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A comparative study of a full value-chain water footprint assessment using two international standards at a large-scale hog farm in China

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ABSTRACT

Water issues have become increasingly critical throughout the world, especially in the developing countries. Methodologies and analytical tools, such as water footprint assessment (WFA) have become more and more important for sustainable water resources management. This paper presents a comprehensive WFA for a typical large-scale intensive hog farming company located in Henan province, China. Two widely used global water footprint standards — established by the Water Footprint Network (WFN) and the International Standardization Organization (ISO) — were applied to study the water footprints of the hog farming company at both organizational and product levels. The study looks at a full value-chain in this hog farming company's operations, including one feed mill, two hog farms, one bio-fertilizer mill, and one neutralization plant. Results show that: 1) results using WFN and ISO 14046 standards present a basically consistent trend; 2) the total product (finishing hog) water footprint (WF) based on WFN standards is 3868 m^3/tonne of which the blue WF is 455 m^3/tonne, the green WF is 2452 m^3/tonne and the grey water footprint is 961 m^3/tonne; The water scarcity footprint (WSF) and water degradation footprint (WDF) based on the ISO 14046 standards is 353.67 m^3H_2O-eq/tonne and 26 000 m^3H_2O-eq/tonne, respectively; 3) the indirect WF generated during the crop cultivation stage, as raw materials for feed production, contributes more than 90% to the total WF; 4) WF produced during the hog farming stage has the greatest impact on water pollution to the water bodies in the vicinity of the farming sites; 5) the studied hog farm has relatively high water use efficiency in its direct operations than the global average, compared with the other studies' results. This paper also analyzes the pros and cons of the two standards and provides references for future research.

1Introduction

Water is an irreplaceable natural resource for human life, ecosystem health and social development. Water crises were ranked as the top systemic global risk (World Economic Forum, 2016) and the Sustainable Development Goals now include a dedicated water goal, both indicating that water challenges have become an issue on both the global and local scales. The issue of water and its management are even pressing in the developing countries like China. In 2015, China's *per capita* water resources were 2039.25 m^3 (NBS, 2015), only about a quarter of the world average. Water scarcity, pollution, and ecosystem degradation have become crucial constraints to China's socio-economic development. In recent years, with the increasing water challenges across the whole country, the Chinese government has launched a series of water policies, including the “water-saving priority” strategy, the ”most stringent” water resources management regulations, and the “Water Ten Plan” to control total water demand, enhance water use efficiency and combat water pollution. Taking effective measures to reduce freshwater consumption and wastewater discharge will be necessary to alleviate China's water crisis and to meet government

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regulations. This drives the need for a better understanding of water use efficiency, water-saving potential, and environmental impacts, and sustainable management of water in every sector and in various contexts.

Water footprint assessment (WFA) has gradually become a widely used analytical tool for sustainable water management (Barbosa et al., 2017, Hoekstra, 2016; Murphy et al., 2017; Yu et al., 2010; Zhang et al., 2017). The water footprint (WF) concept was introduced by Hoekstra and Hung (Hoekstra and Hung, 2002) and subsequently elaborated by Chapagain and Hoekstra (Chapagain and Hoekstra, 2004) as a useful index that indicates and quantifies water use activities that contribute to water scarcity and pollution (Ene et al., 2013). The earliest global standard for WFA was developed by Water Footprint Network (WFN), accounting for blue, green, and grey water footprint; assessing water footprint sustainability from the environmental, social and economic perspectives; and identifying the response strategies (Ene et al., 2013; Hoekstra et al., 2011; Munro et al., 2016; Murphy et al., 2017). The WF developed by WFN actually is a volumetric measure of water consumption and pollution at process, product, organizational, regional, and national levels (Hoekstra et al., 2011). The International Standard Organization (ISO) issued international standard 14 046, “Environmental management − water footprint − principles, requirements, and guidelines,” in 2014 (ISO, 2014). In ISO 14046, WF is defined as a metric that quantifies the potential environmental impacts related to water by following the concept of life cycle assessment (LCA) (ISO, 2014). The WFA developed by the ISO focuses on compilation and evaluation of the inputs, outputs, and potential environmental impacts related to water used or affected by a product, process, or organization.

In recent years, the field of WFAs has amassed a large body of literature, which is evolving over time but shows consistency and coherence (Hoekstra, 2016; Mohammad Sabli et al., 2017). Some scholars have even used the method of bibliometrics to analyze the WF research published in the past 10 years (Zhang et al., 2017). The WF of agricultural operations accounted for the majority of the published research (Barbosa et al., 2017; Chico et al., 2013; García Morillo et al., 2015; Jiang et al., 2017). Among studies reported of WF at livestock operations, few articles address hog farming (Mekonnen and Hoekstra, 2012) and are mostly based on the WF study of animal products (Gerbens-Leenes et al., 2013; Huang et al., 2014; Murphy et al., 2017; Palhares and Pezzopane, 2015). In addition, more and more studies are concerned with comprehensive assessments of the life cycle or supply chain, but few papers provide comparative studies of the two methodologies (WFN and ISO 14046) (Aivazidou et al., 2016; Bakken et al., 2016; Djekic et al., 2014; Fantin et al., 2012; Jefferies et al., 2012; Pellegrini et al., 2016; Ramírez et al., 2015).

Agricultural and food sectors have been the main consumers of freshwater in the world, affecting both local and regional water resources. The need to feed an increasing population demands an intensive use of natural resources in agriculture, mainly water and soil (Rodriguez et al., 2015). Total global freshwater use is estimated at 3800 cubic kilometers; of that, 2700 cubic kilometers (or 70%) is used for irrigation (IWMI, 2007). The WF of agricultural production accounts for 92% of the global total WF, while nearly one-third of the total WF of agriculture in the world is related to the production of animal products (Mekonnen and Hoekstra, 2012). Hog farming is an important part of agriculture, and pork is an essential part of the Chinese diet (MOA, 2016). Pork represents the majority (64%) of meat production in China (NBS, 2015). Already the world's largest pork producer and consumer, China has now achieved the position of world's leading pork importer, projected to account for more than a quarter of global trade in 2017 (USDA, 2016). Hog farming is affected by competing water use, water pollution, climate change, water infrastructure aging, and mismanagement.

This study applied the two widely used WFA methodologies respectively presented in the WFN and ISO 14046 water footprint standards to evaluate the full production chain water footprint of a large-scale intensive hog farming company at both the organizational and product levels. The results of this study were used to provide the basis for the company to develop its sustainable water strategies and water stewardship solutions, and to reduce the WF and water-related potential environmental impacts, hence improving its water use efficiency and sustainability. The paper also discusses and highlights how the two approaches complement each other and possible directions to which the two standards can further develop. This could provide a useful reference for follow-up research.

2. Methodology review of WFN and ISO 14046 approaches

Most of the previous studies on the subject (Hoekstra et al., 2011; ISO, 2014) have introduced WFN and ISO 14046 methodologies in detail. Therefore, this paper only briefly reviews and compares the frameworks and core elements of these two standards.

2.1. Frameworks comparison

Boulay et al (Boulay et al., 2013). presented the WFA frameworks comparison for both standards set by WFN and ISO 14046 (Fig. 1). The first phase of these two standards is basically the same: determining the goals and scope of the study, and the tasks and activities in the second phase are very similar although the WFN standard terms it water footprint accounting while the ISO standard names it inventory analysis. In Phase 3, the WFN's WF sustainability assessment addresses the sustainability of a water footprint using sustainability indicators and criteria from environmental, economic and social perspectives. In the third phase of a water footprint study applying ISO 14046 one will translate the water use inventory results into environmental impact indicator results In the final phase, WFN's standard describes how one identifies and formulates water footprint response strategies, while the ISO standard primarily describes how the assessment results can be interpreted. In addition, WFN provides that the WFA procedure could be determined according to the goals and scope of the study, which might include all of the above phases or be cut off at any phase in water footprint accounting, sustainability assessment, or response formulation such as policy development (Ruini et al., 2013). Similarly, ISO 14046 provides that either inventory analysis or impact assessment could be selected as the emphasis of WFA according to the goals and scope of the study.

2.2. WF accounting and inventory analysis

In the WF accounting, the WF consists of two main components (Hoekstra et al., 2011): direct (operational) WF and indirect (supply-chain) WF. The operational (or direct) WF is the volume of freshwater consumed (blue WF and green WF) and/or polluted (grey WF) resulting from an organization's activities within its direct operations. The supply chain (or indirect) WF is the volume of freshwater consumed (blue WF and green WF) and/or polluted (grey WF) to produce all the goods and services that form the inputs of production of the organization. The direct WF could be accounted relatively easily while the indirect WF is generally difficult to quantify because the data are with the suppliers and usually hard to trace and become available.

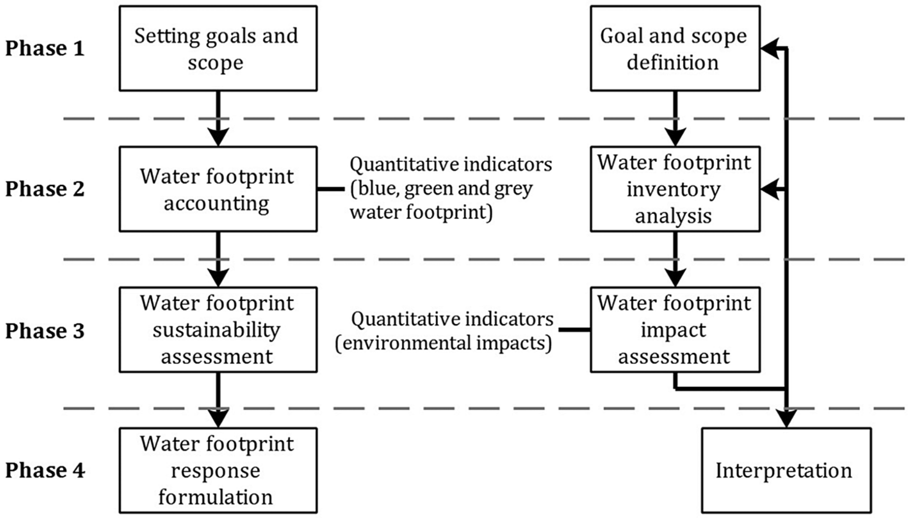

Fig. 1. Comparison of WFA frameworks using WFN and ISO 14046 methodologies (source: after Boulay et al., 2011).

In the ISO 14046 WF inventory analysis, activities to be performed include data collection, validation, relating, and aggregation for water-related inputs and outputs of the unit process according to the definite goal and scope and obtains the complete WF inventory (including direct and indirect inventory) within the system boundary. Regardless of whether using WFN or ISO 14046, freshwater consumption, wastewater discharge, and product water are part of the direct WF, while consumption of purchased materials and energy products are included in the indirect WF.

2.3. *WF sustainability assessment and impact assessment*

WF sustainability can be assessed from environmental, social, and economic perspectives. In this particular study, the sustainability assessment takes only the environmental perspective. Blue water scarcity (BWS) and water pollution level (WPL) are associated with blue WF and gray WF, respectively, which are commonly used environmental sustainability indicators in WFA. According to the ratio of total blue WF and available blue water resources, WFN divides BWS into four levels: low BWS (BWS <1.0), moderate BWS (BWS $= 1.0–1.5$), significant BWS (BWS $= 1.5–2.0$), and severe BWS (BWS> 2.0). Similarly, WPL can be divided into three levels according to the ratio of the total amount of gray WF to the actual runoff in the basin: slight WPL (surface WPL <1.0), significant WPL (surface WPL $= 1.0–2.0$), and severe WPL (surface WPL> 2.0).

In the WF impact assessment, ISO 14046 primarily divides the WF inventory into two major categories: water scarcity (caused by changes in water quantity) and water degradation (caused by changes in water quality). Next, inventory substances are characterized by corresponding characterization factors, and the results are usually the quantitative indicators. Finally, a series of indicator results of different impact categories are obtained. Only ISO 14046 defines the general procedure of impact assessment, and it does not provide a specific calculation method for each impact category characterization model.

2.4. *WF response formulation and interpretation of the results*

WF response formulation primarily identifies key points of water consumption and water pollution, based on the results of WF accounting and sustainability assessment. It then develops a detailed and feasible response plan to improve water efficiency and reduce water risks (Hoekstra et al., 2011).

While the interpretation phase of ISO 14046 mainly includes identification of significant issues and evaluation, which considers completeness, sensitivity and consistency checks, conclusions and limitations of the WFA, based on the results of inventory analysis and/or impact assessment (ISO, 2014).

3. Case study

This case study focuses on a large-scale intensive hog farming company, located in Nanyang City, Henan Province, China. At present, the company has an integrated production chain with plants for feed production, breeding, weaning, feeder-to-finisher farming, and eco-agricultural farming. The company has ranked high in production capacity in China in recent years.

3.1. *System boundary description*

In this study, the WFN water footprint standard (Hoekstra et al., 2011) and ISO 14046 (ISO, 2014) were used to carry out the WFA of the full production chain. The five plants representative of the production chain in this study include the feed mill (FM), hog farm A (HFA), hog farm B (HFB), the bio-fertilizer mill (BFM), and the neutralization plant (NP), corresponding to raw material, manufacturing, disposal, and recycling, respectively. FM produces sow feed, weaned pig feed and grower pig (feeder to finishing) feed. This mill supplies feed to HFA and HFB. The base materials for feed production in the FM are wheat, maize, wheat bran and soybean cake. Wheat and maize were purchased from crop farmers of different provinces. Wheat bran and soybean cake were purchased from oil extraction and grain milling industries which were processing crop products. HFA produces weaned pigs with an average weight of 6 kg/head. Its annual average production in the assessment period is 230,000 heads. HFB (farrow-to-finishing) produces finishing pigs with an average weight of 110 kg/head. Its annual average production in the assessment period is 210,000 heads. BFM makes use of pig manure from HFA and HFB to produce fertilizer through composting. NP disposes of and neutralizes the deceased pigs and uses the neutralized materials to produce three products: high-protein fertilizer, powder fertilizer and fat for industrial use. The system boundary covers

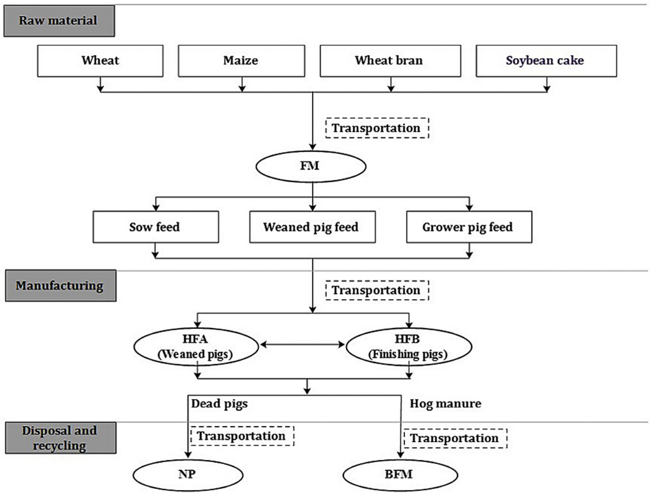

Fig. 2. The system boundary of the case study.

the entire stages of hog farming production from "cradle to grave" (Fig. 2).

3.2. Data and assumptions

The data used in this study was mainly derived from the annual average of measured data for each plant in the period of 2013–2015 (Zhang and Chico, 2016), and collected in factories. For the FM and NP, input and output data might be allocated between co-products in proportion to the economic value of the products. WF of energy, transportation (the dotted line in Fig. 2) and raw materials except for feeds are excluded for the following two reasons. One is the data is not available. The other is the WFs resulting from energy and transport are generally insignificant in the agriculture-based production/business since the WFs from crops in the agricultural stage are dominant.

The freshwater use within the FM is the evaporation that occurs during cooling processes, water incorporated in the feed and domestic water use for employees within the facility. An estimated water content in the feed of 13% was used to calculate the amount of water incorporated in feed. Evaporation was estimated by applying the method used for cooling tower evaporation (Morvay and Gvozdenac, 2008) considering flow rate and cooling range. The water footprints of crops used in producing feed were obtained from Mekonnen and Hoekstra (2011) and accessed from WaterStat Database[2] maintained by WFN.

The freshwater consumption in the two hog farms consists of evaporation in all processes, water drunk by pigs and incorporated into the pigs' body, transpiration loss by the pigs' respiratory process, contained in manure and overhead use by employees. It was assumed that the evaporation loss of the water use in this facility is mainly due to the evaporation from the storage ponds where all treated effluent of this facility is collected and stored. The evaporative loss of the freshwater from the facility was calculated by estimating the evaporation from the effluent storage ponds since there was a lack of process-level evaporation data from the facility. This evaporation was estimated based on the average open water evaporation rate in the area (Bao and Zhang, 2010) and the pond surface area. The estimate of water incorporation into pigs' bodies and transpiration loss through the pigs' respiratory processes were based on the data presented in the Committee on Nutrition Requirements of Swine (NRC, 2012). The effluent includes the collection of the barn cleaning water, urine and water in manure resulting mainly from the hog's drinking water, wastewater from employee's domestic use, and some drainage water from rainfall runoff within the facility premises. For the direct grey water footprint calculation based on the WFN, the maximum allowable concentrations were based on the permitted values for surface water bodies of Category III stipulated in the China national ambient water quality standards GB 3838–2002 (MEP and AQSIQ, 2002), while the natural background concentrations were assumed on the basis of various studies (Franke et al., 2013; Zhang et al., 2014; Udiba et al., 2014). In the ammonia nitrogen load estimation, ammonia loss from fields was estimated at a rate of 20% (Chastain et al., 2003).

The direct water consumption of the BFM is generated by overhead processes and from irrigation for a small patch of land growing crops within the facility premises. This facility and the NP are located within the same premises. Employees of both facilities share work duties and share domestic water uses. Therefore, the direct blue water footprint resulting from overhead processes and the irrigation were assumed to be 50% of the total for each of the two facilities. The effluent discharge of this facility is a part of the total effluent discharge of the entire premises and is mainly composed of the production wastewater from the NP. The total effluent discharge is collectively managed by the NP. Hence, the waste water of the BFM was assumed to be zero.

Since dead pigs are not market products, the water footprint of dead pigs was not considered in this water footprint accounting of NP. The indirect water use of this facility is ignored. The direct water consumption of this facility is generated in boiler water use, cooling, water use for disinfection processes and overhead use by employees. As described for the BMF, which shares the facility premises and overhead water use with the NP, the overhead water use for this facility is 50% of the total overhead fresh water consumption for the entire premises.

Water scarcity index (WSI) (Pfister et al., 2009), Critical water volume (CWV) (Olivier et al., 2003), and ReCiPe (Mark et al., 2009) were used to evaluated water scarcity footprint, water degradation footprint and water eutrophication footprint, respectively. The WSI of the study region was 0.778 and the national average WSI for China (0.478) was used in relation to inputs where the location of production was uncertain.

Data used in this study was sourced from both actual measurements from the facilities under studies and literature. As a result, uncertainties associated with the different data sources will remain. However, given the constraints, the data has been carefully reviewed and analyzed to ensure it is the best available and reliable to the study. Thus, the WF of the study facilities could be best reasonably represented.

3.3. Results

3.3.1. Organizational level

Based on results accounted (Zhang and Chico, 2016) based on the WFN standard, the FM's WF is the largest, followed by HFB, HFA, and then NP and BFM, in terms of the total accounting amount (Table 1). From the composition of direct and indirect WFs, the indirect WF of all the plants account for more than 90% of the total WF for all plants except for NP (0%). For the composition of green water, blue water and grey water, FM, HFA and HFB have more proportion of green WF (60%–70%), BFM has the largest proportion of blue WF (100%), and NP has the largest proportion of grey WF (99%).

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[2] WaterStat Database: http://waterfootprint.org/en/resources/water-footprint-statistics/.

Table 1
Results of organizational WF accounting using the WFN method (m^3).

		FM	HFA	HFB	BFM	NP
Indirect WF	Green WF	2.34×10^8	7.77×10^6	5.67×10^7	0	0
	Blue WF	4.28×10^7	1.43×10^6	1.04×10^7	4.33×10^3	0
	Grey WF	6.81×10^7	2.27×10^6	1.65×10^7	0	0
Direct WF	Green WF	0	0	0	0	0
	Blue WF	4.44×10^4	1.92×10^5	1.12×10^5	1.70×10^2	1.07×10^3
	Grey WF	3.46×10^4	5.23×10^5	5.67×10^6	0	1.27×10^5
Total WF		3.45×10^8	1.22×10^7	8.93×10^7	4.50×10^3	1.28×10^5

Note: FM, feed mill; HFA, hog farm A; HFB, hog farm B; BFM, bio-fertilizer mill; NP, neutralization plant.

Based on the WF accounting results and using the data from Mekonnen and Hoekstra (Mekonnen and Hoekstra, 2015; 2016), the environmental sustainability assessment results using the WFN standard show that the average annual BWS in the two-third area of the Tuanhe basin, where the study area is located, is categorized as severe blue water scarcity hotspot (BWS>3.0). Moreover, the annual water pollution level (WPL) related to the nitrogen pollution of the study area, is greater than 2.0, which is categorized as severe WPL. Therefore, the sustainability assessment results of BWS and WPL both demonstrate that the WF of this company is environmentally unsustainable (Zhang and Chico, 2016).

Water-related inputs and outputs for the WF inventory data of each plant based on ISO 14046 are shown in Table 2. The inputs include net freshwater consumption and the amount of raw material used, while emissions from wastewater and major contaminants are included in the outputs. These inventory data are provided directly for the subsequent WF impact assessment (Table 3).

There are significant differences in each water-related environmental impact assessment result from the five plants. In terms of water scarcity footprint (WSF), FM is the largest, followed by HFB, HFA, and BFM, while NP has the smallest WSF (Table 3). For the composition of direct and indirect WFs, the indirect WSF shows the same characteristic as the total WSF. The largest direct WSF amount appears in HFA, followed by HFB, FM, NP, and HFB in descending order (Fig. 3). In terms of water degradation, the HFB has the largest water degradation footprint (WDF), followed by HFA, NP, FM, and BFM, in descending order (WSF = 0) (Table 3). The composition of WDF indicates that nitrogen pollutants in all the plants, except for BEF, account for the largest proportion of pollutants (70%–85%) (Fig. 4). Phosphorus pollutants account for 16.84% and 18.30%, respectively in HFA and HFB, and 0% in FM and NP. Organic pollutants make up 10%–20% of total pollutants in these four plants (Fig. 4). The water eutrophication footprint (WEF) of HFA and HFB is much higher than in other plants, which illustrates that they have more impact on environment eutrophication in this company, based on the results of WEF (Table 3).

3.3.2. Product level

The WF of the three products in FM calculated using the WFN method is between 900 m^3/tonne and 1200 m^3/tonne (Zhang and Chico, 2016): the sow feed WF is the largest, followed by finishing pig feed and weaned pig feed (Table 4). For the hog farms, the WF of weaned pig is far more than finishing pig. There are large differences in the WF among the three products in NP, where high-protein fertilizer has the highest product WF of 106 m^3/tonne, followed by fat (industrial use) of 90.2 m^3/tonne, and the lowest in powder fertilizer of 22.6 m^3/tonne (Table 4). The product WF of bio-fertilizer is the lowest (1.5 m^3/tonne) among all the products.

Based on the impact assessment of product WF using ISO 14046, the WSF, WDF, and WEF of sow feed are the largest among the three products in FM, followed by finishing pig feed, and the least in

Table 2
Results of organization WF inventory using the ISO 14046 method.

			FM	HFA	HFB	BFM	NP
Input	Freshwater (m^3/year)		4.44×10^4	1.92×10^5	1.12×10^5	1.70×10^2	1.07×10^3
	Raw materials (tonne/year)	Wheat	1.21×10^5	—	—	—	—
		Maize	7.72×10^4				
		Wheat bran	1.66×10^4				
		Soybean cakke meal	2.67×10^4				
		Feed	—	9.39×10^3	7.34×10^4	—	—
		Manure	—	—	—	1.46×10^4	—
Output	Total wastewater discharge (m^3/year)		3.32×10^3	1.09×10^5	3.97×10^5	0	5.22×10^2
	Pollutant discharge (mg/L)	COD_{Cr}	8.50×10^1	4.22×10^3	3.14×10^3	0	9.88×10^2
		BOD	1.77×10^1	8.25×10^2	7.00×10^2		1.89×10^2
		NH_3-N	2.28×10^1	1.31×10^3	1.08×10^3		2.39×10^2
		TP	No data	6.14×10^1	5.54×10^1		No data

Note: FM, feed mill; HFA, hog farm A; HFB, hog farm B; BFM, bio-fertilizer mill; NP, neutralization plant; "—", not applicable.

Table 3
Results of organization WF impact assessment using the ISO 14046 method.

IC	Unit	FM	HFA	HFB	BFM	NP
WSF	m^3H_2O-eq/year	3.33×10^7	1.26×10^6	8.17×10^6	3.50×10^3	8.32×10^2
WDF	m^3H_2O-eq/year	8.99×10^4	1.98×10^8	6.01×10^8	0	1.51×10^5
WEF	$kgPO_4^{3-}$-eq/year	2.50×10^1	6.72×10^4	2.09×10^5	0	4.12×10^1

Note: IC, impact category; FM, feed mill; HFA, hog farm A; HFB, hog farm B; BFM, bio-fertilizer mill; NP, neutralization plant; WSF, water scarcity footprint; WDF, water degradation footprint; WEF, water eutrophication footprint.

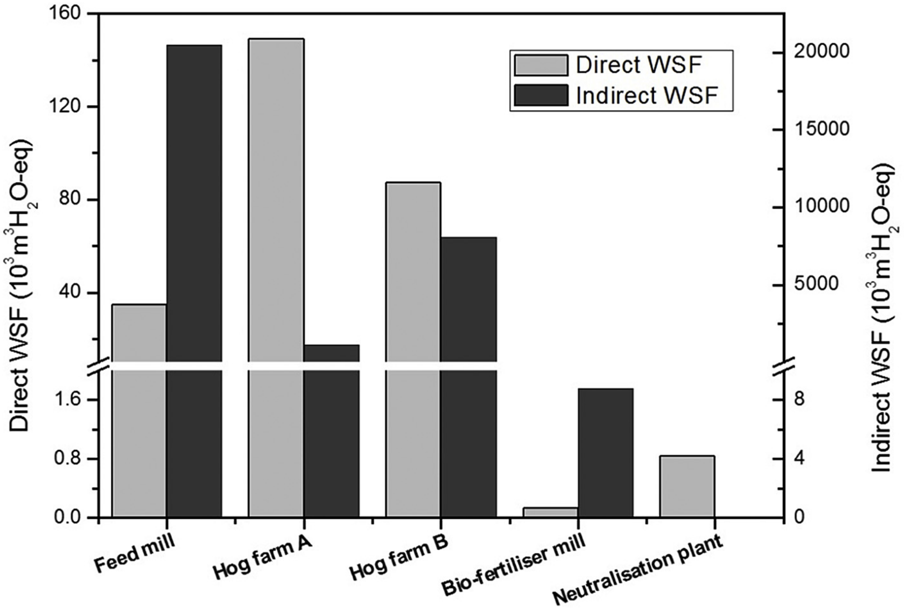

Fig. 3. Results of direct and indirect WSF on the organizational level.

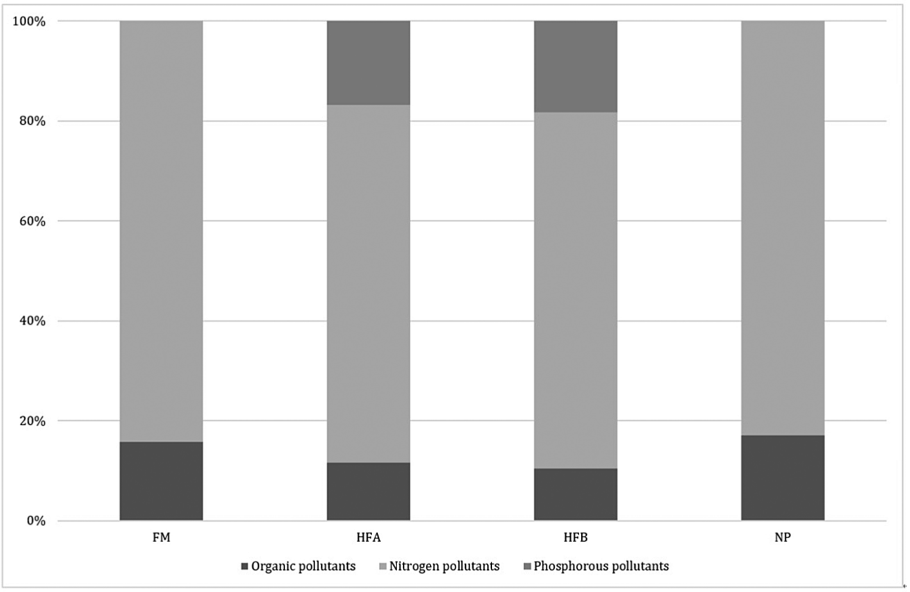

Fig. 4. Proportion of WDF on the organizational level.

weaned pig feed (Table 5). For the two hog farms, the WSF, WDF, and WEF of weaned pig are more than those of finishing pig. Results show that the WSF, WDF, and WEF of high-protein fertilizer are the largest among the three products in NP, followed by fat (industrial use), and then powder fertilizer (Table 5). The product WSF of bio-fertilizer is the lowest (0.9 m^3H_2O-eq/tonne) among all the products; its WDF and WEF are zero.

4. Discussion

4.1. Comparative analysis of the results

The WF of FM and the two hog farms are relatively larger using the WFN method at the organizational level. Among them, the

Table 4
Results of product WF accounting using the WFN method (m^3/tonne).

Plant	Product type	Green WF	Blue WF	Grey WF	Total WF
FM	Sow feed	783	144	228	1155
	Weaned pig feed	666	122	194	982
	Finishing pig feed	725	133	211	1069
HFA	Weaned pig	5632	1172	2022	8826
HFB	Finishing pig	2452	455	961	3868
BFM	Bio-fertilizer	0	1.5	0	1.5
NP	High-protein fertilizer	0	0.8	105.2	106
	Powder fertilizer	0	0.2	22.4	22.6
	Fat (industrial use)	0	0.8	89.4	90.2

Note: FM, feed mill; HFA, hog farm A; HFB, hog farm B; BFM, bio-fertilizer mill; NP, neutralization plant.

Table 5
Results of product WF impact assessment using the ISO 14046 method.

Plant	Product type	WSF	WDF	WEF
		m^3H_2O-eq/tonne	m^3H_2O-eq/tonne	$kgPO_4^{3-}$-eq/tonne
FM	Sow feed	111.60	0.30	8.37×10^{-5}
	Weaned pig feed	94.87	0.26	7.12×10^{-5}
	Finishing pig feed	103.30	0.28	7.75×10^{-5}
HFA	Weaned pig	911.68	1.44×10^5	48.69
HFB	Finishing pig	353.67	2.60×10^4	9.04
BFM	Bio-fertilizer	0.90	0	0
NP	High-protein fertilizer	69.15	125.04	0.034
	Powder fertilizer	15.05	27.22	0.007
	Fat (industrial use)	58.95	106.62	0.029

Note: FM, feed mill; HFA, hog farm A; HFB, hog farm B; BFM, bio-fertilizer mill; NP, neutralization plant; WSF, water scarcity footprint; WDF, water degradation footprint; WEF, water eutrophication footprint.

indirect WF accounts for more than 90% of the total WF. This is because the contribution of feed and its raw materials such as maize, soybean meal, wheat, and wheat bran (Zhang and Chico, 2016). The two hog farms have larger direct WF than the other facilities because the freshwater consumption and the pollution loads in the wastewater discharge are larger. The freshwater consumption in the hog farms includes evaporation, water incorporation in pig bodies, respiratory loss, water contained in manure, and overhead usages by employees. Results from the ISO inventory analysis and impact assessment show freshwater withdrawal in HFA is the highest, revealing the fact that the stage of weaned pig farming has more water scarcity impact than other stages. The fact that FM has the highest WSF can be attributed to the indirect WF produced when growing raw materials. At the same time, the fact that HFB and HFA have higher WDFs explains that the process of hog farming has more impact on water pollution, dominated by nitrogen pollutants. This is the same finding shown by the grey water footprint results using the WFN method.

The results of WF accounting using the WFN method indicate that the product WF in the main production stage (hog farming) is much greater than other stages at the product level. The product WF of weaned pig is greater than that of finishing pig, which implies that producing the same weight of a tonne pig production, weaned pig, characterized by shorter growth cycle and smaller individual weight, is consuming more water than that of finishing pig, with longer growth cycles and larger individual weight. In the feed and raw material processing stage, there is no significant difference in the WF of the three feed products. The product WF of the products from the neutralization plant is smaller, with bio-fertilizer having the smallest WF.

The above analysis shows, although the exact numbers and physical meanings are not the same, that the impact assessment done using the ISO method and the accounting results from WFN present a basically consistent trend. Even the calculated results of similar product do not show much difference. Therefore, the WFA results using these two standards are generally consistent and show a certain correspondence. For example, the ISO's WSF corresponds to WFN's blue WF, which reflect the water consumption. ISO's WDF corresponds to WFN's grey WF, both of which reveal water pollution. It is important to note that the WFN's grey WF is only partially equivalent to the ISO's WDF, because the assessment of WFN only considers the pollutants directly discharged into the water, not taking into account the indirect pollution to water (contaminants discharged in air and soil). The WF accounting is also similar to the CWV method.

For the impact of water quantity and quality, some studies take a weighted WFA index into consideration, which is the sum of weighted WSF and WDF (Ridoutt and Pfister, 2012). In the present study, the water quantity (corresponds to WSF) and quality (corresponds to WDF) assume the same weight (1:1). Take finishing pig as an example. There is a significant difference between the two standards regarding water quality: ISO's WDF accounts for more than 98% of the comprehensive WF, while WFN's grey WF contributes only a quarter of the total WF.

The WF of finishing pig in HFB is contrasted to the global average, since the finishing pig is the main product of this large-scale intensive hog farming company. Due to limitations of ISO 14046, with limited information communicated and relatively few related studies, the WFN results are compared with the global average calculated by Mekonnen and Hoekstra (Mekonnen and Hoekstra, 2012). The WF of finishing pig in this study is significantly lower than the global average (Table 6). The direct blue WF (such as drinking, service, feed mix, etc.) of the global livestock industry accounts for less than 2% of the total WF (Mekonnen and Hoekstra, 2012), while the direct blue WF of the present study accounts for only 0.13% of the total WF (including indirect WF) (Table 1). The above comparisons indicate that the water efficiency of the large-scale intensive hog farming company in this study is significantly greater than the global average (Zhang and Chico, 2016).

In this paper, we do not discuss in detail the WF sustainability assessment by the WFN method versus the impact assessment by ISO 14046. The WFN's water footprint sustainability assessment places the volumetric WF in the river basin or catchment context to evaluate the significance of the WF contribution to the water scarcity level and water pollution level using the blue water scarcity (BWS) and water pollution level (WPL) indices. The ISO 14046 method translates the inventory results, i.e. the volumetric water uses, into various impact category indices, such as WSF, WDF, and WEF. It has been seen that, in a qualitative sense, ISO 14046 based impact assessment results confirm the WFN's method based sustainability assessment results, although the two type of results cannot be quantitatively compared.

4.2. Pros and cons analysis of the standards

Given the equally perceived importance of different types of water source, the absolute volume of the total WF consisting of blue

Table 6
Comparison of the results of the current study with global average.

Study	Period	Average weight (kg)	WF of unit weight (m^3/tonne)
Global average[a]	1996–2005	102	5108
Current study	2013–2015	110	3868

Note:
[a] Mekonnen and Hoekstra, 2012.

WF, green WF, and grey WF within the system boundary can be obtained using the WFN accounting method. The advantages of this methodology lie in the concise principle, high operability, and wide range of applications. The WFN's WFA approach has already been widely applied at process, product, watershed, regional, and national scales (Wang et al., 2013; Xu et al., 2015). The WFA approach of this standard can also be applied in studies that can feed the policy discussion and strategy formulation relating to water allocation and management in different sectors and context, and can also form a starting-point for more in-depth assessments of environmental, social and economic impacts of water use (Miguel-Ayala et al., 2016; Zhang et al., 2013; 2014). However, the current WFN's WFA standard is still under development in the subject of sustainability assessment, particularly in the respect of indicators and criteria for social and economic sustainability assessment. Results from the WFA studies based on this approach often do not present the environmental impacts of water use activities in the level of detail as done by common environmental impact assessment studies.

Looking at LCA, ISO 14046 introduces characterization factors to quantify contributions to the environmental impacts of inventory substances. The result has relative significance by using an equivalent physical quantity based on a specific reference. Because it covers the full product life cycle from “cradle to grave,” LCA has become a conventional method for calculating carbon footprint, whose technical framework is mature, analysis process is normative, and the quantitative results are reliable. However, there are inevitably truncation errors in the process of defining the system boundary in the LCA method, since it is a bottom-up analysis method. Furthermore, the LCA method requires significant data precision and, so generally does not apply to regional and above-scale footprint studies (Fang, 2015). It has been pointed out that ISO 14046 is applicable only to WFA on process, product, and organizational levels. One should also be aware the fact that ISO 14046 is environment impact oriented, therefore, studies using this approach are not intended for policy discussion and strategy formulation related to water resources management in river basin or other geographical levels. In addition, ISO 14046 provides an open platform for different impact categories, since there is no restriction on the use of methods or models to carry out impact assessment in this standard. It is important to improve the characteristic model of different environmental impact categories by finding a characteristic factor that could accurately reflect all of the inventory substances’ contribution to a specific impact category.

Since ISO 14046 was developed, there has been controversy between these two methodologies (Hoekstra, 2016; Pfister et al., 2017), which has played a positive role in promoting the development of the WF theory and methods. The main aim of WFA is to achieve sustainable use of water resources, regardless of whether the WFN or ISO methods are used. This is especially true in developing countries, such as China and India, which are facing the serious water issues. Under such circumstances, it is necessary to meet the needs of rapid socioeconomic development, but also to ensure the eco-environment health (Wichelns, 2015). Developing countries face a water crisis, but they also act as a global manufacturing base. Eliminating green trade barriers is another critical factor to enhance international trade competitiveness. International technical standards should promote technological progress and promote the healthy development of the global economy—and not become technical barriers faced by the developing countries. Considering the limited global freshwater reserves, water resources assigned to a product can no longer be used in the production of another product (Hoekstra, 2016). Whether a WF is generated in a water-rich area or a water-scarce area, it has the same effect on water resource occupation, and a different impact on the local environment. Therefore, the advantages of the two standards should be combined. In practice, the WFA should be carried out from both water resource appropriation and water environment impact perspectives.

5. Conclusion

This study is the first to look at data from the same organization and product through the lenses of two global WF standards. Results show that there is a basically consistent trend in the results achieved using both WFN and ISO methodologies. At the organization level, the WF in FM are the largest, in terms of the total WF (WFN) and the WSF (ISO). At the same time, the WF in HFB are the largest, in terms of the direct WF (WFN) and the direct WSF, WDF and WEF (ISO). At product level, weaned pig has the largest WF and biofertilizer has the lowest WF using both WFN (the green WF, blue WF and grey WF) and ISO (WSF, WDF and WEF) methods. The product WF of finishing pig based on WFN in this case study is $3868 m^3$/tonne, while the product WSF and WDF of finishing pig using the ISO method are 353.67 $m^3 H_2O$-eq/tonne and 26 000 $m^3 H_2O$-eq/tonne, respectively. The company's direct hog farming operation has better water use efficiency than the global average level, based on the results from the relevant studies. For future research related to WFA in developing countries, the following aspects should also be considered. On one hand, basic WF databases need to be further developed, especially regarding agricultural irrigation and production. On the other hand, supporting policies and detailed standards need to be developed and implemented, such as establishing a WF reporting system at the organization level, and an information disclosure system at the product level.

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