Gm^3)			External virtual water rate (%)		
	Green water	Blue water	Total water	Green water	Blue water	Total water	Green water	Blue water	Total water
Asia	352.7	113.5	466.2	311.2	78.4	389.6	46.9	40.9	45.5
Barley	16.0	1.4	17.3	6.6	0.3	6.9	29.1	18.6	28.4
Maize	107.2	8.4	115.7	1.8	0.3	2.2	1.7	3.6	1.8
Rice	146.4	71.0	217.4	160.0	71.9	231.9	52.2	50.3	51.6
Soybeans	11.9	1.0	12.9	2.0	0.2	2.2	14.7	14.1	14.6
Wheat	71.1	31.8	102.9	140.7	5.8	146.5	66.4	15.3	58.7
EU	401.6	52.4	454.1	173.5	17.7	191.2	30.2	25.2	29.6
Barley	54.5	2.3	56.9	29.8	2.3	32.0	35.3	50.0	36.0
Maize	82.3	9.9	92.3	10.9	0.4	11.2	11.7	3.9	10.8
Rice	12.4	10.3	22.7	1.6	1.6	3.2	11.4	13.4	12.4
Soybeans	44.4	2	46.4	1.2	0.2	1.5	2.6	9.1	3.1
Wheat	208	27.9	235.8	130.0	13.2	143.3	38.5	32.1	37.8

40.9% of the total blue water exports were exported to non-Asian countries.

Figure 1 shows the results of the external virtual water rate analyzed by various crops. The largest discharge of virtual water was derived from the wheat and rice trade, and more than 50% of the virtual water was exported outside of Asia. In addition, the external virtual water rate of the soybeans trade continuously increased from 2000 to 2012, reaching 40% in 2012. On the other hand, the barley trade outside of Asia decreased, and the external virtual water rate also decreased to 20% in 2012. Although the total virtual water export decreased, the external virtual water rate increased. Figure 2 shows the amount of virtual water export and the external virtual water rate. In terms of the main food crops, such as barley, rice, and wheat, from 2000 to 2003 the virtual water export increased to 60 Gm^3, but in 2003, the blue water discharge decreased to 30%. This means that at that time, Asian exporters focused on Asian importers. However, from 2003 to 2005, the virtual water export sharply increased, accompanied by an increase of blue water discharge, suggesting that at that time the water resources of Asian exporters were intensively used to export crops to non-Asian importers. Recently, water export significantly increased, yet the external virtual water rate remained at a high level.of water resources

The EU also shares its water resources, trading many crops within its borders. Table 2 presents the results of our

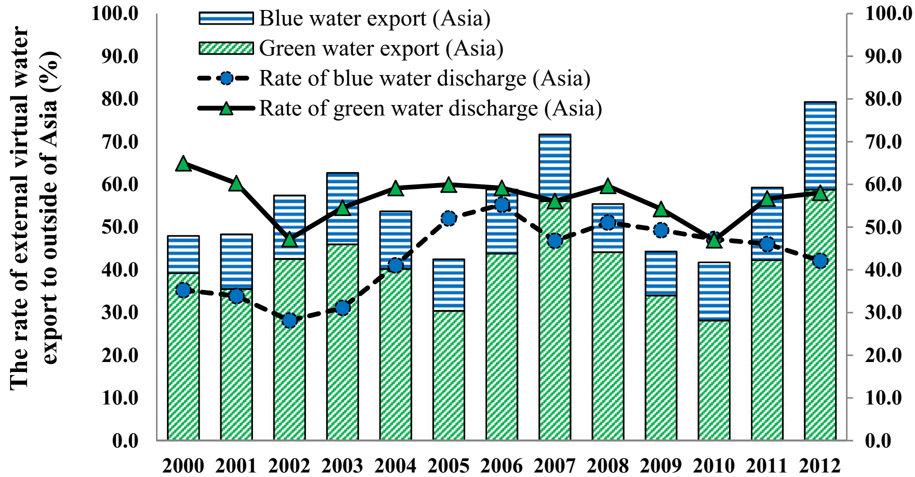
Fig. 1 Temporal external green and blue water export rate of each crop in Asia and the EU from 2000 to 2012. **a** External virtual export rate in Asia, **b** External virtual export rate in EU



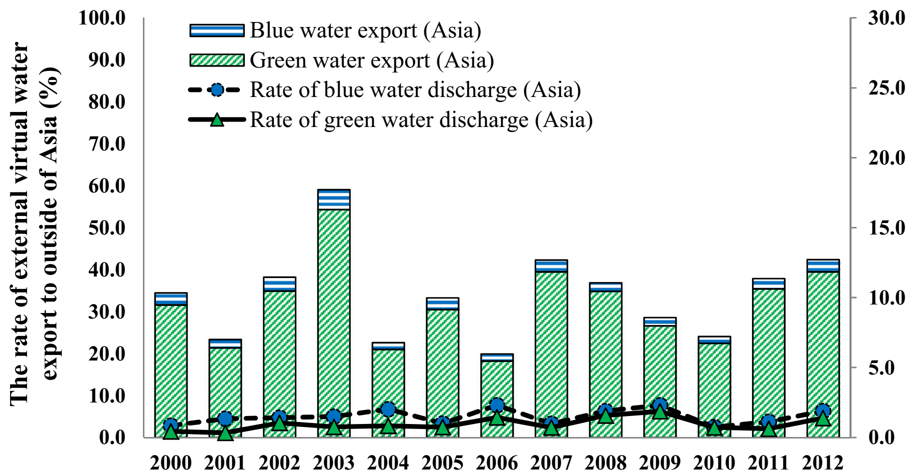
estimate of the amount of water traded within and outside of the EU. The EU exported approximately 575.1 Gm^3 of green water and 70.1 Gm^3 of blue water. However, only 30.2% of the total green water exports and 25.2% of the total blue water exports were discharged to non-EU countries via crop trade. This contrasts with the case of Asia, where most blue water was shared with the EU, suggesting that integrated water management is more applicable in the EU than in Asia. The largest discharge of virtual water was derived from the barley and wheat trade, but in 2012 the external virtual water rate was about 40% (Fig. 1). In addition, in 2000 the external virtual water rate from barley was over 60%, but in 2012 it decreased to 40%, and in 2012 the external virtual water rate by rice, maize, and soybeans trade was less than 20%.

Figure 3 shows the amount of virtual water export and the external virtual water rate in the EU from 2000 to 2012, and the total virtual water export increased slightly, but the external virtual water rate of less than 40% was maintained. In the case of the barley, rice, and wheat trade, the total water export increased from 31 Gm^3/year in 2000 to 48 Gm^3/year in 2012, but the green and blue water discharge decreased to 38% and 25%, respectively. This suggests that in this period, the internal trade within the EU increased, and the water resources were used for residents in the EU. While from 2000 to 2012 the virtual water export via the maize and soybean trade increased, the external virtual water rate during the same period remained more or less constant, although it was less than 15%.

Fig. 2 Total and external virtual water export in Asia from 2000 to 2012. **a** Barely, rice, and wheat, **b** Maize and soybeans



(a) Barely, rice, and wheat



(b) Maize and soybeans

External virtual water rate of main exporters in Asia and the EU

Table 3 and Fig. 4 show that the results of green and blue water discharge by crop exports vary depending on the Asian country. During 2000–2012, Kazakhstan showed the highest external virtual water rate of 71.0%, exporting 187.0 Gm^3 of virtual water through five crops (Table 3), and exporting 133.2 Gm^3 of virtual water to European and African countries including the Russian Federation, Tunisia, and Egypt (Fig. 6). In Asia, Thailand, India, and Pakistan dominated virtual water export through the rice trade. From 2000 to 2012, Thailand exported approximately 110.7 Gm^3 (green water) and 22.8 Gm^3 (blue water) of virtual water to non-Asian countries, while 44.5% of the total virtual water export was traded within Asia via crop trades, such as barley, rice, wheat, maize, and soybeans. Pakistan exported approximately 78.9 Gm^3 of blue water, and discharged approximately 46.6% of blue water. These results show that a large amount of water resources were discharged outside of Asia via crop trade in Kazakhstan, Thailand, and Pakistan. It is thus important to consider an integrated water plan for sharing and conserving water resources in Asia.

In contrast, the external virtual water rate of maize and soybeans, which are usually used for feed crops, remained at a low level in Asia, because these crops produced in Asian countries were mainly exported to other Asian countries. During 2000–2012, for example, Asia exported 117.8 Gm^3 virtual water through the maize trade, while China and India exported 107.3 Gm^3 (91%). China exported 55.7 Gm^3 virtual water through the maize trade, and exported 37.1 Gm^3 (67%) to East Asian countries, such as Korea and Japan, followed by Southeast Asian countries (14.2%), such as Malaysia and Indonesia. India showed a 23.0% external virtual water rate, and exported approximately 32.6 Gm^3 of green water and 11.0 Gm^3 of blue water to Asian countries, such as Malaysia, Bangladesh, and Vietnam. The external virtual water rate indicates the virtual water trade from Asian to non-Asian countries. Therefore, for Asian exporters, the external virtual water rate for maize and soybeans export was lower than for

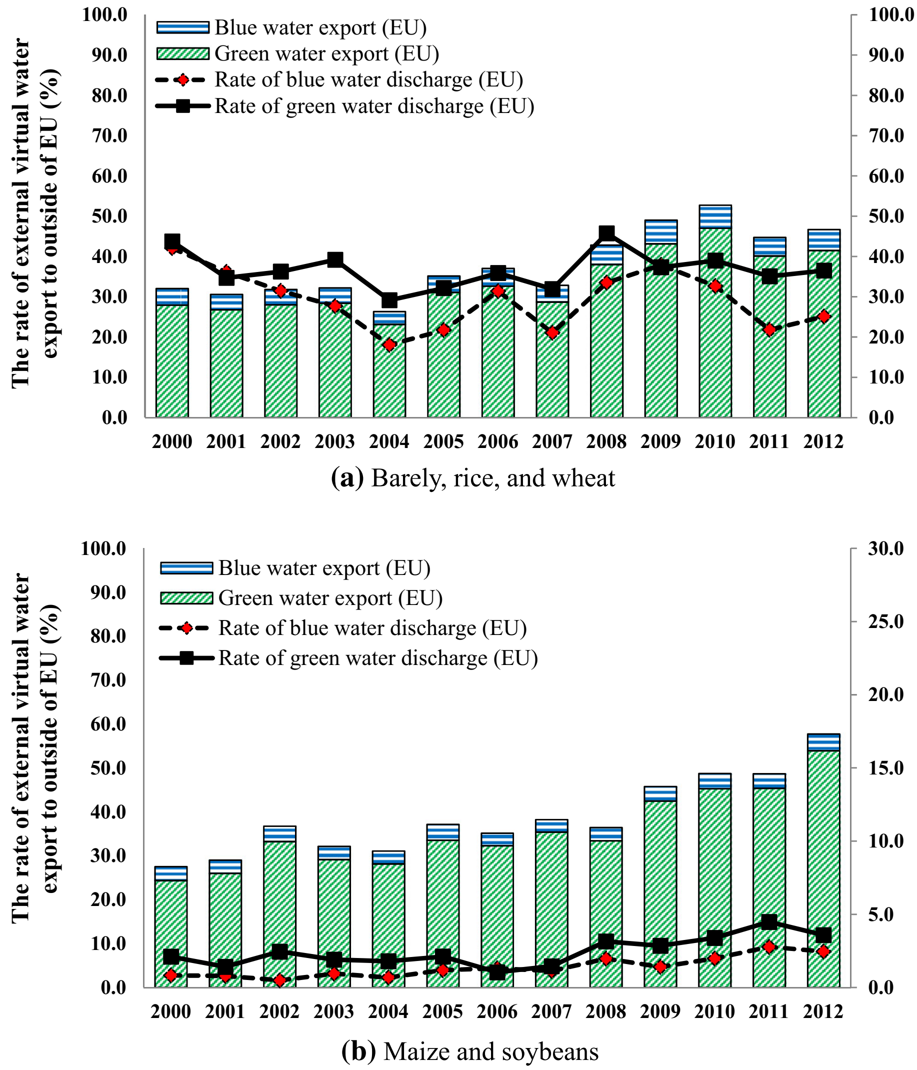
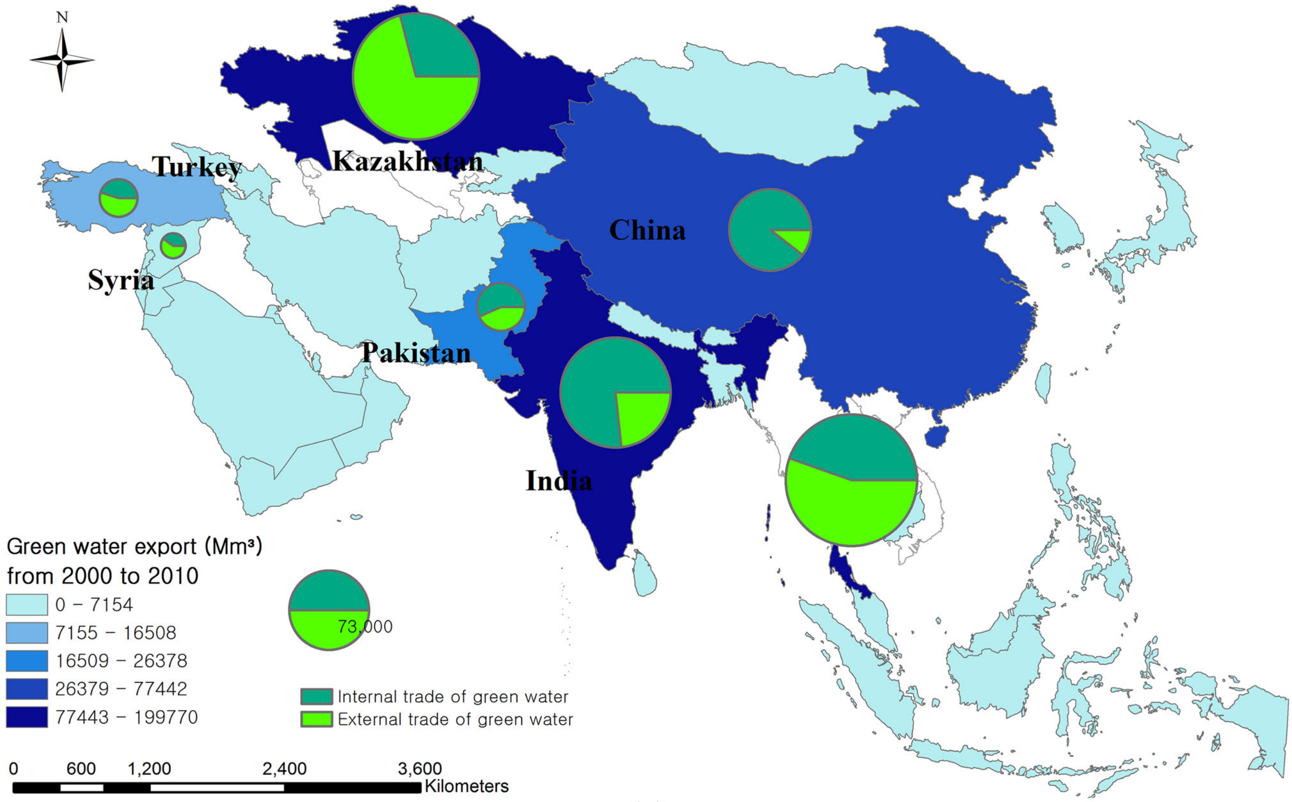


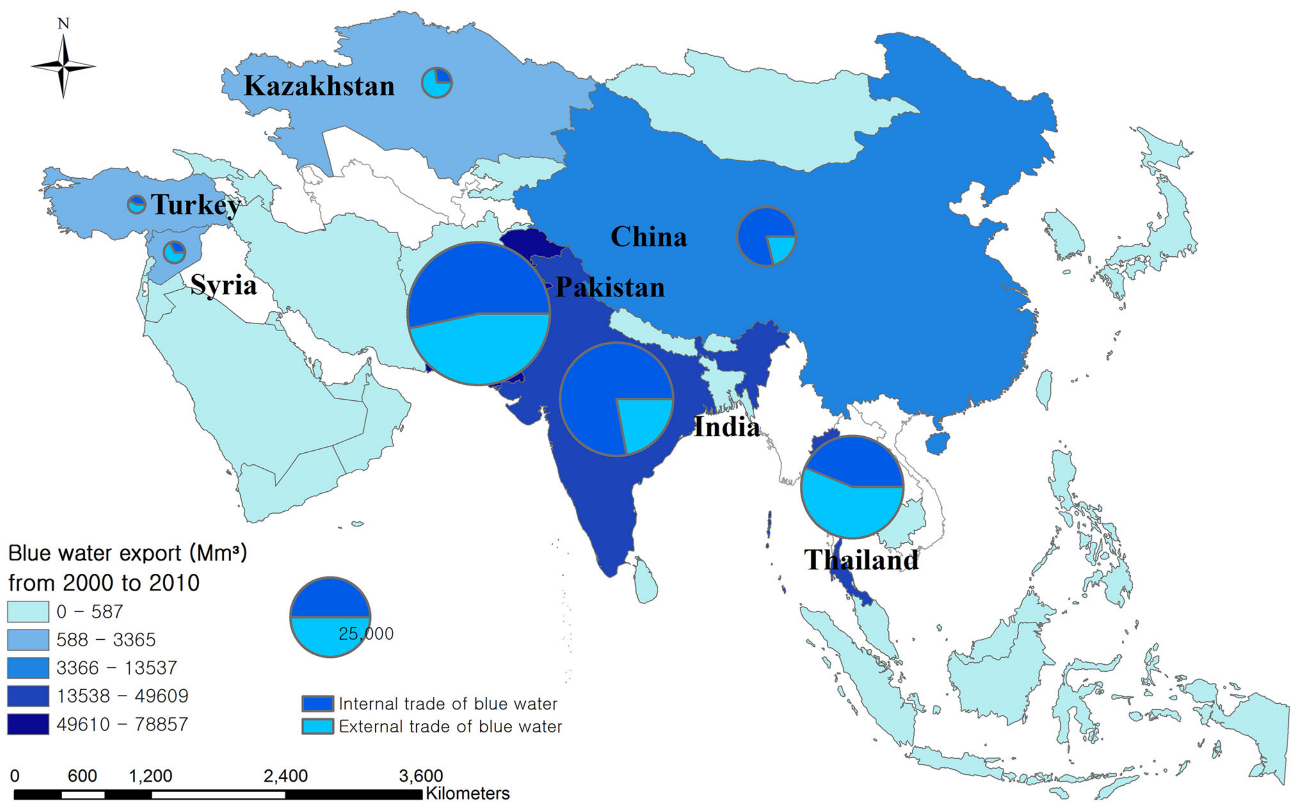
Fig. 3 Total and external virtual water export in the EU from 2000 to 2012. **a** Barely, rice, and wheat, **b** Maize and soybeans

Table 3 Internal and external virtual water export in the main Asian exporters via barley, rice, maize, soybeans, and wheat, traded from 2000 to 2012

Countries (Asia)	Internal VWT in Asia (Gm^3)			External VWT in Asia (Gm^3)			External rate (%)
	Green water	Blue water	Total water	Green water	Blue water	Total water	
Thailand	89.1	17.7	106.8	110.7	22.8	133.5	55.5
India	107.6	38.6	146.2	32.6	11.0	43.6	23.0
Kazakhstan	53.6	0.9	54.5	130.9	2.5	133.4	71.0
Pakistan	14.9	42.1	57.0	11.5	36.8	48.3	45.9
China	68.9	10.7	79.5	8.1	2.9	11.0	12.2
Turkey	7.4	0.5	7.9	9.1	0.7	9.7	55.1
Syria	2.9	0.6	3.4	4.3	1.2	5.5	61.5
UAE	1.9	0.5	2.4	0.2	0.0	0.2	7.7
Georgia	0.1	0.0	0.1	1.9	0.1	2.0	94.5
Iran	1.1	0.5	1.6	0.1	0.1	0.2	10.4


N
Kazakhstan
Turkey
China
Syria
Pakistan
India
Green water export (Mm³)
from 2000 to 2010
0 – 7154
7155 – 16508
16509 – 26378
26379 – 77442
77443 – 199770
73,000
Internal trade of green water
External trade of green water
0
600
1,200
2,400
3,600
Kilometers

(a)


N
Kazakhstan
Turkey
Syria
China
Pakistan
India
Thailand
Blue water export (Mm³)
from 2000 to 2010
0 – 587
588 – 3365
3366 – 13537
13538 – 49609
49610 – 78857
25,000
Internal trade of blue water
External trade of blue water
0
600
1,200
2,400
3,600
Kilometers

(b)

◀**Fig. 4** Internal and external export of green and blue water via five crops traded (barely, rice, maize, soybeans, and wheat) in Asia from 2000 to 2012. **a** Green water export, **b** Blue water export

other crops. In addition, China and India contributed more water resources to Asian countries than to non-Asian countries.

Table 4 and Fig. 5 show the results that the external virtual water rate by crop exports to non-EU countries also varied depending on the EU country. Of the top ten EU exporters, only Romania showed an external virtual water rate of over 50%. Romania is located in the eastern part of the EU, and close to Middle East Asia, where the main food importers are located. Therefore, Romania has a trade network with various countries, including Asian and African countries. During 2000–2012, for example, Romania exported 38.1 Gm^3 virtual water, and 23% of the total virtual water export flowed into Turkey, Egypt, Saudi Arabia, and Syria, which are non-EU countries.

Alternately, other EU countries, such as France, Spain, and Italy, have a more intensive trade network with other EU countries than they do with non-EU countries. From 2000 to 2012, France, which is the largest virtual water exporter in the EU, traded only 34.7% of the total virtual water export to non-EU countries. In addition, Germany, which is the largest blue water exporter, showed less than 40% blue water discharge.

Contribution of water resources of Asian exporters to global regions by virtual water export

Water resources can be shared with other countries. If a country located in the upper region of a river consumes a high amount of water without considering the downstream countries that share the same resource, those countries in the lower region may experience water shortages. In this situation, integrated water management among the countries sharing the water resources should be considered. In particular, agriculture uses high volumes of water, and the main exporters use most of this water for export crops. In this study, we quantified the amount of virtual water use for domestic crop products and exports of the main Asian exporters of India, Thailand, Pakistan, and Kazakhstan to each region, such as Asia, Europe, and Africa (Table 5 and Fig. 6).

From 2000 to 2012, the contribution of virtual water from India to other Asian countries was highest via crop trade. About 77.0% of the total virtual water export was traded with Asian countries, consisting of East Asia (5%), South Asia (22%), South East Asia (24%), and Middle East Asia (26%). If India experiences a water shortage problem caused by drought, other Asian countries could be adversely affected. Pakistan also supplied 54.1% of the total virtual water export to Asian countries. In addition, 37% of the total virtual water export was traded with Africa. However, in Pakistan 77.7% of the water resources were supplied from outside the country. Thus, water resource management in Pakistan might be considered in terms of a global issue. Alternately, for Kazakhstan from 2000 to 2012, most virtual water was exported to Europe, and 64% of the total virtual water was exported. Less than 30% of the total virtual water export was traded within Asian countries, and 24% was traded with South East Asia. In the case of Thailand, 42% of the total virtual water export was traded with Africa, while 45% was traded with other Asian countries, namely East Asia (12%), South East

Table 4 Internal and external virtual water export in the main EU exporters via barley, rice, maize, soybeans, and wheat, from 2000 to 2012

Countries (EU)	Internal VWT in EU (Gm^3)			External VWT in EU (Gm^3)			External rate (%)
	Green water	Blue water	Total water	Green water	Blue water	Total water	
France	128.8	9.0	137.8	68.6	0.5	69.1	34.7
Germany	40.3	17.4	57.7	27.4	11.7	39.1	40.5
Netherlands	39.7	3.5	43.2	0.9	0.3	1.2	2.1
Hungary	35.5	0.1	35.6	7.4	0.0	7.4	17.3
Romania	17.2	0.6	17.8	19.8	0.6	20.4	53.5
Bulgaria	21.0	0.3	21.3	10.0	0.2	10.2	32.3
Spain	10.3	4.7	15.0	4.4	0.9	5.2	29.8
UK	15.7	0.2	15.9	2.1	0.0	2.1	11.6
Czech	11.3	4.2	15.5	1.2	0.5	1.6	9.3
Belgium	11.5	4.0	15.5	1.0	0.6	1.6	8.0
Italy	7.0	3.6	10.6	3.4	0.7	4.1	32.8
Lithuania	7.5	0.0	7.6	7.1	0.0	7.1	48.4
Poland	7.5	0.1	7.6	4.3	0.0	4.3	36.6
Latvia	6.0	0.0	6.0	4.0	0.0	4.0	40.0
Denmark	7.4	0.1	7.5	2.4	0.0	2.4	24.1

Fig. 5 Internal and external export of green and blue water via five crops traded (barely, rice, maize, soybeans, and wheat) in the EU from 2000 to 2012. **a** Green water export, **b** Blue water export

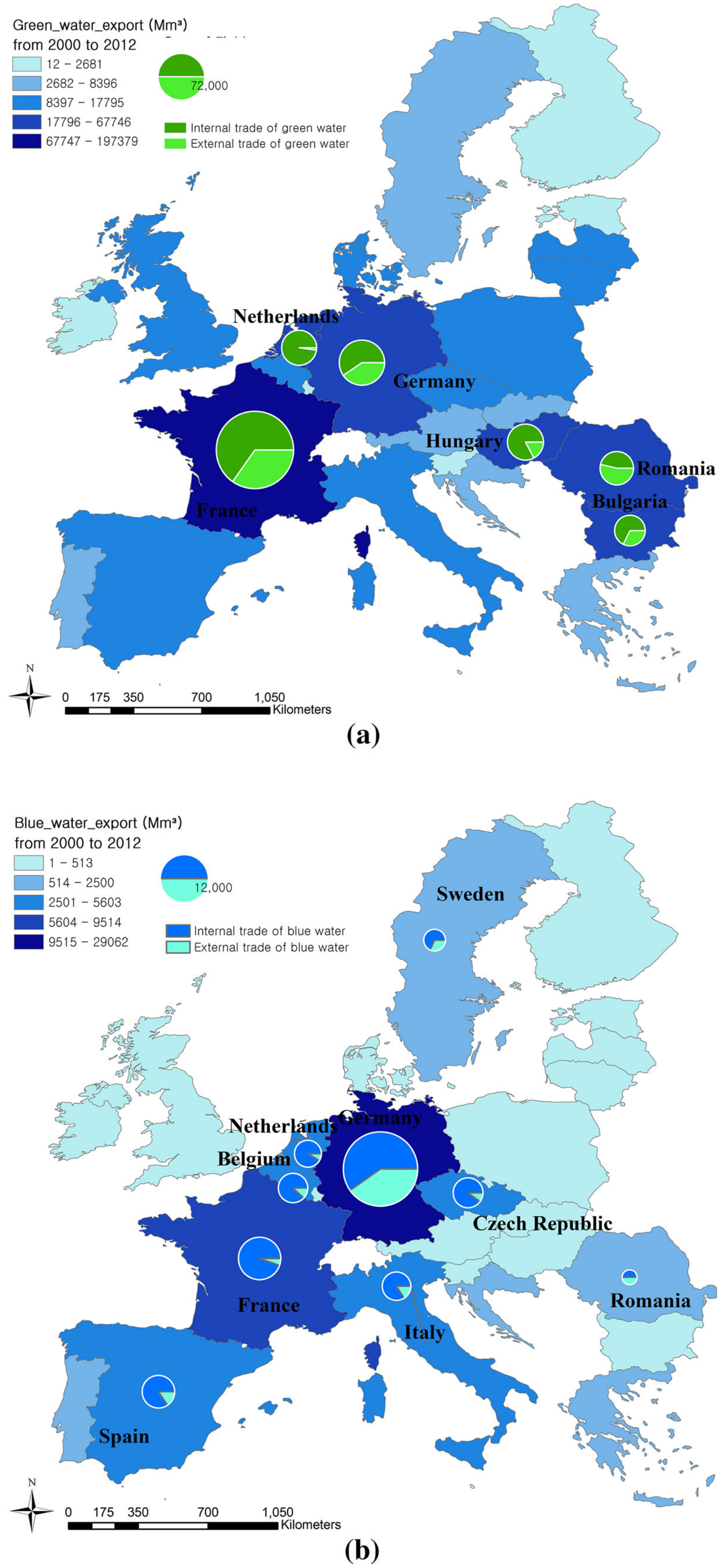


Table 5 Virtual water use for domestic crop products (barley, rice, maize, soybeans, and wheat) and export for the main Asian exporters from 2000 to 2012

Main exporter in Asia	Virtual water use for domestic crop products (Gm^3)			Virtual water export to World (Gm^3)			Virtual water export to non-Asia (Gm^3)		
	Green	Blue	Total	Green	Blue	Total	Green	Blue	Total
India	4143.2	2013.5	6156.7	140.2	49.6	189.8	32.6	11.0	43.6
Kazakhstan	649.1	27.7	676.8	184.5	3.4	187.8	130.9	2.5	133.4
Pakistan	322.0	671.4	993.4	26.4	78.9	105.2	11.5	36.8	48.3
Thailand	797.9	156.5	954.4	199.8	40.5	240.3	110.7	22.8	133.5

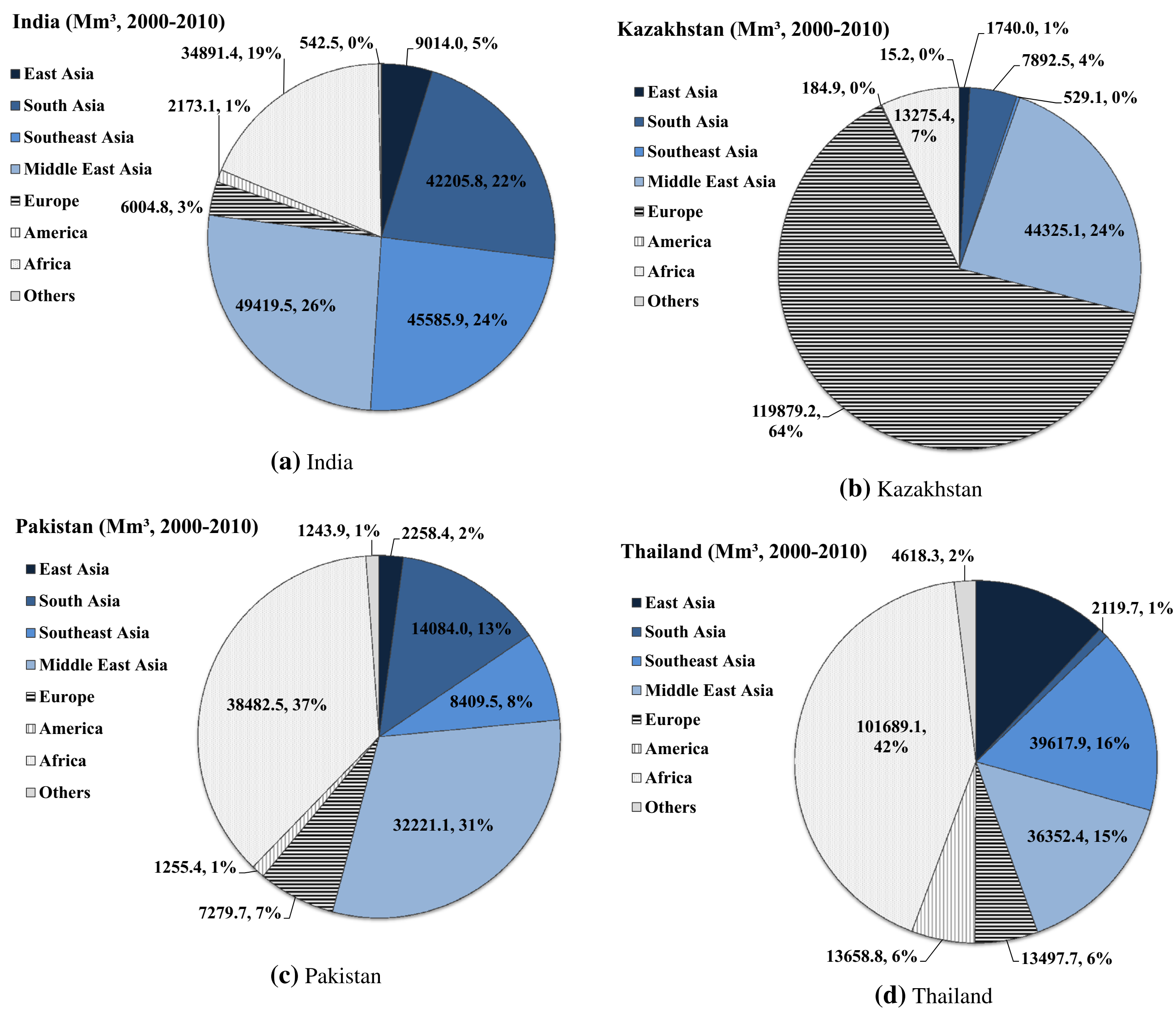


Fig. 6 Virtual water export to global regions for main exporters in Asia from 2000 to 2012

Asia (16%), and Middle East Asia (15%). In addition, for Kazakhstan and Thailand from 2000 to 2012, over 25% of the total virtual water for domestic crop products was exported to the world via crop trade, but these countries obtained over 40% of the total water resources from outside of their own country.

Table 6 Green and blue water imports via five crops traded in Japan, Korea, and Taiwan from 2000 to 2012

Year	Japan		Korea		Taiwan	
	Green water	Blue water	Green water	Blue water	Green water	Blue water
2000	28.9	2.1	14.7	1.2	8.0	0.6
2001	29.7	2.2	14.8	1.1	8.5	0.6
2002	29.0	2.1	16.1	1.3	8.5	0.6
2003	28.4	2.2	16.1	1.5	8.6	0.6
2004	26.4	2.2	14.6	0.9	8.6	0.6
2005	26.7	2.2	15.4	0.9	9.1	0.6
2006	26.7	2.2	14.0	1.0	8.4	0.6
2007	27.1	2.2	14.5	1.4	9.3	0.7
2008	26.8	2.1	12.6	0.9	8.8	0.6
2009	26.5	2.1	14.5	0.7	9.8	0.6
2010	28.0	2.1	15.2	0.9	10.3	0.5
2011	26.2	1.9	15.9	0.9	11.0	0.5
2012	29.9	1.7	20.4	1.6	12.4	0.5
Total	360.2	27.3	198.8	14.4	121.3	7.7

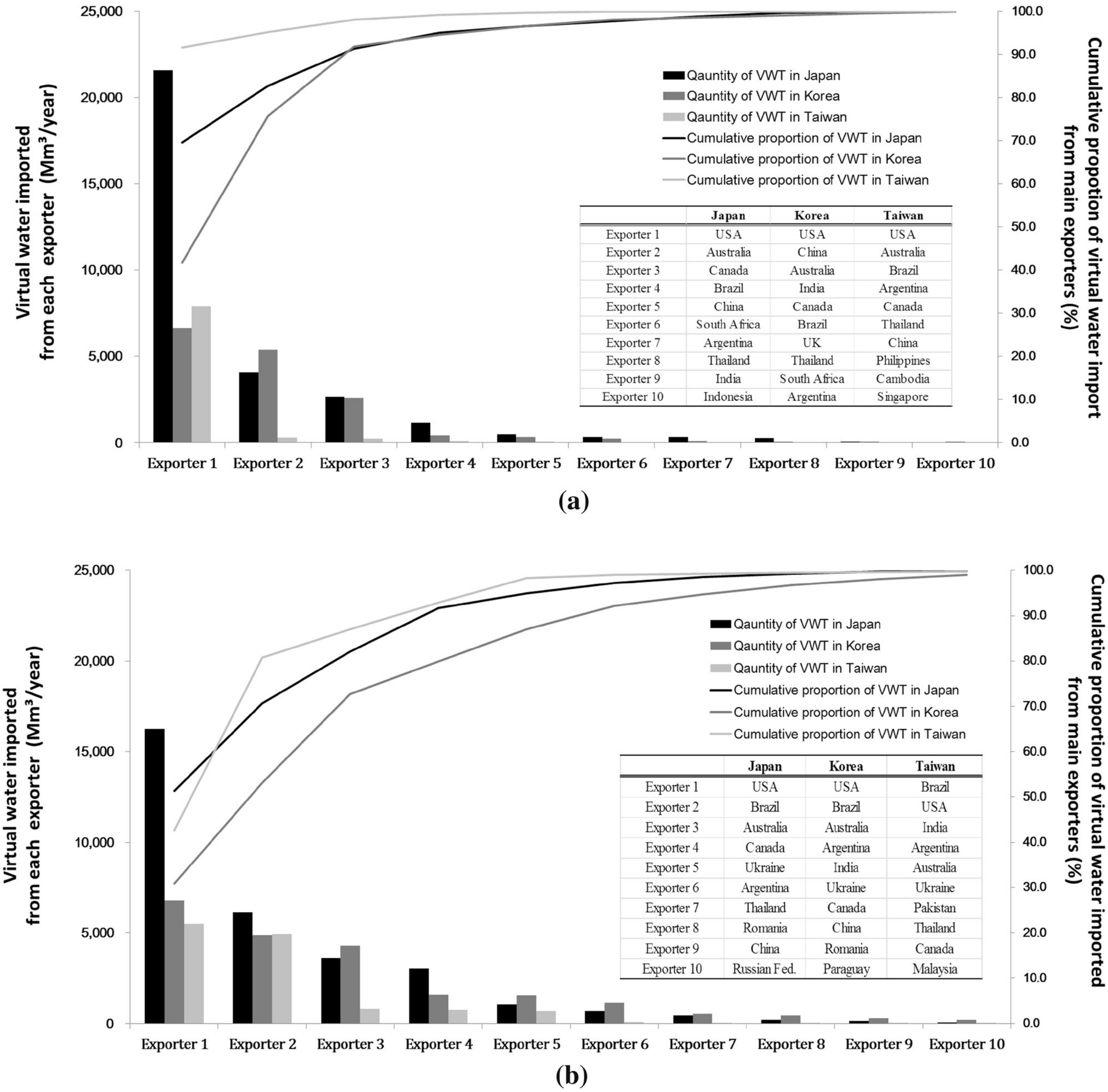
Virtual water dependency of Korea, Japan, and Taiwan on exporters

The characteristics of the main importers could affect the total virtual water trade structure in Asia. The main importers of crops in Asia were Korea, Japan, and Taiwan; their trade structures are related to the exporter's water resources in terms of the virtual water trade. For example, main importers that are connected to a few exporters are susceptible to the circumstances of the exporters, such as drought and climate change.

In this study, we estimated the amount of virtual water imports in Korea, Japan, and Taiwan, and evaluated the virtual water dependency on their exporters. We estimated how many exporters are related to the virtual water trade, and calculated the portion of each exporter in the entire virtual water import. Table 6 shows the amount of green and blue water imports from 2000 to 2012 in Japan, Korea, and Taiwan. Japan imported the largest amount of virtual water via the crop trade, and for this period the amounts of total virtual water imports by crops were 360.2 Gm^3 green water and 27.3 Gm^3 blue water. Korea in the same period imported 198.8 Gm^3 green water and 14.4 Gm^3 blue water in the form of crops (wheat, rice, barley, maize, and soybeans) traded. In comparison to Korea and Japan, Taiwan imported the smallest amount of virtual water. The total amount of virtual water imported via trade crops was 128.9 Gm^3 (121.3 Gm^3 green water and 7.7 Gm^3 blue water). Recently, the virtual water imports in Korea sharply increased in comparison to Japan and Taiwan. In addition, from 2008 to 2012 the virtual water imports in Taiwan also increased slightly. On the other hand, Japan maintained about 28 Gm^3/year virtual water imports.

In short, these countries are dependent on virtual water imports, making it important to evaluate their dependency on exporters, because an importer connected to only a few exporters could be dominated by the water resources of the exporters. Therefore, we calculated the portion of each exporter to the total amount of virtual water imports (Fig. 7). The results show the amount of water resources contributed by exporters to Korea, Japan, and Taiwan, respectively, and the number of exporters involved in virtual water imports for each of these countries. For Korea in 2000, four exporters provided approximately 90% of virtual water imports, and the USA was the most powerful contributor to virtual water imports. In 2000, approximately 41.7% of virtual water was imported from the USA, followed by China (33.9%) and Australia (16.2%). The water dependencies of Japan and Taiwan are greater than that of Korea. In particular, Japan imports the largest amount of virtual water, importing more than 69% of virtual water from the USA. In 2000, Taiwan was the most dependent on the USA, with more than 90% of virtual water imported from the USA via the crops trade. These countries had a virtual water trade whose structure was highly dependent on a few exporters, i.e., the USA, Australia, and China.

In 2012, the amount of virtual water imports in the three countries increased, and in comparison with 2000, Korea showed the highest increase with expansion of the trade boundary. The USA supplied 41.7% of the total virtual water imports in Korea in 2000, decreasing to 30.9% in 2012. In addition, Korea expanded the virtual water trade in 2012, and six exporters accounted for over 90% of the total virtual water imports. However, Japan and Taiwan were still highly dependent on a few exporters. In Japan in 2012, the water import dependency of virtual water imported from the USA decreased from 69.5 to 51.3%, but four exporters (the USA, Brazil, Australia, and Canada) still supplied over 90% of the total virtual water imports. In 2012, the dependency on the exporters of virtual water imports was extremely high in Taiwan, but the virtual water dependency on the USA decreased from 91.6 to 57.4%, due to its relationship with Brazil. However in 2012, Taiwan still imported over 80% of total virtual water from Brazil and the USA. In conclusion, while in 2012, Japan, Korea, and Taiwan attempted to expand their boundaries of virtual water imports, they still demonstrated a high level of dependency on a few exporters of virtual water. These results indicate that these countries have a vulnerable virtual water trade that could easily be dominated by exporters. Therefore, these countries should extend their virtual water trade boundary to include additional exporters.



(a)

	Japan	Korea	Taiwan
Exporter 1	USA	USA	USA
Exporter 2	Australia	China	Australia
Exporter 3	Canada	Australia	Brazil
Exporter 4	Brazil	India	Argentina
Exporter 5	China	Canada	Canada
Exporter 6	South Africa	Brazil	Thailand
Exporter 7	Argentina	UK	China
Exporter 8	Thailand	Thailand	Philippines
Exporter 9	India	South Africa	Cambodia
Exporter 10	Indonesia	Argentina	Singapore

(b)

	Japan	Korea	Taiwan
Exporter 1	USA	USA	Brazil
Exporter 2	Brazil	Brazil	USA
Exporter 3	Australia	Australia	India
Exporter 4	Canada	Argentina	Argentina
Exporter 5	Ukraine	India	Australia
Exporter 6	Argentina	Ukraine	Ukraine
Exporter 7	Thailand	Canada	Pakistan
Exporter 8	Romania	China	Thailand
Exporter 9	China	Romania	Canada
Exporter 10	Russian Fed.	Paraguay	Malaysia

Fig. 7 The cumulative proportion and total quantity of virtual water imported from main exporters in Japan, Korea, and Taiwan via crop trades in 2000 and 2012. **a** 2000, **b** 2012

Summary and conclusions

The virtual water trade not only generates water savings for importing countries but also represents water "losses" for the exporting countries (Chapagain et al. 2006). In particular, in terms of the virtual water trade, Asian countries are the main sources of global water use for crop supplies. Therefore, Asian countries should consider maintaining a balance between water conservation and their virtual water trade. In this study, we calculated the virtual water exports within and outside of Asia and the EU between 2000 and 2012 in terms of the virtual water trade through wheat, rice, barley, maize, and soybeans. In addition, the contribution of water resources by the main exporters of Asia to global regions was evaluated through virtual water exports. The virtual water trade also related to the main Asian importers of Japan, Korea, and Taiwan and we also evaluated the virtual water dependency of these countries on exporters.

In terms of virtual water trade, Asian and EU countries are the main water resources for the world. However, the external virtual water rate, which refers to the virtual water export outside of a boundary such as Asia or the EU, differed between Asia and the EU. For example, the EU conserved water resources through internal virtual water trade, which indicates the trade within the EU. In contrast, most Asian countries such as Kazakhstan, Thailand, Pakistan, and Turkey contribute more water resources to the world than they consume internally. Although India and China showed low external virtual water rates, which means these countries contributed more water resources to Asian countries than to the world, the average external virtual water rate ratio in Asian countries is still higher than in EU countries. Therefore, an integrated water plan among Asia countries needs to be developed that will maintain the balance in Asia between the internal and external virtual water trade.

The virtual water trade related to importing countries is also high, and when the main exporters have problems with food production, the high dependency of importers on a few exporters could cause food and water scarcity. Therefore, we analyzed the dependency on exporters in the virtual water trade of Japan, Korea, and Taiwan, respectively, because these countries are highly dependent on grain crop imports. For example in 2000, over 90% of total virtual water imports in all three countries were supplied by two exporters, i.e., the USA and Australia. Although in 2012 Japan, Korea, and Taiwan expanded their trade boundaries to include Brazil, Argentina, and India, their high dependency on a few exporters has remained. Therefore, when they set policy for water and food security, these importing countries should consider their high dependency on virtual water imports from a few countries.

These results provide information necessary for the development of an integrated water strategy in Asia, and are expected to inform the main Asian importers regarding the risks of their serious dependency on external water resources in terms of a balance between water and food security. For example, for Thailand, 42% of the total virtual water exports were traded with Africa, and Mekong River is one of main resources in Thailand. However, the Mekong River flows through several Asian countries such as China, Vietnam, Laos, and Cambodia; therefore, virtual water trade in Thailand is also related to water management in these other countries. Because of this, in 1995, Laos, Thailand, Cambodia, and Vietnam established the Mekong River Commission to assist in the management and coordinated use of the Mekong's resources. The virtual water exports within or outside of Asia in each country could therefore be useful information for development of integrated water management.

Acknowledgements The country-scale import and export data of agricultural crops for the years 2000–2012 were obtained from the FAOSTAT (http://faostat3.fao.org/download/T/*/E) by the Food and Agriculture Organization of the United Nations Statistics Division. The data results for this study are freely available by contacting the corresponding author.

References

Aldaya MM, Llamas MR (2008) Water footprint analysis for the Guadiana river basin, value of water research report, vol 35. UNESCO-IHE, Delft

Aldaya MM, Allan JA, Hoekstra AY (2010) Strategic importance of green water in international crop trade. Ecol Econ 69:887–894

Allan JA (1996) Water use and development in arid regions: environment, economic development and water resource politics and policy. Rev Eur Commun Int Environ Law (RECIEL) 5(2):107–115. doi:10.1111/j.1467-9388.1996.tb00258.x

Biewald A, Rolinski S, Camoen HL, Schmitz C, Dietrich JP (2014) Valuing the impact of trade on local blue water. Ecol Econ 101:43–53

Bulsink F, Hoekstra AY, Booij MJ (2010) The water footprint of Indonesian provinces related to the consumption of crop products. Hydrol Earth Syst Sci 14(1):119–128

Chapagain AK, Hoekstra AY (2004) Water footprints of nations volume1: main report, value of water research 16. Delft, UNESCO-IHE

Chapagain AK, Hoekstra AY (2008) The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. Water Int 33(1):19–32

Chapagain AK, Hoekstra AY (2011) The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol Econ 70:749–758

Chapagain AK, Hoekstra AY, Savenije HG (2006) Water saving through international trade of agricultural products. Hydrol Earth Syst Sci 10:455–468

Fader M, Gerten G, Thammer M, Heinke J, Lotze-Campen H, Lucht W, Cramer W (2011) Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. Hydrol Earth Syst Sci 15:1641–1660

Falkenmark M, Lannerstad M (2010) Food security in water-short countries—coping with carrying capacity overshoot, Fourth Botin Foundation Water Workshop

Government office for science (2011) Foresight. The Future of Food and Farming, London

Hanasaki N, Inuzuka T, Kanae Oki T (2010) An estimation of global virtual water flow and sources of water withdraw for major crops and livestock products using a global hydrological model. J Hydrol 384:232–244

Hoekstra AY (2003) Virtual water trade: proceedings of the international expert meeting on virtual water trade, value of water research series no.12, UNESCO-IHE, Delft

Hoekstra AY, Chapagain AK (2008) Globalisation of water: sharing the planet's freshwater resources. Blackwell, Hoboken

Hoekstra AY, Hung PQ (2005) Globalisation of water resources: international virtual water flows in relation to crop trade. Glob Environ Change 15:45–56

Hoekstra AY, Mekonnen MM, Chapagain AK, Mathews RE, Richter BD (2012) Global monthly water scarcity: blue water footprints versus blue water availability. PLoS ONE 7(2):e32688

Ma J, Hoekstra AY, Wang H, Chapagain AK, Wang D (2006) Virtual versus real water transfers within China. Philos Trans Soc B 361:835–842

Mekonnen MM, Hoekstra AY (2011) The green, blue and grey water footprint of crops and derived crop products. Hydrol Earth Syst Sci 15:1577–1600

Molden D (2007) Water for food, water for life: a comprehensive assessment of water management in agriculture. Colombo, ISBN-13:978-1844073962

Orlowsky B, Hoekstra AY, Gudmundsson L, Seneviratne SI (2014) Today's virtual water consumption and trade under future water scarcity. Environ Res Lett 9:074007

Pingali P (2006) Westernization of Asian diets and the transformation of food systems: implications for research and policy. Food Policy 32:281–298

Rosegrant MW, Sombilla MA (1997) Critical issues suggested by trends in food, population, and the environment to the year 2020. Am J Agric Econ 79(5):1467–1470

Schyns JF, Hoekstra AY (2014) The added value of water footprint assessment for national water policy: a case study for Morocco. PLoS ONE 9(6):e99705

van Oel PR, Mekonnen MM, Hoekstra AY (2009) The external water footprint of The Netherlands: geographically-explicit quantification and impact assessment. Ecol Econ 69(1):82–92

Wang Z, Huang K, Yang S, Yu Y (2013) An input-output approach to evaluate the water footprint and virtual water trade of Beijing, China. J Clean Prod 42:172–179

Yang H, Wang L, Abbaspour KC, Zehnder AJB (2006) Virtual water trade: an assessment of water use efficiency in the international food trade. Hydrol Earth Syst Sci 10:443–454

Zeng Z, Liu J, Koeneman PH, Zarate E, Hoekstra AY (2012) Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China. Hydrol Earth Syst Sci 16:2771–2781

Zhang C, Anadon LD (2014) A multi-regional input-output analysis of domestic virtual water trade and provincial water footprint in China. Ecol Econ 100:159–172