Advances in Water Footprint Assessment of Agricultural Products: Postprint

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Abstract

Water footprint is an indicator measuring the amount of water resources directly or indirectly consumed by consumers or producers, and has been widely applied in global and regional virtual water trade analysis and research. This paper provides a relatively comprehensive review of research on water footprint assessment of agricultural products at different spatial scales, including global, national, and regional levels. Over the past decade, research on agricultural water footprints has shifted from focusing primarily on the analysis and evaluation of virtual water volumes in global agricultural trade before 2008, to emphasizing detailed accounting studies of direct and indirect water consumption during agricultural production processes at national or regional scales after 2009. Water footprint assessment exhibits significant spatial distribution characteristics; to obtain accurate, comprehensive, and objective information on the water footprint of agricultural production, it is essential to consider factors such as regional geographic features, soil physicochemical properties, climate change, production technologies, and pollutant eco-toxicity. Water resource management decisions should comprehensively incorporate the green, blue, and grey water footprints of agricultural products, as the blue water footprint represents direct consumption of societal freshwater resources and is crucial for international trade policy formulation, while the grey water footprint assessment more explicitly reflects the environmental impacts of agricultural production. Achieving the protection and sustainable utilization of agricultural water resources globally or regionally requires not only improving water use efficiency in agricultural production, but also adjusting agricultural production structures, patterns and directions of virtual water trade in agricultural products, and reducing water waste during product distribution and dietary consumption.

A Review of Water Footprint Assessment for Agricultural Products

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Abstract: Water footprint (WF) is an indicator measuring the direct and indirect water use of consumers or producers and has been widely applied in analyzing global and regional virtual water trade. This paper provides a comprehensive review of water footprint assessment for agricultural products across different spatial scales. Over the past decade, research on agricultural water footprints has shifted from global-scale virtual water trade analysis before 2008 to detailed accounting of direct and indirect water consumption during agricultural production at national or regional scales after 2009. Water footprint assessment exhibits distinct spatial distribution characteristics, necessitating consideration of regional geographic features, soil physicochemical properties, climate change, production technologies, and pollutant ecotoxicity to obtain accurate and comprehensive information on agricultural production water footprints. Water resources management decisions should integrate green, blue, and grey water footprints of agricultural products, as blue water footprints represent direct consumption of social freshwater resources—critical for international trade policy—while grey water footprints more explicitly reflect environmental impacts of agricultural production. Achieving global or regional agricultural water resource protection and sustainable utilization requires not only improving water use efficiency in agricultural production but also adjusting agricultural production structures, patterns, and directions of virtual water trade in agricultural products, while reducing water waste during product distribution and dietary consumption.

Keywords: Agricultural product; Water footprint; Green water; Blue water; Grey water

Introduction

With continuous global population growth and rapid socioeconomic development, human demand for available freshwater resources has increased dramatically, intensifying water supply pressure. Water scarcity has become a bottleneck factor for sustainable human development. Consequently, improving water resource utilization efficiency, optimizing water allocation, and formulating long-term sustainable water use planning decisions—particularly evaluating human water consumption—have become hot research topics among scientists worldwide. The concept of water footprint [1] and its assessment methodology provide practical approaches for accounting water resource utilization and consumption. Although domestic and international scholars still debate whether water footprint assessment can accurately account for water consumption of products or services [2-5], literature retrieval and analysis based on WOS (Web of Science) and CNKI (China National Knowledge Infrastructure) show that since the concept and methodology were proposed in 2002, researchers have conducted extensive studies at global [6-9], national [4,10-13], and regional [14-22] scales on water consumption by producers, consumers, societies, or individuals, as well as sustainable water resource utilization. Despite limited research reports on agricultural product water footprint accounting, studies at different spatial scales have received increasing attention from scientists since 2008. According to water footprint assessment indicators, 91% of global freshwater consumption is used for agricultural production [23], while in Hebei Province—where water resource pressure is most severe in China—96.35% of water consumption is used for agricultural production [19]. Therefore, agricultural production water footprint assessment is crucial for scientifically formulating national or regional water resource management strategies.

As a major agricultural country and one of the world's most water-scarce regions [24], China has seen growing attention from scientists toward water footprint assessment and virtual water trade research for agricultural products [2,18-22]. Since agricultural production is the primary sector of global freshwater consumption and agricultural product yield and quality are significantly affected by water stress [25-26], this paper—based on summarizing domestic and international research status of virtual water trade accounting for grain crops, vegetables, fruits, and other agricultural products—analyzes the validity and importance of agricultural water footprint accounting results at global, national, and regional scales, summarizes limitations of agricultural water footprint assessment methods, and provides future research perspectives.

1.1 Definition of Water Footprint

Water footprint is a volumetric indicator measuring water consumption and pollution [1], specifically referring to the total direct and indirect water resources required for all products and services consumed by a region (a country, area, or individual) within a certain period. Water footprint assessment comprises three components: blue water footprint, green water footprint, and grey water footprint. It includes blue water resources stored in rivers, lakes, wetlands, and shallow groundwater layers (blue water footprint), green water resources stored in unsaturated soil layers and consumed through vegetation evapotranspiration (green water footprint), and “grey water footprint” resulting from pollution.

1.2 Crop Water Footprint Accounting Methods

The water footprint during crop growth includes green, blue, and grey water components. “Green water” consumption refers to total rainwater evapotranspiration in fields during crop growth, while “blue water” consumption refers to evapotranspiration from field irrigation. Agricultural product water footprints are primarily estimated using the Cropwat model [27] or field experimental data based on crop water requirements, growth period precipitation, and irrigation water volume. Green, blue, and grey water footprints consumed during crop growth are estimated through formulas (1)-(3):

$$\mathrm{WF}_{\mathrm{proc,green}} = \frac{\mathrm{CWU}_{\mathrm{green}}}{Y} \quad (1)$$

$$\mathrm{WF}_{\mathrm{proc,blue}} = \frac{\mathrm{CWU}_{\mathrm{blue}}}{Y} \quad (2)$$

$$\mathrm{WF}_{\mathrm{proc,grey}} = \frac{\alpha \times \mathrm{AR}}{(C_{\max} - C_{\mathrm{nat}}) \times Y} \quad (3)$$

where WF_{proc},green, WF_{proc},blue, and WF_{proc},grey represent green, blue, and grey water footprints during crop growth ($\mathrm{m}^3 \cdot \mathrm{t}^{-1}$); CWU_{green} and CWU_{blue} represent “green water” and “blue water” consumption during crop growth—i.e., total rainwater evapotranspiration and irrigation evapotranspiration in fields ($\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$); Y is crop yield ($\mathrm{t} \cdot \mathrm{hm}^{-2}$); AR is fertilizer application rate per hectare ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$); α is leaching rate (proportion of applied chemicals entering water bodies), typically 10%; C_{max} is maximum allowable pollutant concentration ($\mathrm{kg} \cdot \mathrm{m}^{-3}$); and C_{nat} is natural background pollutant concentration ($\mathrm{kg} \cdot \mathrm{m}^{-3}$).

Pollutants typically include fertilizers (N, P, etc.), herbicides, and pesticides. Calculations only consider “wastewater flow” entering freshwater bodies, usually referring to the proportion of applied fertilizers or pesticides entering water bodies from soil. Generally, only the most critical pollutant—producing the largest grey water footprint—needs calculation.

Total green and blue water consumption during crop growth in the above formulas are calculated separately through formulas (4)-(5):

$$\mathrm{CWU}_{\mathrm{green}} = 10 \times \sum_{d=1}^{\mathrm{lgp}} \mathrm{ET}_{\mathrm{green}} \quad (4)$$

$$\mathrm{CWU}_{\mathrm{blue}} = 10 \times \sum_{d=1}^{\mathrm{lgp}} \mathrm{ET}_{\mathrm{blue}} \quad (5)$$

where ET_{green} is green water evapotranspiration (mm); ET_{blue} is blue water evapotranspiration (mm); lgp represents crop growth period length in days; and the constant factor 10 converts water depth (mm) to water volume per unit land area ($\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$).

Crop green and blue water consumption are typically estimated using the crop water requirement method. Based on crop water requirement (CWR, mm) under specific climate conditions, effective precipitation during the same period (Peff, mm), and irrigation requirement (IR, mm), green and blue water consumption are determined using formulas (6)-(8):

$$\begin{aligned} \mathrm{ET}_{\text{green}} &= \min(\mathrm{ET}_c, P_{\text{eff}}) \quad (6) \\ \mathrm{ET}_{\text{blue}} &= \max(0, \mathrm{ET}_c - P_{\text{eff}}) \quad (7) \\ \mathrm{IR} &= \max(0, \mathrm{CWR} - P_{\text{eff}}) \quad (8) \end{aligned}$$

where ET_c is total crop evapotranspiration (mm); CWR is crop water requirement (mm); IR is crop irrigation requirement (mm). Crop water requirement is calculated using the Penman-Monteith model [formula (9)] to estimate reference crop daily evapotranspiration and the crop coefficient method [formula (10)] [28]. Crop irrigation requirement is calculated as the difference between crop water requirement and effective precipitation (i.e., equivalent to crop water deficit). If effective precipitation exceeds crop water requirement, irrigation requirement equals zero. Green water evapotranspiration (rainfall evapotranspiration) is the smaller value between total crop evapotranspiration (ET_c) and effective precipitation (Peff). Blue water evapotranspiration (irrigation water evapotranspiration) equals total crop evapotranspiration minus effective precipitation, with a value of 0 when effective precipitation exceeds crop evapotranspiration.

The Penman-Monteith formula for estimating reference crop daily evapotranspiration is:

$$\mathrm{ET}_{0-\mathrm{PM}} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (9)$$

where ET_0-PM is reference crop daily evapotranspiration estimated by Penman-Monteith ($\mathrm{mm} \cdot \mathrm{d}^{-1}$); (R_n - G) is daily available energy ($\mathrm{MJ} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$); R_n is daily net radiation ($\mathrm{MJ} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$); G is daily soil heat flux ($\mathrm{MJ} \cdot \mathrm{m}^{-2} \cdot \mathrm{d}^{-1}$); γ is the psychrometric constant ($\mathrm{kPa} \cdot {}^\circ\mathrm{C}^{-1}$); Δ is the slope of saturation vapor pressure curve ($\mathrm{kPa} \cdot {}^\circ\mathrm{C}^{-1}$); e_s and e_a are saturation vapor pressure and actual vapor pressure (hPa); T is daily mean temperature (°C); u_2 is daily mean wind speed at 2 m height ($\mathrm{m} \cdot \mathrm{s}^{-1}$); and K_c is crop coefficient.

Under rain-fed agriculture conditions, blue water evapotranspiration during crop growth is 0 (mm), and actual crop water consumption (ET_a) equals green water evapotranspiration (ET_{green}, mm), estimated according to formula (7), while blue water footprint is estimated according to formula (11):

$$\mathrm{WF}_b = \frac{D}{Y} \quad (11)$$

where WF_b is blue water footprint under rain-fed agriculture conditions; D is deep percolation (mm).

Water footprints for crops in protected facilities include blue and grey water components. Water consumption in facilities equals blue water evapotranspiration, which can be calculated based on soil water balance principles [formula (12)]:

$$\mathrm{ET} = I + \Delta W - D \quad (12)$$

where I is irrigation amount (mm); ΔW is change in soil water storage (mm); D is drainage (mm). Generally, protected facilities have flat terrain where surface irrigation runoff is unlikely, so this component is ignored when estimating blue water consumption for protected crops.

2 Current Status of Agricultural Water Footprint Assessment

Water footprint is an indicator measuring direct and indirect water use by consumers or producers and has been widely applied in international and regional virtual water trade analysis. Over the past decade, domestic and international research reports on water footprint assessment (including virtual water trade) have shown rapid growth trends. Based on the WOS database, 3,800 English-language water footprint assessment papers were retrieved from January 1996 to December 2016 [Figure 1a: see original paper]. Based on the CNKI database, 1,436 Chinese-language water footprint assessment papers were retrieved during the same period [Figure 1b: see original paper]. Further classification of retrieved literature showed 240 English papers on agricultural water footprints (6% of all English water footprint literature) and 493 Chinese papers (34.3% of all Chinese literature). Using country-based classification in the WOS database, China' s agricultural water footprint research ranks second only to the United States, accounting for approximately 15.4% [Figure 2: see original paper], indicating that agricultural production and water footprint research has gained widespread attention from Chinese scientists. WOS database retrieval also revealed that agricultural water footprint accounting before 2008 focused primarily on global-scale assessments, emphasizing virtual water trade accounting for crop imports and exports [25]. With increasing impacts of water footprint accounting methods, regional climate characteristics, and local production decisions on agricultural water footprint research, detailed accounting studies at national or regional scales have proliferated since 2009, including long-term field positioning experiments for agricultural water footprint assessment [29]. Zou et al. [30] conducted detailed accounting studies on single or several crops at the national scale in 2010. Overall, although agricultural water footprint accounting research is relatively limited compared to other sectors, it has developed rapidly in recent years.

Global average water footprints differ significantly among agricultural products [1,4,32-36]. Global average water footprints for maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and rice (*Oryza sativa* L.) are 900 $m^3 \cdot t^{-1}$, 1,300 $m^3 \cdot t^{-1}$, and 3,000 $m^3 \cdot t^{-1}$, respectively, while those for chicken, pork, and beef are 3,900 $m^3 \cdot t^{-1}$, 4,900 $m^3 \cdot t^{-1}$, and 15,500 $m^3 \cdot t^{-1}$ [23]. Geographic, climatic, production technology, and yield differences among countries or regions make global average water footprint estimates difficult to reflect actual local conditions. For example, milk water footprint is 1,422 $m^3 \cdot kg^{-1}$ under conventional farming but 1,510 $m^3 \cdot kg^{-1}$ under organic farming [35]. Spain' s pork production and processing water footprint is 19.5 billion $m^3 \cdot a^{-1}$, with green, blue, and grey water footprints accounting for 82%, 8%, and 10% [37], respectively—significantly different from global average accounting methods and values.

2.1 Global-Scale Agricultural Water Footprint

Hoekstra and Hung first conducted global-scale water consumption assessments for major agricultural products in 2002 [1], though this study did not separately account for green, blue, and grey water footprints [25]. Subsequently, Hoekstra' s research team and others conducted a series of global-scale agricultural water footprint studies [1,4,8-9,23,31-36], reporting global agricultural water consumption of 6,390 $Gm^3 \cdot a^{-1}$ during 1997-2001. Crop virtual water consumption is significantly lower than virtual water trade among countries or regions, enhancing water-scarce countries' dependence on water-rich countries, alleviating freshwater depletion in water-scarce regions, and achieving water resource savings globally and nationally [38]. Global water footprints show that 16% originates from external market trade [7], and improving virtual water trade distribution based on embedded product virtual water analysis could save 222 $Gm^3 \cdot a^{-1}$ globally. Water footprint assessments of trade in goods and services between arid/semi-arid countries (Morocco) and humid countries (Netherlands) revealed that international virtual water trade from high water productivity to low water productivity countries could save 6.4$×10ˆ{8}$ $m^3 \cdot a^{-1}$ [10]. However, external virtual water trade also presents disadvantages and risks, including reduced food self-sufficiency, decreased agricultural employment, and increased environmental impacts of export-import production [3].

Water footprints vary considerably among different cropping systems. High spatial resolution studies on major crops show maize has the lowest water footprint (1,222 $m^3 \cdot t^{-1}$), wheat the highest (1,827 $m^3 \cdot t^{-1}$), and rice intermediate (1,644 $m^3 \cdot t^{-1}$), approaching the average for all crops [27,39-40]. Sugar crops and vegetables have relatively low water footprints (200 $m^3 \cdot t^{-1}$ and 300 $m^3 \cdot t^{-1}$, respectively), while fruit trees and oil crops have higher values (1,000 $m^3 \cdot t^{-1}$ and 2,400 $m^3 \cdot t^{-1}$). Legumes, spices, and nuts have the highest water footprints, ranging from 4,000–9,000 $m^3 \cdot t^{-1}$. Global water footprint during 1996–2005 was 9,087 $Gm^3 \cdot a^{-1}$, with green, blue, and grey water footprints accounting for 74%, 11%, and 15%, respectively [41]. Agricultural production water footprint comprises 91% of the global total, with crop production consuming the most water. For example, global average wheat production water footprint is 1,088 $Gm^3 \cdot a^{-1}$, with green, blue, and grey components at 70%, 19%, and 11% [41].

2.2 National or Regional-Scale Agricultural Water Footprint

Recent research has extensively evaluated water footprints of major crops including cotton (*Gossypium hirsutum* L.), rice, and potato (*Solanum tuberosum* L.) at national or regional scales. Cotton production water footprint (including grey water) studies show that 15 major cotton-producing countries have an average water footprint of approximately 9,800 $Gm^3 \cdot a^{-1}$, with the United States having the lowest. Most countries except China and the United States are water-intensive cotton producers. Brazil has relatively low blue water footprints, likely due to abundant green water resources [31].

Crop water consumption accounts for 86% of total water consumption in Indonesia. Using US-EPA (2005) nitrogen standards for grey water footprint calculation, coffee (*Coffea* sp.) has the largest water footprint at 22,907 $m^3 \cdot t^{-1}$ (96% green, 0% blue, 4% grey), followed by cacao (*Theobroma cacao* L.) at 9,414 $m^3 \cdot t^{-1}$ (94% green, 0% blue, 6% grey) [31]. Cassava (*Manihot esculenta* Crantz) has the smallest at 514 $m^3 \cdot t^{-1}$. However, considering cultivation area, rice has the highest water footprint at 3,473 $m^3 \cdot t^{-1}$ (73% green, 21% blue, 6% grey) [31]. Thailand's oil palm (*Elaeis guineensis* Jacq.) average water footprint is 1,063 $m^3 \cdot t^{-1}$, with blue, green, and grey components at 68%, 18%, and 14%, respectively. Oil palm production directly consumes relatively low blue water [42], but has the largest virtual water flow [43]. Dutch coffee and tea [*Camellia sinensis* (L.) O. Ktze.] production and consumption water footprints are 140 $dm^3 \cdot cup^{-1}$ and 34 $dm^3 \cdot cup^{-1}$, respectively [44-45].

UK potato production water footprint averages 75 $m^3 \cdot t^{-1}$ (85% green, 15% blue) [15], Tunisia' s is 260 $m^3 \cdot t^{-1}$ (50% green, 42% blue, 8% grey) [46], Argentina' s is 324 $m^3 \cdot t^{-1}$ (56% green and blue, 44% grey) [47], and China' s sweet potato [*Dioscorea esculenta* (Lour.) Burkill] is 823 $m^3 \cdot t^{-1}$ (59% green, 29% blue, 12% grey) [48]. These variations likely relate to local climate conditions and agricultural management practices. Tomato water footprint research dominates vegetable studies, with Spanish tomatoes averaging 81.3 $m^3 \cdot t^{-1}$, including 7.2 $m^3 \cdot t^{-1}$ grey water footprint [49].

2.3 China' s Agricultural Water Footprint

Recent years have seen numerous studies on agricultural water footprints at China' s national and provincial scales [FIGURE:1b, FIGURE:3], focusing primarily on water resource utilization for grain production in water-scarce regions [14,16-18,20,50-51]. Among CNKI-retrieved agricultural water footprint papers, 63.2% address planting and livestock water footprints and virtual water trade, while 36.8% examine sectoral perspectives. Spatially, provincial/regional studies are most common, accounting for 51.5% [Figure 3a: see original paper]. Overall, 73.5% of studies consider only green and blue water footprints, 14.7% comprehensively account for all three components, while grey water footprint-only studies are relatively rare at 11.8% [Figure 3b: see original paper]. Given China' s severe water shortage, low agricultural water use efficiency, deteriorating agricultural water environment, and serious water waste, agricultural water footprint assessment holds significant scientific importance.

Currently, approximately 67% of China' s agriculture is irrigated [16], with agricultural water consumption accounting for about 70% of total water use [52]. Hebei Province has the highest agricultural water consumption among provincial regions, representing 96.35% of the province' s total water use [19]. Provincial water availability also varies significantly, with Guangdong Province in the south having the most (27.5 billion $m^3 \cdot a^{-1}$) and Qinghai Province in the north the least (2.72 billion $m^3 \cdot a^{-1}$) [14]. During 1998-2000, China' s average grey water footprint was 481.43 billion $m^3 \cdot a^{-1}$, with economic effects being the main factor influencing grey water footprint efficiency changes [53].

Analysis of water footprints for 27 vegetable and animal products shows China' s per capita dietary consumption water footprint is 673 $m^3 \cdot a^{-1}$, primarily influenced by rice and pork products, with food waste adding 18 $m^3 \cdot a^{-1}$ [17]. Therefore, beyond improving water use structure and reducing agricultural water footprints, reducing water waste deserves attention.

Research on China' s major grain crops (wheat, maize, and rice) shows rice has the highest water footprint (1.36 $m^3 \cdot kg^{-1}$) and maize the lowest (0.91 $m^3 \cdot kg^{-1}$) [54]. Rice water footprint approaches the global average (1,325 $m^3 \cdot t^{-1}$) [8] but is significantly higher than South Korea' s (844.502 $m^3 \cdot t^{-1}$) [55] and lower than Indonesia' s (3,473 $m^3 \cdot t^{-1}$) [31]. Considering only green and blue water footprints, grain crops average 57% green and 43% blue [16]. Insufficient precipitation severely affects wheat and maize cultivation and water footprints in the Hetao Irrigation District. However, with improved irrigation efficiency, the district' s blue water footprint decreased from 9.25 $m^3 \cdot kg^{-1}$ in 1960 to 0.79 $m^3 \cdot kg^{-1}$ in 2000 [56]. These studies demonstrate blue water consumption' s significant impact on agricultural water footprints, further confirmed in cereal crop production water footprint research [57-58]. In the Hetao region during 2005-2008, major grain crop production water footprints ranged 1.43-1.67 $m^3 \cdot kg^{-1}$, with grey water footprints at 0.159-0.043 $m^3 \cdot kg^{-1}$, both showing yearly decreasing trends likely due to new water-saving irrigation technology promotion [20]. Although China' s maize water footprint is below the global average, grey water proportions are substantial in some regions, indicating high potential environmental pollution risk. For example, Beijing' s maize production water footprint is 868 $m^3 \cdot t^{-1}$ (48.5% green, 0.5% blue, 51.0% grey) [48], suggesting high potential environmental pollution risk.

In the North China Plain (Hebei, Beijing, and Tianjin), wheat production water footprint is 17.20$×10^{9}$ m^3 (green 3.085$×10^{9}$ m^3, blue 10.25$×10^{9}$ m^3, grey 3.865$×10^{9}$ m^3), and maize production water footprint is 17.31$×10^{9}$ m^3 (green 10.11$×10^{9}$ m^3, blue 2.692$×10^{9}$ m^3, grey 4.509$×10^{9}$ m^3). The total water footprint for wheat and maize production is 2.2 times the available water resources in the North China Plain (15.49$×10^{9}$ m^3 in 2007) [50]. Therefore, adjusting agricultural production structure is crucial for alleviating water resource pressure, beyond merely improving water use efficiency.

Input-output model-based studies on regional water footprint trends show central China has the largest water footprint. Domestic virtual water trade directions differed between 2002 and 2007: southern coastal, central, northwestern, and southwestern regions were net virtual water exporters in 2002, while northeastern, northwestern, and Beijing-Tianjin regions were net exporters in 2007 [59]. During 1992-2008, China annually net-imported approximately 2.0$×10^{9}$ m^3 of virtual water in grain [60].

Beijing, one of China' s most water-scarce cities, has a blue water footprint of 4.498$×10^{9}$ m$^3 \cdot$ a^{-1}, with 51% being virtual water imported from other regions. Beijing' s agricultural product water footprint is 1.524$×10^{9}$ m$^3 \cdot$ a^{-1}, with about 56% from other regions [61]. Beijing' s agricultural grey water footprint decreased 45% from 9.4$×10^{8}$ m$^3 \cdot$ a^{-1} to 5.2$×10^{8}$ m$^3 \cdot$ a^{-1} during 1995-2009 [62]. Therefore, China' s agricultural production should improve water use efficiency and adjust virtual water trade patterns to achieve domestic water savings.

2.4 Fruit Production and Consumption Water Footprint

Currently, limited research exists on fruit production and consumption water footprints. WOS database retrieval found 27 papers from 2009 to present. In South Africa' s Sundays River Valley, citrus (*Citrus reticulata* Blanco) average blue water consumption is 58.7 Mm^3 in normal years and 89.2 Mm^3 in drought years [63]. Life cycle assessment (LCA) studies on citrus and strawberry (*Fragaria* × *ananassa* Duch.) production across countries show China has the highest per-unit-yield citrus virtual water consumption, followed by Spain, Italy, and Brazil, while the United States has the lowest. However, per-area citrus virtual water consumption is similar across most countries (e.g., China and US both ~5,000 m$^3 \cdot$ hm^{-2}). Thus, yield differences primarily explain citrus water footprint variations (China and US yields are 7.5 t $\cdot$ hm^{-2} and 38.7 t $\cdot$ hm^{-2}, respectively). For strawberry production, Spain has the highest per-area water consumption. Although UK and Poland have similar per-area consumption (~2,500 m$^3 \cdot$ hm^{-2}), UK' s higher per-area yield results in lower per-unit-yield water consumption than Poland [64-65]. Australia produces 44,692 t of mango (*Mangifera sylvatica* Roxb.) annually, with average orchard virtual water consumption of 2,298 $m^3 \cdot t^{-1}$. However, serious losses occur during product logistics, causing annual waste of 26.7 Mm^3 green water and 16.6 Mm^3 blue water from production sites to households [66]. Thus, reducing logistics losses is important for alleviating freshwater scarcity.

3 Research Limitations and Prospects

Water footprint assessment results show distinct spatial distribution characteristics. However, lacking detailed spatial geographic information, previous global-scale studies cannot accurately reflect global water footprint changes, exhibiting uncertainty [67] and limiting effectiveness as accurate water resource management indicators [5]. Therefore, future water footprint assessments must provide explicit temporal and spatial information to evaluate human appropriation of water resources and the sustainability and equity of water use. Since green, blue, and grey water footprints have different opportunity costs and impacts, global virtual water trade [68] and production process water footprints should be accounted separately. Additionally, virtual water-based agricultural product water footprint accounting only considers water consumption and pollution volumes, not directly reflecting environmental impacts, while LCA-based agricultural water footprint assessment remains immature and requires further improvement [26,42,69-70].

Most agricultural grey water footprint studies consider only nitrogen (N) leaching (leaching rate = 10%), ignoring phosphorus (P), pesticides, and other pollutants. However, NEWS (global nutrient export from watersheds) model studies on 1,000 river basins show that 2/3 of global rivers have varying N and P pollution levels, with 54% of river pollution exceeding P standards and only 11% exceeding N standards [71]. Future grey water footprint accounting must address reliable regional-scale pollutant discharge data (including N, P, pesticides) and scientific accounting of corresponding water pollution volumes. Furthermore, grey water footprint accounting lacks locally specific maximum allowable concentration indicators, often adopting US-EPA [45 $mg(NO_3\text{-}N) \cdot dm^{-3}$], EPA drinking water standards (TN, 10 $mg \cdot L^{-1}$), or EU [50 $mg(NO_3\text{-}N) \cdot dm^{-3}$] limits. Chinese researchers also frequently use China' s "Groundwater Quality Standard" (GB/T 14848-93) and "Surface Water Environmental Quality Standard" (GB 3838-2002).

Despite significant achievements in China' s agricultural water footprint assessment over the past decade, improvements are urgently needed. First, watershed water compensation and runoff aspects of agricultural water footprints require attention, particularly in regions with severe water scarcity, fragile water ecosystems, and serious agricultural water pollution. Second, LCA-based water footprint assessments for local or regional major agricultural products should be strengthened to enable comparative analysis across products, production stages, and origins. Establishing and improving information databases on production technologies, water-saving measures, pesticides, and fertilizer types for various agricultural products across regions is essential. Additionally, integrated research on carbon, nitrogen, and water footprints throughout agricultural production, trade, and consumption processes should be enhanced to comprehensively and objectively evaluate regional agricultural water use efficiency, sustainability, and environmental impacts.

References

[1] Hoekstra A Y. Virtual water trade: Proceedings of the international expert meeting on virtual water trade[R]. Value of Water Research Report Series No. 12. Delft, The Netherlands: UNESCO-IHE, 2003

[2] Wang Y Y, Wang H X, Cai Y. Calculation and analysis of water footprint in Beijing City[J]. Chinese Journal of Eco-Agriculture, 2011, 19(4): 954-960

[3] Fader M, Gerten D, Thammer M, et al. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade[J]. Hydrology and Earth System Sciences, 2011, 15(5): 1641-1660

[4] Vanham D, Bidoglio G. A review on the indicator water footprint for the EU28[J]. Ecological Indicators, 2013, 26: 1-9

[5] Perry C. Water footprints: Path to enlightenment, or false trail[J]. Agricultural Water Management, 2014, 134: 119-125

[6] Lovarelli D, Bacenetti J, Fiala M. Water Footprint of crop productions: A review[J]. Science of the Total Environment, 2016, 548/549: 236-251

[7] Chapagain A K, Hoekstra A Y. 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[J]. Water International, 2008, 33(1): 19-32

[8] Chapagain A K, Hoekstra A Y. The blue, green and grey water footprint of rice from production and consumption perspectives[J]. Ecological Economics, 2011, 70(4): 749-758

[9] Mekonnen M M, Hoekstra A Y. The green, blue and grey water footprint of crops and derived crop products[J]. Hydrology and Earth System Sciences, 2011, 15(5): 1577-1600

[10] Hoekstra A Y, Chapagain A K. The water footprints of Morocco and the Netherlands: Global water use as a result of domestic consumption of agricultural commodities[J]. Ecological Economics, 2007, 64(1): 143-151

[11] Galli A, Wiedmann T, Ercin E, et al. Integrating ecological, carbon and water footprint into a "footprint family" of indicators: Definition and role in tracking human pressure on the planet[J]. Ecological Indicators, 2012, 16: 100-112

[12] Tian Y H, Zhu D J, Wang H M, et al. Water footprint calculation of China's main food crops: 1978-2010[J]. China Population, Resources and Environment, 2013, 23(6): 129-136

[13] Wang Y B, Wu P T, Sun S K, et al. Impact of virtual water flows of grain on water resources and regional economy in China[J]. Transactions of the Chinese Society for Agricultural Machinery, 2015, 46(10): 208-215

[14] Dong H J, Geng Y, Fujita T, et al. Uncovering regional disparity of China' s water footprint and inter-provincial virtual water flows[J]. Science of the Total Environment, 2014, 500/501: 120-130

[15] Hess T M, Lennard A T, Daccache A. Comparing local and global water scarcity information in determining the water scarcity footprint of potato cultivation in Great Britain[J]. Journal of Cleaner Production, 2015, 87: 666-674

[16] Cao X C, Wang Y B, Wu P T, et al. An evaluation of the water utilization and grain production of irrigated and rain-fed croplands in China[J]. Science of the Total Environment, 2015, 529: 10-20

[17] Song G B, Li M J, Semakula H M, et al. Food consumption and waste and the embedded carbon, water and ecological footprints of households in China[J]. Science of the Total Environment, 2015, 529: 191-197

[18] Cai Z H, Shen L X, Liu J G, et al. Applying input-output analysis method for calculation of water footprint and virtual water trade in Gansu Province[J]. Acta Ecologica Sinica, 2012, 32(20): 6481-6488

[19] Han Y, Yang X L, Chen Y Q, et al. Assessment of water resources in Hebei Province based on water footprint[J]. Chinese Journal of Eco-Agriculture, 2013, 21(8): 1031-1038

[20] Cao L H, Wu P T, Zhao X N, et al. Evaluation of grey water footprint of grain production in Hetao Irrigation District, Inner Mongolia[J]. Transactions of the CSAE, 2014, 30(1): 63-72

[21] Zhang L Q, Zhao X Y, Guo F, et al. Water footprint analysis of different livelihood strategies of farmers in the middle reaches of Heihe River[J]. Chinese Journal of Eco-Agriculture, 2014, 22(3): 356-362

[22] Shi L J, Wu P T, Wang Y B, et al. Assessment of water stress in Shaanxi Province based on crop water footprint[J]. Chinese Journal of Eco-Agriculture, 2015, 23(5): 650-658

[23] Chapagain A K, Hoekstra A Y. Water footprints of Nations, volume 1: Main report[R]. Value of Water Research Reports Series No. 16. Delft, The Netherlands: UNESCO-IHE, 2004

[24] van Oel P R, Mekonnen M M, Hoekstra A Y. The external water footprint of the Netherlands: Geographically-explicit quantification and impact assessment[J]. Ecological Economics, 2009, 69(1): 82-92

[25] Hoekstra A Y, Hung P Q. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade[R]. Value of Water Research Report Series No. 11. Delft, the Netherlands: UNESCO-IHE, 2002

[26] Ridoutt B G, Pfister S. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity[J]. Global Environmental Change, 2010, 20(1): 113-120

[27] Hoekstra A Y, Chapagain A K, Aldaya M M, et al. The Water Footprint Assessment Manual: Setting the Global Standard[M]. London, UK: Earthscan, 2011

[28] Allen R G, Pereira L S, Raes D, et al. Crop evapotranspiration: Guidelines for computing crop water requirements[R]. FAO Irrigation and Drainage Paper 56. Rome: Food and Agriculture Organization, 1998

[29] Lu Y, Zhang X Y, Chen S Y, et al. Changes in water use efficiency and water footprint in grain production over the past 35 years: A case study in the North China Plain[J]. Journal of Cleaner Production, 2016, 116: 71-79

[30] Zou J, Hu J, Yang Y R, et al. Virtual water equilibrium of foodstuff production and consumption in China[J]. Resources and Environment in the Yangtze Basin, 2010, 19(8): 864-869

[31] Chapagain A K, Hoekstra A Y, Savenije H H G, et al. The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries[J]. Ecological Economics, 2006, 60(1): 186-203

[32] Gerbens-Leenes P W, Mekonnen M M, Hoekstra A Y. The water footprint of poultry, pork and beef: A comparative study in different countries and production systems[J]. Water Resources and Industry, 2013, 1/2: 25-36

[33] Mekonnen M M, Hoekstra A Y. A global assessment of the water footprint of farm animal products[J]. Ecosystems, 2012, 15(3): 401-415

[34] Oki T, Sato M, Kawamura A, et al. Virtual water trade to Japan and in the world[R]. Value of Water Research Report Series No 12. Delft, The Netherlands: UNESCO-IHE, 2003: 201-205

[35] Palhares J C P, Pezzopane J R M. Water footprint accounting and scarcity indicators of conventional and organic dairy production systems[J]. Journal of Cleaner Production, 2015, 93: 299-307

[36] Pahlow M, van Oel P R, Mekonnen M M, et al. Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production[J]. Science of the Total Environment, 2015, 536: 847-857

[37] de Miguel Á, Hoekstra A Y, García-Calvo E. Sustainability of the water footprint of the Spanish pork industry[J]. Ecological Indicators, 2015, 57: 465-474

[38] Chapagain A K. Globalisation of Water: Opportunities and Threats of Virtual Water Trade[M]. Leiden: Taylor & Francis Group PLC, 2006

[39] Mekonnen M M, Hoekstra A Y. A global and high-resolution assessment of the green, blue and grey water footprint of wheat[J]. Hydrology and Earth System Sciences, 2010, 14(7): 1259–1276

[40] Chapagain A K, Hoekstra A Y. The green, blue and grey water footprint of rice from both a production and consumption perspective[R]. Value of Water Research Report Series No. 40. Delft, The Netherlands: UNESCO-IHE, 2010

[41] Mekonnen M M. Spatially and temporally explicit water footprint accounting[D]. Twente: University of Twente, 2011

[42] Suttayakul P, H-Kittikun A, Suksaroj C, et al. Water footprints of products of oil palm plantations and palm oil mills in Thailand[J]. Science of the Total Environment, 2016, 542: 766–775

[43] Bulsink F, Hoekstra A Y, Booij M J. The water footprint of Indonesian provinces related to the consumption of crop products[J]. Hydrology and Earth System Sciences, 2010, 14(1): 119–128

[44] Chapagain A K, Hoekstra A Y. The water needed to have the Dutch drink coffee[R]. Value of Water Research Report Series No. 14. Delft, the Netherlands: UNESCO-IHE, 2003

[45] Chapagain A K, Hoekstra A Y. The water footprint of coffee and tea consumption in the Netherlands[J]. Ecological Economics, 2007, 64(1): 109–118

[46] Chouchane H, Hoekstra A Y, Krol M S, et al. The water footprint of Tunisia from an economic perspective[J]. Ecological Indicators, 2015, 52: 311–319

[47] Rodriguez C I, Ruiz de Galarreta V A, Kruse E E. Analysis of water footprint of potato production in the pampean region of Argentina[J]. Journal of Cleaner Production, 2015, 90: 91–96

[48] Huang J, Zhang H L, Tong W J, et al. The impact of local crops consumption on the water resources in Beijing[J]. Journal of Cleaner Production, 2012, 21(1): 45–50

[49] Chapagain A K, Orr S. An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes[J]. Journal of Environmental Management, 2009, 90(2): 1219–1228

[50] Gai L Q, Xie G D, Li S M, et al. A study on production water footprint of winter-wheat and maize in the North China Plain[J]. Resources Science, 2010, 32(11): 2066–2071

[51] Sun S K, Liu W Y, Liu J, et al. Sensitivity and contribution rate analysis of the influencing factors of spring wheat water footprint in Hetao irrigation district[J]. Scientia Agricultura Sinica, 2016, 49(14): 2751–2762

[52] Dong H J, Geng Y, Sarkis J, et al. Regional water footprint evaluation in China: A case of Liaoning[J]. Science of the Total Environment, 2013, 442: 215-224

[53] Han Q, Sun C Z, Zou W. Grey water footprint efficiency measure and its driving pattern analysis on provincial scale in China from 1998 to 2012[J]. Resources Science, 2016, 38(6): 1179-1191

[54] Wang Y B, Wu P T, Engel B A, et al. Application of water footprint combined with a unified virtual crop pattern to evaluate crop water productivity in grain production in China[J]. Science of the Total Environment, 2014, 497/498: 1-9

[55] Yoo S H, Choi J Y, Lee S H, et al. Estimating water footprint of paddy rice in Korea[J]. Paddy and Water Environment, 2014, 12(1): 43-54

[56] Sun S K, Wu P T, Wang Y B, et al. The impacts of interannual climate variability and agricultural inputs on water footprint of crop production in an irrigation district of China[J]. Science of the Total Environment, 2013, 444: 498-507

[57] Xu Y J, Huang K, Yu Y J, et al. Changes in water footprint of crop production in Beijing from 1978 to 2012: A logarithmic mean Divisia index decomposition analysis[J]. Journal of Cleaner Production, 2015, 87: 180-187

[58] Liu J, Sun S K, Wu P T, et al. Evaluation of crop production, trade, and consumption from the perspective of water resources: A case study of the Hetao irrigation district, China, for 1960-2010[J]. Science of the Total Environment, 2015, 505: 1174-1181

[59] Deng G Y, Ma Y, Li X. Regional water footprint evaluation and trend analysis of China-based on interregional input-output model[J]. Journal of Cleaner Production, 2016, 112: 4674-4682

[60] Lei Y T, Wei C P, Zou Y Y, et al. Study on virtual water trade of grain in China[J]. Ecological Economy, 2010, (8): 133-136

[61] Zhang Z Y, Yang H, Shi M J. Analyses of water footprint of Beijing in an interregional input-output framework[J]. Ecological Economics, 2011, 70(12): 2494-2502

[62] Zeng Z, Liu J G. Historical trend of grey water footprint of Beijing, China[J]. Journal of Natural Resources, 2013, 28(7): 1169-1178

[63] Munro S A, Fraser G C G, Snowball J D, et al. Water footprint assessment of citrus production in South Africa: A case study of the lower Sundays River Valley[J]. Journal of Cleaner Production, 2016, 135: 668-678

[64] Mordini M, Nemecek T, Gaillard G. Carbon & water footprint of oranges and strawberries: A literature review[R]. Switzerland: Agroscope Reckenholz-Tänikon Research Station ART, 2009

[65] Morillo J G, Díaz J A R, Camacho E, et al. Linking water footprint accounting with irrigation management in high value crops[J]. Journal of Cleaner Production, 2015, 87: 594-602

[66] Ridoutt B G, Juliano P, Sanguansri P, et al. The water footprint of food waste: Case study of fresh mango in Australia[J]. Journal of Cleaner Production, 2010, 18(16/17): 1714-1721

[67] Mekonnen M M, Hoekstra A Y. Water footprint benchmarks for crop production: A first global assessment[J]. Ecological Indicators, 2014, 46: 214-223

[68] Hoekstra A Y, Chapagain A K. Globalization of Water: Sharing the Planet' s Freshwater Resources[M]. Oxford, UK: Blackwell Publishing, 2008

[69] Hu T T, Huang K, Jin Z J, et al. Spatial pattern of the agricultural water footprint and its environmental impact in Lake Dianchi Basin[J]. Acta Scientiae Circumstantiae, 2015, 35(11): 3719-3729

[70] Yang Y X, Zhao X, Yang J. Accounting and impact of virtual water and water footprint in Xinjiang[J]. China Population, Resources and Environment, 2015, 25(5S): 228-232

[71] Liu C, Kroeze C, Hoekstra A Y, et al. Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers[J]. Ecological Indicators, 2012, 18: 42-49

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