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Article Title: Savings and losses of global water resources in food-related virtual water trade

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Abstract

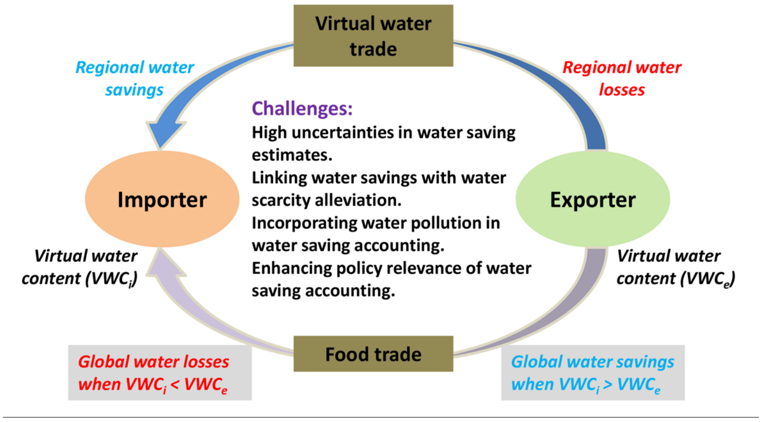
International food trade entails virtual water flows across trading partners. It has been proposed to attenuate regional water scarcity by importing water-intensive commodities from water-abundant regions. In addition to alleviating water scarcity in virtual water importing countries, existing studies have reported that food trade also generates global water savings. However, little is known how these global water savings may alleviate water scarcity, which is more relevant to the sustainable use of water resources than only assessing the savings. In this paper, we conducted a comprehensive review on studies of water savings and losses associated with food trade on different spatial scales.

We found that the concept of global water savings is built on the disparities in water productivity across countries, whereas the regional water savings measure the inflows of virtual water trade. The significance of water savings is dimmed by the fact that the savings are often not driven by water scarcity. Meanwhile, lacking policy relevance impairs the usefulness of water saving accounting. Future studies should link water savings to alleviating water scarcity at various levels. The water saving accounting needs to go to finer scale, e.g., to subnational and river basin scales, to support real water resources management. In the meantime, interdisciplinary efforts are necessary to enhance the water savings as a holistic measure for addressing water scarcity on regional and global scales.

Keywords

global food trade, virtual water trade, water savings and losses, water scarcity

Graphical/Visual Abstract and Caption



Caption

Water savings and losses related to food trade highlight the in- and out-flow of virtual water and differences in water productivities between food importers and exporters. Challenges in accounting for water savings and losses remain and should be carefully addressed.

1 INTRODUCTION

Owing to socioeconomic development, continuously population growth and uneven spatiotemporal distribution of global water resources, our planet is facing great challenges in dealing with water scarcity (Liu et al., 2017a; Oki and Kanae, 2006; Perrone and Hornberger, 2014). It is estimated that over four billion people are currently suffering from severe water scarcity at least one month of a year (Mekonnen and Hoekstra, 2016). Therefore, enhancing water supply and alleviating water scarcity have become critical concerns in many parts of the world (Hoekstra, 2014; Hoekstra and Mekonnen, 2012).

For water scarce regions, importing water-intensive commodities, instead of producing them by using local limited water resources, can be an effective way to compensate for their own water deficiencies. This is called virtual water strategy (Allan, 1993; Allan, 1998). The concept of virtual water has generated a flourishing literature since its inception in the mid-1990s. Many studies have quantified the amount of virtual water exchanged across borders at the global (Carr et al., 2013; Han et al., 2018; Hoekstra and Mekonnen, 2012), regional (Antonelli et al., 2017), intra-country (Faramarzi et al., 2010) and catchment levels (Salmoral and Yan, 2018). Following the introduction of virtual water concept, another similar terminology, water footprint, emerged in the early 2000s (Hoekstra and Hung, 2002). Both, virtual water and water footprint measure the water use for the production of commodities. Water footprint assessment focuses on the whole processes of production or consumption, while virtual water flow analysis is mostly related to international and interregional trade (Yang et al., 2013). In the context of both virtual water and water footprint, water resources and uses have been categorized into blue water and green water (Hoekstra et al., 2011). By definition, blue water refers to surface water and groundwater, green water refers to soil moisture stored in unsaturated zone (Falkenmark 1997; Savenije, 2000). Agricultural irrigation uses blue water. Rainfed production uses green water only. It may be noted here that green and blue water resources are closely related in hydrological systems (Savenije, 2000). The division of blue and green water is to emphasize the different characteristics of the two components. In addition to blue virtual water/water footprint and green virtual water/water footprint, grey virtual water/water footprint is also widely used in the water footprint community (Franke et al., 2013; Hoekstra et al., 2011). Grey water footprint refers to water requirements for diluting pollutants into water bodies to an acceptable water quality standard. Therefore, grey water footprint is on a different dimntion as to green and blue water footprint. It is mainly used to indicate water pollution intensity of production (Liu et al., 2017b).

Falkenmark, M. (1997), Meeting water requirements of an expanding world population, Philos. Trans. R. Soc. Lond. B. Biol. Sci., 352, 929-936, doi: 10.1098/rstb.1997.0072.

Savenije, H. H. G. 2000. Water scarcity indicators; the deception of the numbers Phys. Chem. Earth (B), 25 (3): 199-204. (First part: Color of water, second part: Water scarcity and the deception of the numbers

Through globalisation of products, water resources are also transferring around trading partners globally (D'Odorico et al., 2010; Hoekstra and Hung, 2005). The global virtual water trade was estimated to be as high as 1,700 km^3 yr^{-1} for the period of 1996–2005 (Hoekstra and Mekonnen, 2012) and showed an increasing tendency (Carr et al., 2013; Dalin et al., 2012a). In addition to reducing local water consumption for importing regions, virtual water trade could also play an important role in saving global water resources if trade occurs from regions with higher water productivity, defined as water use per unit of production, to regions with lower water productivity.

The saved water resources are called global water savings (Oki and Kanae, 2004). However, global water savings could be negative, i.e. global water losses, when trade flows from regions with lower water productivity to regions with higher one. Given the fact that global virtual water trade is rapidly increasing, it is important to improve our understanding regarding how virtual water trade saves and costs global water resources.

There is a large number of studies that have quantified global water savings and losses associated with international and/or interregional trade (Dalin et al., 2012a; Konar et al., 2016; Oki and Kanae, 2004; Yang et al., 2006, among others), although the concept of water savings has been debated (Wichelns, 2015). Dalin and Rodriguez-Iturbe (2016) reviewed the impacts of international food trade on water uses and concluded that the influences are mainly beneficial. Also, Hoekstra (2017) and Konar et al. (2013) briefly reviewed studies on water savings related to food trade. However, it is not clear if the saved water contributes to global water stress alleviation. Enhancing the policy relevance of water savings is still facing great challenge. To the best of our knowledge, no studies have systematically reviewed the current water saving accounting and fully addressed the limitations. More importantly, there is no literature that has proposed ways to improve water saving accounting towards global water stress alleviation.

Here, we provide a critical review about the current researches on water savings and losses generated from food trade at the global and regional levels. Food trade is the focus of this review mainly because the largest proportion (~92%) of water is consumed for the production of agricultural products (Hoekstra and Mekonnen, 2012). Following this introduction, we clarify the conceptual bases and calculation methods of water savings and losses on the global and regional scales in Section 2. The current estimations of water savings and losses from the global and regional perspectives are provided in Section 3. Limitations and challenges in the studies of trade related water savings are critically addressed in Section 4. The outlook of future research directions is discussed in Section 5. Finally, Section 6 synthesizes the major findings of this review.

2 CONCEPTUAL BASES AND CALCULATION METHODS OF WATER SAVINGS AND LOSSES ON GLOBAL AND REGIONAL SCALES

The term of water savings/losses associated with food trade can be defined in two dimensions: global water savings/losses and regional water savings/losses.

2.1 Global water savings and losses

The idea that virtual water trade can act as a 'saving mechanism' for global water resources has been introduced in the early 2000s by Oki and Kanae (2004), where they found that the 'real water' use for producing traded product in exporting countries was generally lower than the 'hypothetical water' use assuming the traded products were produced locally by the importing countries. From a global perspective, water savings are the difference between the amount of water used in the exporting country and the amount of water that would have been used in the importing country for producing the same commodity.

Savings can also be achieved when exporters produce under rainfed conditions (with green water), while importers would have needed to rely on irrigation (blue water) to produce the same product (de Fraiture et al., 2004). de Fraiture et al. (2004) argued that only when trade reduces pressure on blue water resources real savings occur, as green water cannot be automatically reallocated to other uses.

Global water savings can be calculated by following equations:

$$GWS_{i,e} = \sum_{p=1}^{n} T_{i,e,p} \cdot (VWC_{i,p} - VWC_{e,p}) \quad \text{(Eq. 1)}$$

where $\mathrm{GWS_{i,e}}$ is the global water savings [m^3 yr^{-1}] associated with food trade between importing region i and exporting region e; n is the number [-] of products considered; $\mathrm{T_{i,e,p}}$ is the amount [ton yr^{-1}] of trade of product p between importing region i and exporting region e; $\mathrm{VWC_{i,p}}$ and $\mathrm{VWC_{e,p}}$ are virtual water content [m^3 ton^{-1}] of product p for importing region i and exporting region e, respectively.

For blue and green water use in agricultural production, VWC can be estimated as:

$$VWC = \frac{WU}{Y} \quad \text{(Eq. 2)}$$

where WU is water use [m^3] and Y is crop yield [ton]. WU generally means evapotranspiration (ET) during the growing season.

For grey water footprint in agricultural production, according to Hoekstra et al. (2011), VWC is calculated as:

$$VWC = \left(\frac{L}{C_{max} - C_{nat}}\right) \cdot \frac{1}{Y} \quad \text{(Eq. 3)}$$

where L is the amount of pollutant loads into water bodies [kg]; $\mathrm{C_{max}}$ and $\mathrm{C_{nat}}$ are the ambient water quality standard for the pollutant [kg m^{-3}] and its natural background concentration in the receiving water bodies [kg m^{-3}].

By definition, both positive and negative values of $\mathrm{GWS_{i,e}}$ could be expected. A positive value of $\mathrm{GWSi.e}$ shows global water savings, whereas a negative $\mathrm{GWSi.e}$ indicates global water losses. For convenience, we use the terminology global water savings to indicate the concept of global water savings/losses.

2.2 Regional water savings and losses

Regarding regional water savings, if the importing amount of a product for a region is higher than its exporting amount, then this region has a net virtual water import, which saves domestic water resources to meet its own food consumption. Regional water savings can be calculated as:

$$RWS_a = \sum_{p=1}^{n} VWC_{a,p} \cdot (T_{net,a,p} - T_{a,p}) \quad \text{(Eq. 4)}$$

where $\mathrm{RWS_a}$ is the regional water savings [m^3 yr^{-1}] for region a; $\mathrm{VWC_{a,p}}$ is the virtual water content [m^3 ton^{-1}] of product p for region a; $\mathrm{Imp_{a,p}}$ and $\mathrm{Exp_{a,p}}$ are amounts [ton yr^{-1}] of imported and exported product p for region a, respectively. Similar to global water savings, value of RWS could also be positive and negative. A positive $\mathrm{RWS_a}$ indicates water savings of region a, while a negative

RWS_a denotes regional water losses. Consistent with global water savings, we also use the terminology of regional water savings to indicate the concept of regional water savings/losses.

2.3 Comparison between global and regional water savings/losses

An illustration of global and regional water savings associated with wheat trade between water abundant country France and water limited country Morocco is presented in Figure 1. Morocco imported wheat from France, therefore Morocco generated regional water savings while France lost part of its local water resources to produce the exported wheat. As France produced wheat with high water productivity (i.e. lower virtual water content) for blue water, green water, and grey water compared to Morocco, hence, wheat exporting from France to Morocco also led to global water savings.

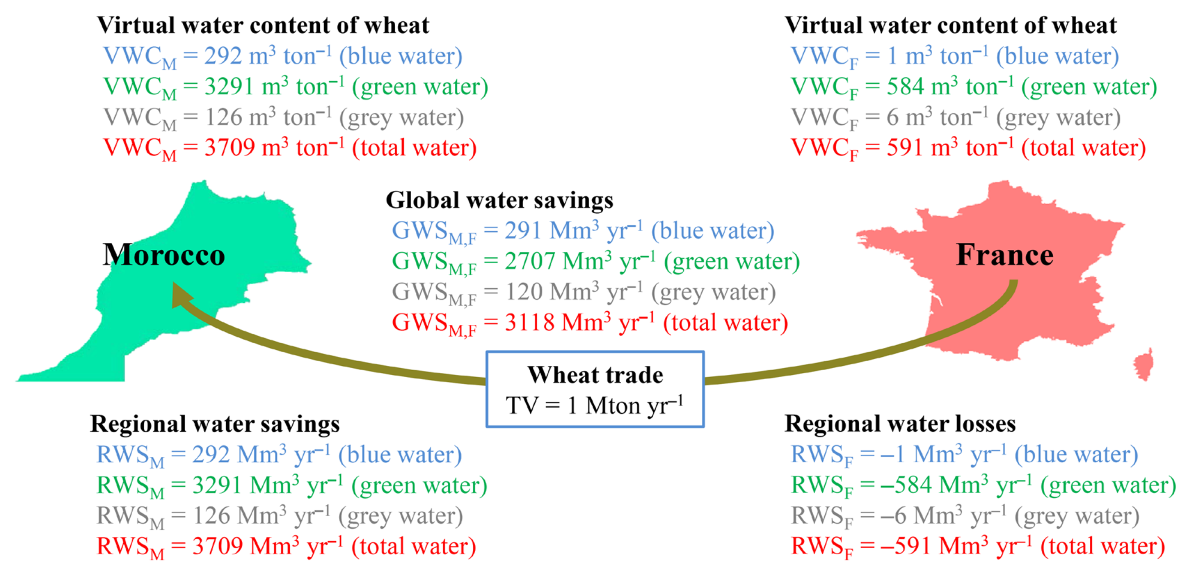


FIGURE 1 Illustration of global and regional water savings associated with wheat exporting from France to Morocco for the period of 1996–2005. Data are from Mekonnen and Hoekstra (2010). VWC_M and VWC_F are virtual water contents for producing wheat in Morocco and France, respectively; T is trade volume of wheat from France to Morocco; $GWS_{M,F}$ is global water savings due to wheat trade from France to Morocco; RWS_M and RWS_F are regional water savings of Morocco and France, respectively.

It should be highlighted here that global water savings and regional water savings differ not because of research scale but due to source of savings. Regional water savings are just the net virtual water importing, while global water savings are generated due to the difference in water productivity between importing and exporting regions. Therefore, only global water savings are real savings of global water resources. By definition, regional water savings and global water savings present quite different perspectives of water savings. First, global water savings are not limited to virtual water trade on a global scale; trade between two regions can also generate global water savings. Second, global water savings are achieved considering all trade partners in a virtual water trade network, whereas regional water savings are only for one region or country. Third, the sum of regional water savings and losses for a trade network will get the result of global water savings/losses.

From Eq. 1 and Eq. 4, it is clear that three items determine the accounting of global and regional water savings, i.e. products considered, virtual water content, and the amount of trade. Food products considered in virtual water trade studies generally include cereal crops, oil crops, sugar, vegetables, fruits, and livestock, etc. However, due to data availability and focus of interests, different crop types and different crops in each type were often used for analysis. As for virtual water content accounting, Yang et al. (2013) made the first effort to give a comprehensive review in terms of the most commonly used methods for estimating virtual water content. Two groups of approaches were categorized in their review: bottom-up and top-down (Feng et al., 2011). Bottom-up approach includes 'rule of the thumb' (Liu et al., 2007c), 'crop modelling' (Liu et al., 2018c), and 'life cycle assessment' (Ridoutt and Pfister, 2010), while top-down approach considers 'input-output' (Zhang et al., 2012) and 'multi-region input-output' (Zhao et al., 2015). Information of amount of trade is generally derived from the FAOSTAT database (http://www.fao.org/faostat/en/#home) at the national level, that's why most of virtual water studies were conducted at national level and Chapagain et al. (2006) defined regional water savings directly as 'national water savings'.

3 GLOBAL AND REGIONAL WATER SAVINGS AND LOSSES ASSOCIATED WITH FOOD TRADE

3.1 Global water savings and losses

Global water savings and losses associated with food trade have attracted much attention (Dalin and Rodriguez-Iturbe, 2016), as these water savings are associated with beneficial gains on global water productivity. Therefore, this review mainly focuses on studies of global water savings and losses. A detailed literature review of global water savings and losses is presented in Table 1.

The first study on global water savings was conducted by Oki et al. (2003). In their study, the global water (including blue and green water) savings associated with trade of 5 crop products and 3 livestock products were estimated to be 455 km^3 yr^{-1} in 2000. However, this study is largely limited by the approach for estimating virtual water content, as it simply assumed constant daily crop water demand, i.e. 15 mm day^{-1} for rice and 4 mm day^{-1} for maize, wheat, barley, and soybean, across the whole world. Following the study conducted by Oki et al. (2003), many researchers reported their findings with respect to global water savings derived from food trade. These later studies generally enlarged the number of crops included (e.g. 285 crop products and 123 livestock products were included in Chapagain et al. (2006)), and improved the ways for estimating virtual water contents (e.g. a GIS-based crop model was developed for simultaneously estimating crop yields and crop water requirements in Liu et al. (2007a)), and emphasized whether the savings are blue water or total water use (e.g. de Fraiture et al., 2004). Some also addressed the blue and green virtual water in terms of opportunity costs (Yang et al., 2006) and highlighted the significance of research scales (Dabrowski et al., 2009a). The study conducted by Mekonnen and Hoekstra (2011) presented a comprehensive investigation on water saving accounting. They used a water balance model to estimate global crop water requirements at a high spatial resolution of 5 arc minutes. Detailed information on global water savings with respect to three components of water, i.e. blue water, green water, and grey water, was firstly presented in their study. The datasets produced in their study provide basis of virtual water calculation for many following studies. Dalin et al. (2012a) provided the first attempt to use the H08 model to estimate historical virtual water content

(Hanasaki 2016) and demonstrate the evolution of global water savings for a long time period of 1986–2007, while most water saving studies focused on only a specific time point or an average over a time period (Table 1). The global water savings were found to have a faster increasing trend than the rising trend of virtual water trade volume; global water savings represented 18% of the global virtual water trade volume in 1986 and 42% in 2007, particularly due to wheat and maize trade, and soy trade after 2001 (Dalin et al., 2012a).

Overall, global food trade has saved water resources, including blue water, green water, and grey water (i.e., reduced the total pollution) (Table 1). However, the estimated total global water savings, where major crops were included, presented high variations with a range from 263 $km^3\ yr^{-1}$ (Fader et al., 2011) to 950 $km^3\ yr^{-1}$ (Biewald et al., 2014), mainly due to different numbers of food commodities considered and the selected approaches for estimating virtual water content. For a single crop, the trade of wheat related food commodities saved the most water resources, while the trade of rice was reported to cause global water losses (Konar et al., 2013). However, positive global water savings for rice were recently reported by Liu et al. (2018c). Generally, food trade showed consistent water savings of green water, which is mainly because exporting regions have higher green water productivity (i.e. lower virtual green water content), mostly due to higher nutrient and technology inputs (Yang et al., 2006). However, global water losses were reported in several studies for blue water, especially international and interregional trade associated with China (Dalin et al., 2014; Sun et al., 2013; Zhuo et al., 2016b). Food trade also reduced global grey water footprint because major exporting countries produced food in a cleaner way regarding pollutant loss intensity than their trade partners, but only a limited number of studies explored this aspect (Lamastra et al., 2017; Mekonnen and Hoekstra, 2010).

As water scarcity studies account for mostly only blue water resources (Cao et al., 2017), saving blue water is often regarded as a priority target even with sacrifice on green water. For example, wheat trade between the USA and Egypt lost water resources of green water, because the USA needs much more green water to produce one unit of wheat production than Egypt does (Aldaya et al., 2010). An insightful investigation found that wheat trade between these two countries generated blue water savings, although green water was lost. This trade partnership not only benefits global blue water resources as a whole but is crucial for water scarce country Egypt through importing green water to compensate for local blue water scarcity. Also, in France wheat production is almost entirely based on green water use, while wheat production in Morocco depends on blue water. Therefore, wheat exporting from France to Morocco generated water savings as green water compensates blue water consumption (Figure 1). However, international and interregional food trade patterns were not always flowed in this desired direction, for instance, maize trade among the southern African countries (Dabrowski et al., 2009a) and food trade within China (Sun et al., 2013) saved green water but compromised blue water resources.

Previous studies on global water savings provided useful and informative messages regarding whether food trade enhance global water productivity and which types and what connections of food trade contribute to the most global water savings (Table 1). However, a quantitative investigation of the significance of each type of water savings on reducing water scarcity is lacking. Besides, large uncertainties could be observed in calculation of global water savings. Only few studies (4 out of 28 in Table (1)) explored this important aspect in global water saving accounting.

3.2 Regional water savings and losses

Importing food to a water scarce region can be used as an effective way for attenuating local water scarcity (Porkka et al., 2017). Therefore, regional water savings are more relevant to water scarce regions. Two comprehensive studies (Chapagain et al., 2005; Mekonnen and Hoekstra, 2011) that explicitly explored regional (national) water savings and losses are highlighted here. Chapagain et al. (2005) provided the first attempt to quantify regional water savings and losses due to food trade among 243 countries for a period of 1997–2001. Japan, Mexico, Italy, China and Algeria were reported to save the most water (total of blue and green water) through international food trade, while the USA, Australia, Canada and Brazil lost the most water. Mekonnen and Hoekstra (2011) upgraded the research by Chapagain et al. (2005) to a more recent period of 1996–2005 and also improved the accounting methodology in estimating virtual water content. Another considerable improvement in Mekonnen and Hoekstra (2011) is that blue water, green water, and grey water embodied in food trade were separately considered. Japan, Mexico, and Italy were reported to save the most total water resources (sum of blue, green and grey water), while the USA, Argentina, and Australia had the largest total water losses. In terms of blue water, Mexico, Spain, Japan, presented the largest regional water savings, whereas Pakistan, India, and Australia lost the most blue water resources associated with food exporting.

Besides these two important researches on quantifying regional water savings and losses, there are a large number of studies on investigating regional water savings for individual countries and regions, which were reviewed by Hoekstra (2017). Particularly, Islam et al. (2007) and Oki et al. (2017) quantitatively assessed the effect of virtual water trade on national water scarcity by adding the volume of imported virtual water into national renewable water resources. For food net importing regions, they have trade-related regional water savings. The gains in water resources are locally beneficial, at least in a short term. However, such beneficial gains may induce the potential risks for importing countries on a long term (Porkka et al., 2013), as it is not helpful to improve water productivity in virtual water importing regions (Yang et al., 2006) and water rich counties were projected to likely reduce virtual water export (Suweis et al., 2013).

The major challenges of current studies on regional water savings lie on how to transform these informative accounting into holistic measure for addressing local water scarcity issues, i.e. in which regions and to what extent virtual water importing can attenuate local water shortages (Dalin and Rodriguez-Iturbe, 2016; Islam et al., 2007).

TABLE 1 Literature review of global water savings associated with food trade (presented with an ascending order of the publication year).

Num.	Region	Food products	Time period	Global water savings (km^3 yr^{-1})	Virtual water content accounting	Trade data	Uncertainties studied	References
1[a]	Global	5 crops and 3 livestock	2000	455[4]	Global constant crop water requirement and reported yields	FAOSTAT	No	(Oki and Kanae, 2004; Oki et al., 2003)
2	Global	cereal crops	1995	164[4]; 112[1]	IMPACT estimated ET and reported yields	FAOSTAT	No	(de Fraiture et al., 2004)
3	Global	285 crop products and 123 livestock products	1997-2001	352[4]	Estimated ET based on FAO method and reported yields	FAOSTAT	No	(Chapagain et al., 2005; Chapagain et al., 2006)
4[b]	Global	20 crops	1997-2001	337[4]	Estimated ET based on FAO method and reported yields	FAOSTAT	Yes (±20% of baseline virtual water content)	(Yang et al., 2006)
5	Netherlands-Morocco	285 crop products and 123 livestock products	1997-2001	0.631[4]	Estimated ET based on FAO method and reported yields	FAOSTAT	No	(Hoekstra and Chapagain, 2007)
6[c]	Global	wheat	2000	77[4]	GEPIC estimated ET and yields	FAOSTAT	No	(Liu et al., 2007a)
7[d]	Southern Africa	maize	2003	3.126[4]; -0.066[1]	CROPWAT estimated ET and reported yields	FAOSTAT	Yes (Scale)	(Dabrowski et al., 2009a)
8	UAS-Egypt	wheat	2000-2004	-2.43[4]; 0.79[1]	CROPWAT estimated ET and reported yields	FAOSTAT	No	(Aldaya et al., 2010)
9[e]	Global	wheat	1996-2005	65[5]; 25[1]; 31[2]; **8[3]**	Water balance model estimated ET and reported yields	FAOSTAT	No	(Mekonnen and Hoekstra, 2010)
10	Global	11 plant functional types	1998-2002	263[4]	LPJmL estimated ET and yields	COMTRADE	No	(Fader et al., 2011)
11[f]	Global	97 crop products and 8 animal types	1996-2005	369[5]; 98[1]; 217[2]; **54[3]**	Water balance model estimated ET and reported yields	FAOSTAT	No	(Mekonnen and Hoekstra, 2011)
12[g]	Global	37 crop products and 21 livestock products	1986-2007	50–250[4]	H08 estimated ET and reported yields	FAOSTAT	No	(Dalin et al., 2012a)

Num.	Region	Food products	Time period	Global water savings (km^3 yr^{-1})	Virtual water content accounting	Trade data	Uncertainties studied	References
13	Global	37 crop products and 21 livestock products	1986-2008	52–119[(1)]; 39–105[(2)]	H08 estimated ET and reported yields	FAOSTAT	No	(Konar et al., 2012)
14	Korea	7 cereal crops	2003-2007	7.25[(4)]	Estimated ET based on FAO method and reported yields	Korea Agricultural Trade Information	No	(Yoo et al., 2012)
15	Africa	58 food commodities from 5 crops and 3 livestock	2008	8.7[(4)]	H08 simulated ET and reported yields	FAO	No	(Konar and Caylor, 2013)
16	Global	rice, soy, and wheat	2001	-3.67[(4)] (rice); 18.6[(4)] (soy); 105[(4)] (wheat)	H08 simulated ET and reported yields	GTAP	Yes (Climate and crop productivity)	(Konar et al., 2013)
17	China	maize, rice, and wheat	2009	-7.84[(1)]; 11.47[(2)]	CROPWAT simulation ET and reported yields	Estimated based on supply and demand	No	(Sun et al., 2013)
18	Global	19 crop types and 5 livestock products	2005	949[(4)]	LPJmL estimated ET and yields	GTAP	No	(Biewald et al., 2014)
19	China	17 products derived from 4 crops and 3 livestock	2005	47[(4)] (China global); -3.1[(1)] (China Intra); 5.9[(2)] (China Intra)	H08 estimated ET and CHINAGRO estimated yields	CHINAGRO estimated trade	No	(Dalin et al., 2014)
20	China	cereals, beans and tubers	2010	47.9[(1)]; 10[(2)]	CROPWAT simulation ET and reported yields	Estimated based on supply and demand	No	(Wang et al., 2014b)
21	China-Germany	Crop and livestock products between China and Germany	2008-2010	-0.40[(5)]; -0.019[(1)]; -0.31[(2)]; **-0.075[(3)]**	Water balance model estimated ET and reported yields	Federal Statistical Office of Germany	No	(Jiang and Marggraf, 2015)
22	Southern Africa	47 food commodities from 5 crops and 3 livestock	1986-2011	0-15[(4)]	H08 estimated ET and yields	FAOSTAT	No	(Dalin and Conway, 2016)
23	Global	maize, soy, rice, wheat	2001	~115[(4)]; ~43[(1)]	H08 estimated ET and yields	GTAP	Yes (Climate and trade policy)	(Konar et al., 2016)

Num.	Region	Food products	Time period	Global water savings (km^3 yr^{-1})	Virtual water content accounting	Trade data	Uncertainties studied	References
24	China	grains	2010	58[4]; 48[1]	Water use statistics and reported yields	Estimated based on supply and demand	No	(Sun et al., 2016)
25	China	22 crops	2008	108[4] (China global); 120[4] (China intra); -9[1] (China intra)	AquaCrop etiamted ET and yields	Estimated based on supply and demand	No	(Zhuo et al., 2016b)
26	China-Italy	Top 10 agri-food products between China and Italy	2010-2015	**-0.129[5]**	Water balance model estimated ET and reported yields	Trade statistics for international business development	No	(Lamastra et al., 2017)
27[h]	China	Agricultural sector	2010	-16.1[4]	Water use statistics and economic output	Interprovincial input-output transactions table of China	No	(Zhao et al., 2018)
28[i]	Global	Maize, rice, wheat	1998-2002	104.8[4]; 85[1]	PEPIC estimated ET and yields	FAOSTAT	No	(Liu et al., 2018c)

[1]blue water saving; [2]green water saving; [3]grey water saving; [4]blue and green water saving; [5]blue, green and grey water saving.

[a]first research on GWS; [b]different opportunity costs of blue water and green water were highlighted; [c]a grid-crop model was developed to estimate crop water use and yields for virtual water accounting; [d]scale issue was highlighted; [e]first study providing comprehensive estimation of blue, green, and grey water saving; [f]industrial products were included in the research, but excluded here; [g]first study providing long time evolution of GWS; [h]VWC with input-output analysis is quantified as a unit value of product(m^3/currency); [i]this study is first in literature to investigate the effects of food trade on reducing nitrogen pollution.

Negative values are highlighted with red colour, indicating global water losses; values of grey water GWS are highlighted in **bold**.

4 SHORTCOMINGS IN THE STUDIES OF GLOBAL AND REGIONAL WATER SAVINGS AND LOSSES

4.1 Global water savings do not address the water scarcity

International and interregional food trade leads to a large amount of global water savings in many cases (Table 1). However, global water savings are generated due to differences in productivity rather than water scarcity. Therefore, these informative accountings are difficult to be used directly as relevant strategies for coping with water scarcity, as there is no direct linkage between global water savings and water endowments (Dalin and Rodriguez-Iturbe, 2016). Besides, if importing countries/regions cannot produce the product at all due to climate and other constraints, global water savings should be ignored in such trade links as accounting the associated water savings could be meaningless (Zhao et al., 2018). Furthermore, global water saving accounting could sometimes draw misleading conclusions. For example, several studies have shown that interprovincial food trade in China generated global water savings (Sun et al., 2016; Wang et al., 2014b). This indicates that food trade network in China was conducted in a resource-efficient way. However, many studies concluded that virtual water in China was flowed from the water scarce Northern China to water abundant Southern China (Dalin et al., 2014; Guan and Hubacek, 2007; Wang et al., 2014a; Zhao et al., 2016; Zhuo et al., 2016a). Such food trade patterns in China do not help mitigate water scarcity in the food importing regions, but exacerbate the water stress in the food exporting regions (Zhao et al., 2015). In fact, irrigation in arid and semi-arid regions plays a key role to understand the interlink between water scarcity and productivity. Irrigation in these areas causes water scarcity while it drastically pushes up agricultural productivity. This is the fundamental mechanism to explain why virtual water trade both alleviates and exacerbates blue water scarcity (Liu et al., 2007b; Tuninetti et al., 2015).

As global water savings do not address the water scarcity, the concept of global water savings is being criticized of lacking of policy relevance (Horlemann and Neubert, 2006; Wichelns, 2015). Beneficial global water savings could be further enlarged if we relocate more production to high water productivity regions. However, such relocation would pose challenges on sustainability of virtual water trade (Fader et al., 2011; Yang et al., 2006) due to several reasons: 1) food importers would more rely on exporting countries and it can be more difficult to improve their own water productivity; 2) many poor countries may not be able to import food commodities due to lack of economic power, as elaborated by Oki et al. (2017) and Porkka et al. (2017); 3) expansion of food exporting could result more intensified water scarcity in exporting regions. This is especially so when regional water losses are derived from scarce blue water. In some productive agricultural areas, such as California's Central Valley and High Plains, losses of water resources for virtual water trade have caused overexploitation of aquifer (Marston and Konar, 2017; Marston et al., 2015). Also, virtual water exporting is challenging the sustainability of groundwater resources, particularly in Pakistan and India (Dalin et al., 2017; Gleeson et al., 2012).

Alternatively, investigation on global scarce water savings, in which accounting virtual water content is weighted by water scarcity, could provide more useful information. Weighting virtual water content by water scarcity has been conducted in previous studies on various scales (Feng et al., 2014; Qu et al., 2018; Ridoutt and Pfister, 2010). Regional water savings have been estimated with this concept (Islam et al., 2007; Oki et al., 2017), while global scarce water savings have been rarely investigated. To the best of our knowledge, only one example was found (Zhao et al., 2018). They compared water savings with and without considering water scarcity in China and found that commodity trade for the whole agricultural sector resulted in different water losses. However, the multi-regions input-output analysis approach employed in their study is limited due to its inability to present the detailed information regarding which type of crop trade has a large effect. There is a high demand to deepen the water savings studies in this direction, although the concept of water scarcity weighted virtual water content is still on debate (Hoekstra, 2016; Pfister et al., 2017).

Currently, maintaining groundwater resources, especially non-renewable water, at a sustainable level is facing a great challenge due to growing water demand in water scarce regions, mainly resulting from irrigation for food production (Rodell et al., 2009; Wada et al., 2012). It was estimated that about 290 $km^3 yr^{-1}$ non-renewable groundwater was used for producing global food products in 2010, of which 11% (25 $km^3 yr^{-1}$) of total non-renewable groundwater was embodied in international food trade (Dalin et al., 2017). A similar estimate of food trade induced non-renewable groundwater losses was reported by Hanasaki et al. (2010) to be 26 $km^3 yr^{-1}$. However, until now it is still absent in the literature on quantifying global water savings and losses related to non-renewable water resources. This is mainly because there is great challenge to estimate usage of non-renewable water in the importing regions, as it is particularly difficult to speculate where the crops would be produced in an importing region without food import.

4.2 Missing water pollution in water saving accounting

In the context of international and interregional food trade network, food exporters not only virtually transfer wa ter resources to importing regions, but also retain substantial pollutants (e.g. nitrogen and phosphorus) in their own territories and degrade water quality (Liu et al., 2018c). The environmental externalities of food trade have been showed in many aspects, e.g. nitrogen pollution (Liu et al., 2018c; O'Bannon et al., 2014; Oita et al., 2016; Wan et al., 2016), phosphorus pollution (Liu et al., 2018b; Lun et al., 2018), pesticide pollution (Dabrowski et al., 2009b), and chemical oxygen demand (Zhao et al., 2016). Grey water footprint could be much higher than green and/or blue water footprint if multi-pollutants are considered (Dabrowski et al., 2009b). The growing grey water footprint implies losses of water assimilation capacity and also water resources. It was reported that pollution assimilation capacity has been fully consumed in about two thirds of global river basins only taking nitrogen and phosphorus into account (Liu et al., 2012). The environmental impacts of international food trade were also highlighted in Dalin and Rodriguez-Iturbe (2016). However, the effects of water pollution on global water savings were untouched in their review. Obviously, it is of importance to include grey water footprint for estimating trade effects on saving global water resources. Only a small proportion (4/28) of water saving studies considered grey water (Table 1), mainly due to unavailability of pollutant data. In addition, the methods applied to calculate grey virtual water content is rather simple. For example, Mekonnen and Hoekstra (2011) multiplies nitrogen fertilizer application rates by a constant leaching ratio to estimate pollutant loads to water bodies. Using a constant ratio largely ignores influences of other factors, e.g. precipitation, fertilizer rates, and crop growth condition, on nitrogen leaching (Liu et al., 2016b). There is still a considerable space for improving grey water footprint assessment (Liu et al., 2017b).

4.3 Uncertainties in estimating water savings and losses

4.3.1 Estimation of virtual water content of green, blue and grey components

Several approaches have been applied to estimate virtual water content, which is the most important factor influencing water saving accounting (Table 1). Using different estimation methods can lead to variable results in terms of water footprint and water saving accounting (Feng et al., 2011). Crop models are commonly used to estimate virtual water content (Table 1), e.g. AquaCrop (Steduto et al., 2009), CROPWAT (Smith, 1992), GEPIC (Liu et al., 2007a), H08 (Hanasaki et al., 2010), LPJmL (Fader et al., 2011), and PEPIC (Liu et al., 2016a; Liu et al., 2018c), due to their advantages in simulating crop water use and crop yields simultaneously, therefore estimating directly the virtual water content. However, model parameter- and/or structure-induced uncertainties on virtual water content estimation could be quite high. For instance, the impacts of selection of different potential ET estimation methods on simulating crop–water relations were investigated at the climate zone level by using the PEPIC model (Liu et al., 2016a). High variations of virtual water content were found in a given climate zone by using different potential ET estimation methods (Figure 2). The differences of virtual water content estimation are even larger when comparing among different climate zones. Many other factors, for instance input data (e.g. precipitation), available water content, crop calendar, and maximum yields, could also result in significant uncertainties in virtual water content estimation (Tuninetti et al., 2015; Zhuo et al., 2014). Besides, estimates of crop water use and crop yields could also be significantly different by using different crop models, which have been highlighted by the community of Agricultural Model Intercomparison and Improvement Project (AgMIP) (Müller et al., 2017; Porwollik et al., 2017; Rosenzweig et al., 2014). However, as there is no way to precisely observe virtual water content globally in all agricultural products, the inter-model discrepancy will be less likely converged in a short term. Compared with virtual water content of blue and green components, uncertainties related to grey virtual water content of food products could be even higher but less touched (Liu et al., 2017b).

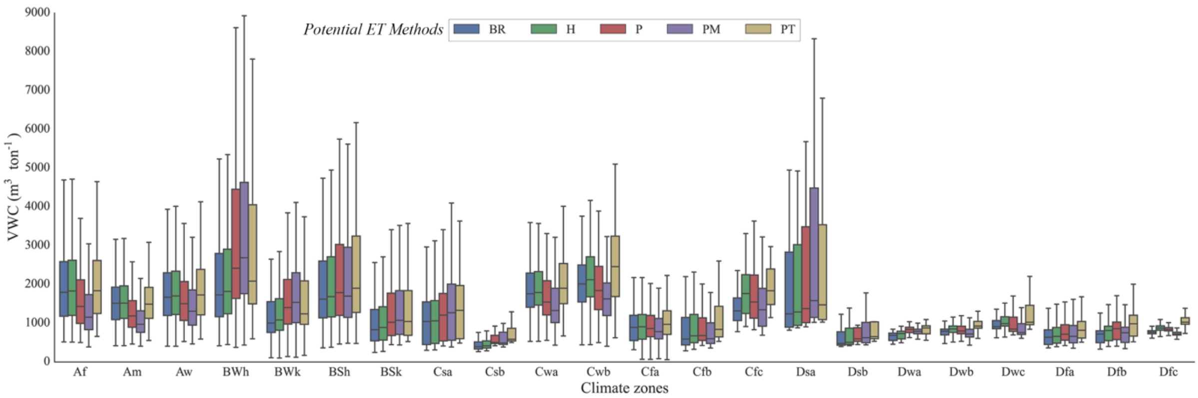


FIGURE 2 Uncertainties of virtual water content (VWC, m^3 ton^{-1}), including blue and green water, of maize associated with selection of different potential evapotranspiration (ET) methods in different climate zones. Graph is modified from Liu et al. (2016a), in where also the potential ET methods and climate zones are defined.

4.3.2 Estimating water savings and losses on finer scales

Another important issue related to estimation of water savings and losses is the scale on which the accounting is aggregated. Virtual water content is particularly sensitive to the selected scale. Most studies in this field estimated virtual water content at a national scale. However, using virtual water content aggregated into a national scale could result in quite different estimations depending on the way how it is aggregated. For example, the total global water savings were estimated to be as high as 949 $km^3 yr^{-1}$ in Biewald et al. (2014), while total global water savings were only 455 $km^3 yr^{-1}$ in Oki and Kanae (2004) and 352 $km^3 yr^{-1}$ in Chapagain et al. (2006). Although it is difficult to directly compare the three different numbers regarding global water savings due to different approaches employed (e.g. models used for accounting virtual water content, number of crops and livestock reported, and research year considered), Biewald et al. (2014) attributed the substantial differences to the possibilities of capturing different regional livestock efficiencies at a finer spatial resolution adopted in their study. Conducting research on a finer spatial scale, especially on a grid scale (Mekonnen and Hoekstra, 2014), is able to provide detail information and should be the future focus (Fader et al., 2011). However, it raises another issue related to food trade data.

In order to derive water savings, bilateral trade information is required. The most detailed and freely available bilateral trade information can be obtained from FAOSTAT at the national level. That is why most studies on water savings were conducted at this level. However, using aggregated information of virtual water content for large countries, for example, China, India, ant the USA, could hide the useful information as elaborated above. Several researchers have estimated water savings associated with food trade at provincial level in China (Dalin et al., 2014; Wang et al., 2014b; Zhuo et al., 2016b). The inter-provincial food trade data were mainly estimated by analysing the difference between food demand and food supply for a province (Ma et al., 2006; Zhuo et al., 2016b). However, these studies contain large uncertainties as they simply assumed that the closest food surplus province as the source region for a given importing province. Another way for estimating subnational food trade can be based on input-output analysis or multi-regional input-output analysis (Guan and Hubacek, 2007; Zhang et al., 2011; Zhao et al., 2015). However, crop-specific information is largely lacking by using these top-down methods. More advanced approaches should be proposed to estimate reliable regional/subnational food trade data and reduce the uncertainties.

5 FUTURE RESEARCH DIRECTIONS OF WATER SAVINGS THROUGH FOOD TRADE

5.1 Exploring water savings contributing to water scarcity alleviation

Given the criticism that water savings, especially global water savings, associated with food trade do not address water scarcity, there is a great need to improving the linkage between water savings and water scarcity at the regional and global levels. This linkage should explicitly demonstrate the extent to which water savings are related to water scarcity mitigation (Islam et al., 2007; Oki et al., 2017). One way is to overlap the regional water saving map on top of a water scarcity map. Only in the water scarce regions (where the scarcity index is over a threshold), we account the water savings or losses. Then it can inform how much water is saved or lost in what degree(s) of scarcity regions. Another way is to explore scarce water savings, in which accounting water savings are weighted by different factors with regard to local water endowments, as has been done by Pfister et al. (2009) and Yano et al. (2015). However, it is still a challenge to determine the reasonable weighting factors, e.g. weighting factors should vary with different water stress levels and for different water sources. A high weighting factor should be given to water savings for water limited regions, while a low factor to water rich regions. The weighting factor may be directly linked to water scarcity. In the estimation of global water savings, the difference of virtual water content among trading partners could be replaced by the difference of scarce virtual water content. That is to say that the original virtual water content is scaled by water scarcity. In this context, both regional and global water savings can reflect the regions where the saved water is more significant and identify the hotspot regions of water savings and losses.

Green water, blue water, and grey water present different properties of water and show different relevance to water scarcity. For example, it is widely discussed that green water has lower opportunity cost than blue water (Aldaya et al., 2010; Yang et al., 2006). Hence, water savings of the three components play varied roles in dealing with water scarcity. In addition to estimating scarce water savings, different weighting factors may be given to savings of the green, blue and grey components for the purpose of strengthening the usefulness of water savings. Future research should focus on proposing reasonable and practical weighting values for the three aspects.

5.2 Expanding global water savings of grey component

Compared with global blue and green water saving accounting, global water savings of grey component are much less studied (Table 1), mainly due to limitations on data availability for assessing grey water footprint. Three items determine the grey water accounting, i.e. pollutant loads, water quality standards, and natural background concentration of investigated pollutant in water bodies (Eq. 3). Therefore, future studies need to collect the data related to these three items, especially those related to pollutant loads. Also other pollutants, in addition to nitrogen and phosphorus covered in previous studies (Liu et al., 2012; Mekonnen and Hoekstra, 2015; Mekonnen and Hoekstra, 2018; O'Bannon et al., 2014), should be considered in estimating grey water footprint. These include, for example, metal, pesticides, among others. State-of-the-art crop models offer high opportunities to take these multi-pollutants into consideration in an integrated system, as they can simultaneously simulate the dynamics of crop growth, nutrient, metal, and pesticides transports. For instance, the PEPIC model was applied to simulate global nitrogen and phosphorus losses at the grid level and then the data are aggregated to different spatial scales (Liu et al., 2016b; 2018b), which facilitates the estimation of grey water footprint (Liu et al. 2017b). Water quality standards for different pollutants should be put forward for different regions by considering local hydrological and ecosystem conditions, as this information is largely absent in many regions, especially in poor countries. More approaches should be proposed and applied to determine water quality standards, e.g. toxicity tests of aquatic species in Canada and the 25th percentile of measured concentrations from surface water in the USA are used to set the nitrate standards (Liu et al. 2017b). Global biogeochemical model could be used to quantify the natural background concentration, e.g. the NEWS model was applied to estimate the background concentration of nitrogen and phosphorus (Liu et al., 2012). Liu et al. (2017b) conducted a comprehensive elaboration on the effects of water quality standards, multi-pollutants, and research scales on grey water footprint accounting and found that these factors could render substantial impacts. Their findings provided a good direction towards improvement on grey water footprint assessment. Still, much effort is needed to enhance the robustness of grey water footprint. Improvements in grey water footprint assessment are crucial for appropriately incorporating the grey water component in global water saving assessment.

5.3 Enhancing policy relevance of water savings through food trade

If importing regions are drier and depend on irrigation for food production, blue water savings have high policy relevance, as this may suggest that rainfed production in the importing regions is more stressed, while exporting regions could use more green water to produce the same commodity. However, accounting of global and regional water savings has so far had little direct linkage with local water resources management, i.e. whether these saved water sources could be allocated to other purposes and how they could address water scarcity. Therefore, future water saving studies should strengthen their policy relevance in order to contribute to the formulation of robust policy decisions on addressing real water management issues (Yang and Zehnder, 2007), e.g. which cropping patterns and trade policies would be more appropriate for alleviating local water stress (Konar et al., 2016), especially for those water scarce but small and poor countries as they are more likely to be exposed to water scarcity vulnerability (Yang et al., 2003). Policies should particularly pay attentions to land investments and land use changes associated with virtual water trade. As for importing regions, importing-induced land use changes may require more water to produce other crops and generate more water pollution. For example, increased soybean importing to China led there to conversion of soybean cropland to maize and rice cultivation, which in turn resulted in increased nitrogen emissions to water bodies (Sun et al., 2018). This extra water pollution increased country’s grey water footprint.

Global and regional water savings should be estimated at a subnational or watershed levels to provide insightful investigation of benefits and tradeoffs of food trade on local water security (Dabrowski et al., 2009a). The lack of subnational trade data and the difficulties in sharing some of the trade data make it difficult to account for water savings and losses on a finer spatial level. To solve this limitation, regional or subnational trade data should be recorded in statistics in the future and available to the public. However, time consumption and expense in collecting such trade data set a major constraint in this direction. Alternatively, regional trade data could be estimated by analysing the drivers and structure of food trade using different approaches, e.g. network analysis (Dalin et al., 2012b; Suweis et al., 2011), gravity law (Tamea et al., 2014; Tuninetti et al., 2017), community structure analysis (D'Odorico et al., 2012), decomposition analysis (Duarte et al., 2016), and economic trade modelling (Liu et al., 2018c). These methodologies provide possibilities to derive regional food trade information.

In addition to the absence of regional data, large uncertainties in water saving accounting also impair the usefulness of this concept for informing robust policy decisions. Possible uncertainties in calculating water savings, resulted from estimating virtual water content and deriving subnational food trade data, should be carefully investigated in the future research, not just a single value as presented in many previous studies.

In addition to food trade, several other mechanisms contribute to water savings, e.g. food losses and waste reductions (Jalava et al. 2016; Kummu et al., 2012; 2017), change in diet (Jalava et al. 2016; Kummu et al, 2017), crop water management (Jägermeyr et al., 2016), and optimizing crop distribution (Davis et al., 2017). Effects of each of the mechanisms on saving water have the same order of magnitude (between 10% and 36% based on D'Odorico et al. (2018) and Kummu et al. (2017)). Therefore, policy makings should also consider combining food trade with other different measures to further enlarge the water savings. However, the discussion on different alternatives for water savings is beyond the scope of this study.

Looking forward, interdisciplinary efforts in improving methodologies regarding virtual water content calculation, collecting and sharing trade and pollution data, and arising awareness of water savings, are greatly necessary to enhance the water savings as a holistic measure for addressing water scarcity on regional and global scales.

6 CONCLUSIONS

Since the inception of the concepts of virtual water trade and the related water savings and losses, a growing number of studies has been conducted to quantify global and regional water savings associated with food trade. However, global water savings and regional water savings present quite different perspectives in water savings. The former is derived from differences in water productivities between food trade partners, while the latter just measures the in-/out-flows of virtual water trade. Many studies demonstrate that international and interregional food trade have saved global water resources. Savings of green water were mostly positive, while savings of blue water exhibited a mixed situation, i.e. there are blue water savings or losses. The conclusion on grey water footprint related savings was still not clear due to limited researches on this aspect.

Water saving accountings so far are highly uncertain (but rarely studied) and do not address water scarcity. These shortcomings impair the usefulness of the water saving concept in water resources management. Also, studies are lacking in quantification of savings of grey water footprint. Future studies should focus on improving sustainability and efficiency of virtual water trade and its associated water savings. Efforts from scientific community are largely required to strengthen the policy relevance of water savings by integrating green water, blue water, and grey water in a consisting system and addressing water scarcity issues at global and subnational levels simultaneously.

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