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Key Points:
- Over 80% of the blue water footprint of pork production in China is unsustainable
- One-third of pork-related scarce water is consumed in low-water-scarce provinces
- One-fifth of the north-to-south virtual water embodied in feed returns by pork

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
L. Zhuo and P. Wu, zhuola@nwafu.edu.cn; gjzwpt@vip.sina.com

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Author Contributions:
Conceptualization: La Zhuo, Pute Wu
Data curation: Yilin Liu, Bianbian Feng
Methodology: Xiangxiang Ji, Dong Xie, La Zhuo
Resources: Bianbian Feng
Software: Xiangxiang Ji, Dong Xie
Supervision: La Zhuo, Pute Wu
Validation: Yilin Liu, Bianbian Feng

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Water Footprints, Intra-National Virtual Water Flows, and Associated Sustainability Related to Pork Production and Consumption: A Case for China

Xiangxiang Ji1, Dong Xie1,2,3, La Zhuo1,4, Yilin Liu1, Bianbian Feng1, and Pute Wu1,4

1Northwest A & F University, Yangling, China, 2School of Environment, Harbin Institute of Technology, Harbin, China, 3School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China, 4Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling, China

Abstract Growth in water consumption with intensified virtual water (VW) flows from increased production and consumption of both meat and feed crops threatens the sustainability of water resources in water-scarce countries and export regions. However, a sustainability assessment of both water footprints (WFs) and VW flows related to animal products at a subnational scale is lacking. Here we estimate direct and indirect WFs as well as the inter-provincial VW flows associated with pork production and consumption in China for the years 2008 and 2017. The contributions of feed crop production and consumption were identified. Both life cycle assessment and WF network frameworks were applied to evaluate the sustainability of blue WF and VW flows. Results show that the national annual consumptive (green-blue) WF and degradative (gray) WF of pork production increased by 8.7% and 15.8%, respectively. More than 80% of the blue WF in pork production was unsustainable. By 2017, 62% of the unsustainable blue WF and 64% of the water scarcity footprints of pork production in the south resulted from consuming the feed crops from the north. This analysis highlights the importance and provides feasible approaches to uncover remote geographical effects on regional water scarcities from different steps in the value chains of livestock products.

1. Introduction

The livestock industry consumes 35% of global crop production (FAO, 2020), alongside one-third of the world’s agricultural water consumption (Hoekstra & Mekonnen, 2012) and one-fifth of the international virtual water (VW) trade in food (Hanasaki et al., 2010). Driven by growth in both individual consumption demand and population in middle-income countries by 19% and 29%, respectively, from 2008 to 2017 (FAO, 2020), the continuous increase in meat production and trade will undoubtedly exacerbate the water crisis in producing and exporting countries that are already facing water shortages. This will lead to difficulties in ensuring the security of food and animal feed production under limited water and land resources (Chung et al., 2020; Godfray et al., 2018).

The water footprint (WF) of animal products measures the quantity of freshwater consumed in the production of animal products and their impact on the water environment (Hoekstra et al., 2011). The WF of livestock feeding consists of direct and indirect WFs. The direct WF consists of the water used for drinking and other services, and for diluting concentrations of contaminants in animal excrement. Indirect WF measures the water appropriation associated with producing feed crops that are consumed during the livestock feeding cycle (Hoekstra et al., 2011). Depending on different sources of water resources, the WF can also be categorized by blue WF (i.e., surface and groundwater), green WF (i.e., rainwater), and gray WF (i.e., water required to assimilate anthropogenic loads of pollutants to freshwater bodies). The blue and green WFs are further categorized as consumptive WFs, and the gray WF is the degradative WF (Hoekstra, 2013).

Several studies have quantified and analyzed the spatiotemporal evolutions in the WF of animal products at different spatial scales. Gerbens-Leenes et al. (2013) demonstrated that WFs of meat production were driven by feed conversion efficiencies, feed composition, and feed origin in the cases for China, Brazil and the United States. Ibiidhi et al. (2017) revealed that the average WF of chicken meat (6.0 m³ kg⁻¹) was smaller than that of sheep meat (18.9 m³ kg⁻¹), which was the smallest in the agro-pastoral system in Tunisia. Mekonnen et al. (2019) found that the combined effect of increased animal productivity and increased feed crop yields led to a decrease in the average WF of animal feed, which resulted in a 36% decrease in the total WF production of animal products in the United States from 1960 to 2016. Xie et al. (2020) quantified the spatiotemporal evolution of the WF of pork at
the provincial scale under different farming scales within China over the period 2000–2014. However, few studies have quantified the VW flows induced by the consumption of animal products and their intrinsic relationships with the WF and the VW flow related to feed crops. Only Hanasaki et al. (2010) and Dalin et al. (2014) clarified the international trade of major meat products and the inter-provincial VW flow in China, respectively, but there is a lack of information on the VW flows directly associated with feed trade and consumption. This lack of information prevents the exploration of regions that actually pay for the water consumed in the production of animal products. Only one such study exists by Zhuo et al. (2019), who estimated inter-provincial maize-related VW flows in China, and distinguished between consumption for food and feed.

Two frameworks exist for assessing the impact of the WF on blue water resources, including the WF network (WFN) framework (Hoekstra et al., 2011) and the life cycle assessment (LCA) framework (ISO, 2014; Pfister et al., 2009; Ridoutt & Pfister, 2013). With totally different quantification perspectives and units while resembled purposes, the debates on feasibility or rationality of the two frameworks are still on, mostly with mutual criticisms (Hoekstra, 2016; Pfister et al., 2017; Vanham & Mekonnen, 2021). However, the two leading scholars for each method co-published a viewpoint and claimed that the two frameworks have different foci in assessments and could take advantage of the strengths of each approach (Boulay et al., 2013). However, there is still a lack of convincing evidence to demonstrate the synergy between the two approaches. For the WFN framework, when the blue WF in a certain area exceeds renewable blue water, thereby violating environmental flow standards and consuming groundwater, the area’s blue WF is defined as the “unsustainable blue WF.” The VW consumed and embedded in trade products under the same cases is called unsustainable virtual blue water (Hoekstra & Mekonnen, 2016). Within the WFN framework, Rosa et al. (2019) found that 52% of the world’s irrigation water is unsustainable, 15% of which is for export; Mekonen and Hoekstra (2020) reported that 57% of the global blue WF of crop production is unsustainable, of which nearly 70% is contributed by the production of wheat, rice, cotton, sugar cane, and fodder; Gao et al. (2020) found that the flow of unsustainable virtual blue water related to major crops between provinces in mainland China increased by 8% from 2004 to 2013. For the LCA framework, multiplying the blue WF with the local WS index obtains the water scarcity footprint (WSF; ISO, 2014; Pfister et al., 2009; Ridoutt & Pfister, 2013), and the corresponding VW export is scarce weighted VW (SVW; Lenzen et al., 2013). The relative assessment tends to express the potential environmental impact caused by blue water consumption in the unit H2O-eq, meaning that one cubic meter equivalent of WF represents the burden on freshwater systems of one cubic meter of freshwater consumption based on the WS index. Applying the LCA framework, Wiedemann et al. (2017) observed lower WSF per kg of chicken meat produced in Queensland compared to South Australia. Using the same framework, Bai et al. (2018) quantified the WSF of the finishing hog in a typical large-scale intensive pig farming company in Henan Province, China, with a value of 353.67 m3 H2O-eq t−1. However, to the best of our knowledge, a sustainability evaluation of the WF and VW flow of animal products at the intra-national scale is still lacking. Moreover, studies seldom consider that their feed ingredients come from different water-scarce regions and tend to assume that the WS in the studied area is the same level. This will lead to the key information that the scarce water consumed locally comes from other export regions being hidden and ignored, and the stress on regional water resources will be underestimated or overestimated, thus affecting decision-making. This issue matters because over 90 percent of the WF of livestock comes from producing feed crops (Mekonnen & Hoekstra, 2012; Xie et al., 2020). For instance, if water-rich region A imports feed crops for livestock from water-scarce region B, then pervious WS assessments would attribute WF of the livestock to region A’s water endowments, which would be misleading remote water scarcities within the value chain of animal products. Although Lenzen et al. (2013) and Zhao et al. (2018) have examined the scarcity in VW flows at the international and subnational scales, respectively, the evaluation of specific animal products is lacking.

To fill the abovementioned research gaps, the current study uses mainland China—the world’s largest pork producer—as a study case, aims to comprehensively assess and compare the sustainability of WFs and inter-provincial VW flows related to pork for the years 2008 and 2017. Distinguishing between North and South China (Xie et al., 2004; Figure 1) is a widely used approach of regional delimitation in water impact assessments given its easier reminder and comparison to the world’s largest physical water transfer project the South-to-North Water Transfer projects (e.g., Ma et al., 2006; Zhao et al., 2015; Zhuo et al., 2016). Other than its role as the largest pork producer, China has been facing increasingly intensive inter-regional crop-related VW flows, mainly from the relatively drier north to the wetter south (Ma et al., 2006; Zhuo et al., 2016). The monsoon climate defines the uneven water endowments between the north and south (Piao et al., 2010), while the land distribution defines the mismatch of water supply and demands for agriculture. By the year 2019, Northern Provinces accounted for 58%
Meanwhile, the southern provinces account for a more developed economy (27% higher per capita gross domestic production), more population (55% of national total), and more pigs (56% of national total; NBSC, 2020). Specifically, in this analysis, the contribution of production and inter-provincial consumptive (green and blue) VW flows of feed crops to the WF as well as the consumptive VW flows related to pork are clarified, based on consumptive and degradative (gray) WF accounting for pork production at provincial scales. With focus on the blue water, which is the common water source for all water use sectors and becoming increasingly limited and vied with the uneven spatial distribution as well as mismatch between supply and demand (Figure 1), the impact of pork production and inter-provincial trade on regional blue water resources is further evaluated using both the WFN and LCA frameworks. To our knowledge, this is the first study to evaluate the subnational scale animal product's production WF and VW flow and the corresponding impact on blue water resources. Through the case of pork production and consumption in China, this study provides an inter-regional perspective on assessing water consumption based on WF and VW flows and uncovers the associated effects on regional water scarcities from different steps in the value chains of animal product production and consumption.

2. Methods and Data

The methodology of estimating inter-provincial consumptive VW flows embedded in feed for pork production is introduced in Section 2.1. Section 2.2 interprets the method to calculate the inter-provincial consumptive VW flows related to pork consumption, followed by the WF accounting method for pork production. Finally, in Section 2.3, two frameworks for assessing the sustainability of blue WF and VW flows are presented.

2.1. Estimating Inter-Provincial VW Flow Embedded in Feed for Pork Production

The volume of VW embedded in feed crop flow from province \( m \) to province \( n \) \( (VW_{\text{feed}}[m,n], \text{m}^3 \text{y}^{-1}) \) is calculated as follows:

\[
VW_{\text{feed}}[m,n] = \sum_i (WF_{i,\text{prod}}[m] \times R_i \times Feed_i[n] \times S[n] \times a_i[m,n])
\]  

where \( WF_{i,\text{prod}}[m] \) (\( \text{m}^3 \text{ kg}^{-1} \)) is the WF per unit of crop production in province \( m \). \( R_i \) is the share of crop \( i \) in concentrates, which was estimated based on the corresponding crop use recorded in the China Feed Industry Yearbooks (CNKI, 2020). For roughage (i.e., silage maize), which does not involve trade flows, the VW flow of...
roughage is zero. The $a_i[m,n]$ is the proportion of the WF of the inter-provincial traded feed crops in local pork production.

$$a_i[m,n] = \frac{I_i[m,n]}{\text{Prod}_i[n] - E_i[n] + \sum_n I_i[m,n] + \sum_{ce} I_{ce,n}}$$  \hspace{1cm} (2)

where $\text{Prod}_i[n]$ (kg y$^{-1}$) represents the feed crop production quantity of crop $i$ in province $n$, $E_i[n]$ (kg y$^{-1}$) is the export volume of crop $i$ from province $n$, $I_i[m,n]$ (kg y$^{-1}$) represents the import quantity of crop $i$ from exporting province $m$, and $I_{ce,n}$ (kg y$^{-1}$) represents the import quantity of crop $i$ from exporting country $ce$. We assumed that the import proportion of byproducts of feed crops (rice bran, DDGS) is equal to the import ratio of its crop raw materials (wheat and maize).

In this study, it was assumed that maize, wheat, wheat bran, rice bran, distillers dried grains with soluble (DDGS), rapeseed meal, cottonseed meal and soybean meal were the raw materials for making concentrate. Following Liu et al. (2016), roughage was considered to be silage maize. The unit WF of each feed crop considered was computed with the “fast track” method (Tuninetti et al., 2017) with values referenced from the average level for the 1996–2005 decade (Mekonnen & Hoekstra, 2011). The method assumes that the variability of crop unit WF over time is mainly represented by the ratio of the WF of corresponding crop yield. The method was tested as valid within 10% of error through a global scale uncertainty analysis (Tuninetti et al., 2017). Gao et al. (2020) found that the method has an error of less than 20% at the provincial level in China. The method has the characteristics of low calculation cost and high reliability of results and has been widely used (Gao et al., 2020; Soligno, Malik & Lenz, 2019; Soligno, Rodolfi & Laio, 2019; Tamea et al., 2020; Xie et al., 2020).

Provincial trade balances (i.e., net imports) for each crop considered were estimated considering international trade, production, and consumption of each crop for feed, food, and manufactured products and seed and waste on the basis of the national food balance sheets in FAOSTAT (FAO, 2020) combining livestock and population units in each province (Ma et al., 2006; Zhuo et al., 2016). Under the assumption that inter-provincial trade flow minimizes the total transportation cost of trade, linear programming optimisation was used to determine the annual inter-provincial trade volume of feed crops and pork (Dalin et al., 2014; Zhuo et al., 2019).

2.2. Estimating Inter-Provincial VW Flows Related to Pork Consumption

The inter-provincial consumptive VW flow embedded in pork transfers driven by pork consumption can be calculated as follows:

$$VW_{\text{pork}}[n, x] = T_{\text{pork}}[n, x] \times WF_{\text{cons.pork}}[n]$$  \hspace{1cm} (3)

where $VW_{\text{pork}}[n, x]$ (m$^3$y$^{-1}$) is the VW embedded in pork flows from province $n$ to province $x$, $T_{\text{pork}}[n, x]$ (kg y$^{-1}$) is the volume of pork trade from province $n$ to province $x$, and $WF_{\text{cons.pork}}[n]$ (m$^3$ kg$^{-1}$) is the consumptive WF of pork production in province $n$. The inter-provincial trade balance of pork is obtained using the same methods and assumptions as in the feed crop trade circulation in the previous section.

The WF of pork production includes the consumptive WF and gray WF. The consumptive (green and blue) WF of pork production ($WF_{\text{cons.pork}}[n]$, m$^3$ kg$^{-1}$) depends on the consumptive WF of pigs ($WF_{\text{cons.pig}}[n]$, m$^3$ head$^{-1}$) and processing water (PWR, m$^3$ head$^{-1}$). The gray WF of pork ($WF_{\text{grey.pork}}[n]$, m$^3$ kg$^{-1}$) depends on the gray WF of a pig ($WF_{\text{grey.pig}}[m]$, m$^3$ head$^{-1}$).

$$WF_{\text{cons.pork}}[n] = (WF_{\text{cons.pig}}[n] + PWR) \times \frac{v_f[n]}{pf[n]}$$  \hspace{1cm} (4)

$$WF_{\text{grey.pork}}[n] = WF_{\text{grey.pig}}[m] \times \frac{v_f[n]}{pf[n]}$$  \hspace{1cm} (5)

where $pf[n]$ is the product fraction of pork in province $n$, defined as the quantity of pork obtained per quantity of pig. The $v_f[n]$ is the value fraction of the pork, defined as the ratio of the market value of pork from the pig to the sum of the market values of all products from the pig (Chapagain & Hoekstra, 2003).

$$pf[n] = \frac{P_{\text{pork}}[n]}{S[n] \times W[n]}$$  \hspace{1cm} (6)
\[ v_f[n] = \frac{\text{price}_{\text{pork}}[n] \times P_{\text{pork}}[n]}{\sum_{p=1}^{\text{z}} \left( \text{price}_p[n] \times P_p[n] \right)} \]  

(7)

where \( p_{\text{pork}}[n] \) (kg y\(^{-1}\)) is the pork production of province \( n \), \( S[n] \) (head y\(^{-1}\)) represents the head of pigs slaughtered in province \( n \), \( W'[n] \) (kg head\(^{-1}\)) is the weight per pig. \( \text{price}_p[n] \) (USD kg\(^{-1}\)) is the market value of product \( p \) in province \( n \). The denominator is summed over the \( z \) output products (\( p = 1 \) to \( z \)) that originate from the pig. Here \( p \) represents the pork.

The consumptive WF of pig production consists of the consumptive WF of feed production (WF\(_{\text{cons,feed}}[n] \), m\(^3\) head\(^{-1}\)), service water (WF\(_{\text{serv}}[n] \), m\(^3\) head\(^{-1}\)), and drinking water (WF\(_{\text{drink}}[n] \), m\(^3\) head\(^{-1}\); Mekonnen & Hoekstra, 2012).

\[ \text{WF}_{\text{cons,pig}}[n] = \text{WF}_{\text{cons,feed}}[n] + \text{WF}_{\text{drink}}[n] + \text{WF}_{\text{serv}}[n] \]  

(8)

\[ \text{WF}_{\text{feed}}[n] = \text{WF}_c[n] \times \text{Feed}_c[n] + \text{WF}_f[n] \times \text{Feed}_f[n] + \text{WF}_{\text{mixing}}[n] \]  

(9)

where \( \text{WF}_c[n] \) and \( \text{WF}_f[n] \) (m\(^3\) kg\(^{-1}\)) are the WFs of the concentrates and roughage, respectively, \( \text{Feed}_c[n] \) and \( \text{Feed}_f[n] \) (kg head\(^{-1}\)) are the quantity of concentrates and roughage consumed by a pig throughout its life cycle, respectively. \( \text{WF}_{\text{mixing}}[n] \), (m\(^3\) head\(^{-1}\)) is the water consumption of feed mixing. The consumptive green WF of a pig consists of the green WF of feed by a pig consumed. The consumptive blue WF of a pig consists of the blue WF of feed consumed by a pig, drinking water, and service water.

The gray WF of a pig (WF\(_{\text{grey,pig}}[n] \), m\(^3\) head\(^{-1}\)) consists of gray WFs related to feed (WF\(_{\text{grey,feed}}[n] \), m\(^3\) head\(^{-1}\)) and water polluted by excrement (WF\(_{\text{excrement}}[n] \), m\(^3\) head\(^{-1}\)).

\[ \text{WF}_{\text{grey,pig}}[n] = \text{WF}_{\text{grey,feed}}[n] + \text{WF}_{\text{excrement}}[n] \]  

(10)

The WF\(_{\text{excrement}}[n] \) was calculated as the maximum freshwater volume needed to assimilate the water contaminant (i.e., chemical oxygen demand, biochemical oxygen demand, ammonia-nitrogen, and phosphorus) resulting from pig excrement.

\[ \text{WF}_{\text{excrement,j}}[n] = \frac{L_j[n]}{C_{\text{nat,j}}} \]  

(11)

where \( \text{WF}_{\text{excrement,j}}[n] \) represents the water for assimilation of water contaminant \( j \) from a pig’s excrement of province \( n \), \( L_j[n] \) (kg head\(^{-1}\)) represents the quantity of \( j \) in the excrement of a pig, and \( C_{\text{nat,j}} \) refers to the ambient water quality criteria for \( j \).

### 2.3. Assessing Sustainability of WF and VW Flow

#### 2.3.1. Unsustainable Blue WF and Unsustainable Virtual Blue Water Flow Based on WFN

Following Hoekstra and Wiedmann (2014), we identified areas of unsustainable blue water consumption as those where local renewable blue water resources are less than the local total water blue consumption (WF > WA), which is the same as WS > 1 in Mekonnen and Hoekstra (2016). We used the WS estimates from Mekonnen and Hoekstra (2016) at the grid level and then aggregated the values to the provincial level in China using the arithmetic average of the grid WS within that province. The following blue WS thresholds were used: values from 0 to 1 (low blue WS), 1–1.5 (moderate blue WS), 1.5–2 (significant blue WS), and >2 (severe blue WS).

The inter-provincial unsustainable blue VW flows related to pork consumption were calculated by multiplying the inter-provincial pork trade volume by the unsustainable blue WF per unit pork in the exporting region. The unsustainable blue WF per unit pork production \( \text{WF}_{\text{uns,pork}}[n] \) (m\(^3\) kg\(^{-1}\)) in province \( n \) is calculated as follows:

\[ \text{WF}_{\text{uns,pork}}[n] = \frac{\text{AWF}_{\text{uns,pork}}[n]}{P_{\text{pork}}[n]} \]  

(12)
2.3.2. WSF and Scarcie Virtual Water (SVW) Flow Based on LCA

The water scarcity footprint (WSF) based on LCA can be applied to assess the degree of the potential environmental impact of the water consumption of products and services and considers the water scarcity level along the pathway at midpoint or endpoint (Berger et al., 2014; Boulay et al., 2015; Kounina et al., 2013; Pfister et al., 2009). The WSF of a product can be assessed by multiplying the blue water consumed in a life cycle inventory of the product production by the WS index of the region where the product is produced. The WS index from Mekonnen and Hoekstra (2016) was applied to calculate the WSF of pork production.

Inter-provincial scarce virtual water (SVW) flows of pork consumption were calculated by multiplying the inter-provincial pork trade volume by the WSF per unit pork production ($WSF_{pork}[m,n]$ m³ H₂O-eq kg⁻¹) in the exporting region.

\[
WSF_{pork}[n] = \frac{AWSF_{pork}[n]}{P_{pork}[n]} 
\]

(16)

\[
AWSF_{pork}[n] = \sum_{m} SVW_{feed}[m,n] + WF_{blue,pork}[n] \times WS[n] 
\]

(17)

\[
SVW_{feed}[m,n] = WS[m] \times V_{blue,feed}[m,n] 
\]

(18)

where $AWSF_{pork}[n]$ (m³ H₂O-eq kg⁻¹) is the annual WSF of pork production, is calculated using blue water consumption (surface water and groundwater). $SVW_{feed}[m,n]$ (m³ H₂O-eq kg⁻¹) is the SVW embedded in feed export from province $m$ to province $n$.

2.3.3. Loss of Scarce Water Resources of Inter-Provincial Pork Trade

Dalin et al. (2012) displayed that the international food trade promotes global water conservation over time. If the trade relationship flows from a country with relatively high-water productivity (low VW content) to a country with relatively low water productivity, then such a trade relationship will contribute to global water savings, which conversely, will generate the loss of global water resources (Chapagain et al., 2006; Dalin et al., 2012). There will also be savings and losses for scarce water resources (Zhao et al., 2018). The significance of the losses of virtual scarce water resources (i.e., unsustainable blue VW in WFN and SVW in LCA) is that this loss will generate more unnecessary environmental impacts on the export area compared with no trade.

\[
SWS_{pork}[m,n] = (WSK_{pork}[n] - WSK_{pork}[m]) \times T[m,n] 
\]

(19)
where $A_{SWSpork}[m, n]$ is the volume of SVW loss in the trade of pork between provinces $m$ and $n$, where a positive value means saving, and a negative value means loss. WSR represents the unsustainable virtual blue water and SVW of pork, respectively, when calculating the loss of unsustainable virtual blue water and the loss of SVW.

2.4. Data

The reference values of the WF for feed crop production in each province from 1996 to 2005 were provided by the WaterStat Data set (Mekonnen & Hoekstra, 2011). Data on provincial production, yield of each considered feed crop, pork production, and heads of slaughtered pigs were derived from the National Bureau of Statistics of China (NBSC, 2020). When calculating the feed composition, the consumption data for each feed crop were derived from the China National Knowledge Infrastructure (CNKI, 2020). The head of pigs slaughtered at different farming scales was derived from the “China Animal Husbandry and Veterinary Yearbook” (CNKI, 2020). Data on concentrate consumption, roughage consumption cost, pig weight, and pig life cycle were taken from the “Compilation of Cost and Income Data of Agricultural Products in China” (NDRC, 2019). Roughage is defined as a feed with a natural water content of under 60% and crude fiber fraction greater than 18% in dry matter (Chen et al., 2015). The prices of roughage (i.e., silage maize) production in China in 2008 and 2017 were taken from the FAOSTAT database (FAO, 2020), and the cost of roughage consumption and the price of silage maize production were used to calculate the consumption of roughage. The water consumed by the mixed feed, the daily service water and drinking water for a pig, the water used for processed pork products and the value fraction of pork products were adopted from Chapagain and Hoekstra (2003). The quantity of pig excrement was acquired from Bao et al. (2018). The average contaminant content and pollutant emission criteria in pig excrement were derived from the Ministry of Environmental Protection of the People’s Republic of China (MEPC, 2015a, 2015b). The WF of roughage was assumed to be equal to that of the WF of silage maize production (Xie et al., 2020). The characteristics of WS were taken from Mekonnen and Hoekstra (2016).

3. Results

3.1. Inter-Provincial and International VW Flows Embedded in Pig Feed

An increasingly frequent flow of feed-related VW between provinces, due to the feed consumption caused by pork production in China's provinces has formed. A major reason for this is the significant disparity in the spatial distribution of pork production and feed production. Feed-related VW flowed from the water-scarce north to the water-rich south China. The net export of VW embedded in the feed from north to south was 52 Gm³ y⁻¹ in 2008 and 55 Gm³ y⁻¹ in 2017. The four provinces with the largest exports of feed-related VW were Henan, Shandong, Heilongjiang, and Jilin (Figure 2). The largest VW imports embedded in feed were the major pork-producing provinces, such as Hunan, Sichuan, Guangdong, and Yunnan. The VW embedded in international imported feed for pigs was 41 Gm³ y⁻¹ in 2008 and 46 Gm³ y⁻¹ in 2017, with an increase of 12%. The increased soybean imports were the dominant.

As a result, the WF of per unit of pork production displayed apparent regional differences (Figure S3 in Supporting Information S1). Consumptive WF was higher in most of the north, the southwest, and coastal provinces. This is because the WF of scatter feeding pigs is the largest compared to the small, medium, and large scales, and the areas with a larger scale of the scatter feeding pigs are distributed in western and northern China (Figure S2 in Supporting Information S1). Overall, the national average consumptive WF per unit pork production decreased by 8%. The main reason is that the consumptive WF of concentrates which is the largest component of pork’s consumptive WF, decreased by 14.7% on average (due to an improvement in the agricultural water-saving technology, an increase in the yield of feed crops, and a reduction in the WF of feed crops). The national average of the gray WF of pork production decreased by 3%; this was mainly related to the decreased gray WF of feed crops, which reduced by 12.7%. South China had a larger annual total consumptive WF of pork production than north China (Figure 3). The province with the largest consumptive WF and gray WF in 2017 was Hunan with 61.2 million head y⁻¹ of slaughtered pigs, accounting for 8.7% of the national total (Table S3 in Supporting Information S1).
3.2. Inter-Provincial and International VW Flows of Pork

The south-to-north VW flow embedded in pork was 13.4 Gm³ y⁻¹ in 2008 and 10.1 Gm³ y⁻¹ in 2017. This means that approximately only a quarter and one-fifth of the water embodied in feed exports from north to south China returned in the form of pork in 2008 and 2017, respectively. The large province of pork production was also a large VW exporter embedded in pork, and most of them flowed from provinces with low WS to those with high WS. Hunan, Yunnan, and Sichuan accounted for more than 50% of the pork-related VW exports in China in both 2008 and 2017.

The VW embedded in pork imports of Zhejiang increased by two times over the study period, due to halved number of pigs slaughtered, plus more consumption requirement by the growing population (increased by 5.4...
With the increase in pork production (Figure S1 in Supporting Information S1) while the decrease in population, Guizhou, Heilongjiang, and Shandong provinces changed from VW importers in 2008 into VW exporters in 2017. Fujian Province changed from a VW exporter into an importer because of the decrease in the head of pigs slaughtered (Figure 4). During the study period, China’s international pork import volume increased by 282%, which led to a nearly three-fold increase in international VW imports.
3.3. Unsustainable Blue WF Blue VW Flows Based on the WFN Framework

More than 80% of the blue WF of pork production in China was unsustainable (Figures 3c and 3d) with an increasing trend by 8%. The unsustainable blue WF of pork production in the northern region accounted for 61% in 2017 (Figures 5a and 5b). The provinces with the largest unsustainable blue WF were Shandong, Hebei, Liaoning, and Henan provinces, which accounted for 37% of the country’s total value in 2017. The unsustainable blue WF of Xinjiang, Inner Mongolia, Jilin, Liaoning (which had large blue WFs originally), and Guangdong provinces (which had a large population increase) increased significantly compared to 2008. One-third of the unsustainable blue WF of pork production in areas with low WS was imported in the form of feed from areas with higher WS. Most of the remaining areas (WS > 1) consume their local unsustainable blue water resources (Figures 5a and 5b). The unsustainable blue WF increased the most due to the increase in slaughtered pigs in Shandong Province.

Figure 4. Inter-provincial virtual water flow of pork in 2008 (upper) and 2017 (lower). The arrows show virtual water flows larger than 0.5 Gm$^3$y$^{-1}$. Detailed data on inter-provincial pig feed related virtual water flows can be found in Table S7 in Supporting Information S1.
In the stage of pork production, the unsustainable virtual blue water embedded in feed for pigs imported through international trade accounted for 7% of the total unsustainable blue WF of domestic pork production. In 2008, the total quantity of unsustainable virtual blue water related to pig feed flowing between provinces in China was 12 Gm³ y⁻¹, which increased slightly to 12.2 Gm³ y⁻¹ in 2017, representing 43% and 41% of the total blue WF of unsustainable pork production, respectively. Hebei, Henan, Shandong, and Xinjiang provinces accounted for more than 90% of the net exports of virtual blue water. In the stage of pork consumption, the unsustainable virtual blue water net imports embedded in the international pork trade increased by 1.6 times over the study period. The total inter-provincial unsustainable virtual blue water flow related to the pork trade increased by 31.8%, accounting for 13% of the total unsustainable blue WF of pork production by 2017.

The net exported unsustainable virtual blue water embedded in the feed from north to south was 8.25 and 7.22 Gm³ y⁻¹ in 2008 and 2017, respectively. Therefore, 59% and 62% of the blue water resources that competed with the environmental flow in 2008 and 2017 for pork production in the southern region came from the north. Afterward, the total quantity of net unsustainable virtual blue water embedded in pork exported from south to north was 1.37 and 1.16 Gm³ y⁻¹, which means that 16.6% and 16.1% were returned to the north, respectively.

The loss of unsustainable virtual blue water mostly occurs between provinces with relatively low WS (Figures 6a and 6b). In 2017, the number of trade chains that caused the loss of unsustainable virtual blue water increased from eight to 15 in the year 2008, with a total loss of 0.3 Gm³ y⁻¹, accounting for 7% of inter-provincial
unsustainable virtual blue water flow. Substantial losses occurred between Liaoning and Heilongjiang in 2008, due to relatively large quantities of pork imported by Heilongjiang from Liaoning.

3.4. WSF and SVW Flows Based on LCA Framework

The WSF of national pork production increased by 15%. The spatial distribution of the total WSF of pork production (Figures 6c and 6d) was similar to that of the unsustainable blue WF (Figures 6a and 6b). The WSF of pork production in the northern region accounted for 63% of the total pork production in the country in 2017. Similar to the unsustainable blue WF of pork production based on the WFN framework, areas with low WS (WS < 1) generated more than one-third of the total WSF of pork production in China.

In the pork production stage, the SVW embedded in feed imported through international trade accounted for approximately 4% of the total WSF of domestic pork. The volume of SVW embedded in feeds flowing between provinces in China increased only 2%. In the stage of pork consumption, the international pork SVW import
increased by 155.6%. The total quantity of inter-provincial SVW flows associated with the pork trade increased by 37% nationwide from 9.8 Gm³ H₂O-eq y⁻¹ in 2008.

The net SVW embedded in feed exported from north to south was 28.6 Gm³ H₂O-eq y⁻¹ in 2008 and 24.9 Gm³ H₂O-eq y⁻¹ in 2017, respectively. Namely, the northern region contributed 89% and 86% to the environmental impact caused by the water consumption of the total pork production in the country in 2008 and 2017, which is different from the evaluation of the unsustainable virtual blue water based on WFN. The total quantity of net SVW embedded in pork exported from south to north was 4.6 Gm³ H₂O-eq y⁻¹ and 3.6 Gm³ H₂O-eq y⁻¹, respectively, accounting for 15.9% and 14.6% of the scarce VW for the feed from north to south.

Loss of SVW was also generated generally between provinces with relatively low WS (Figures 6c and 6d). By the year 2017, the number of trade chains that generated the loss of unsustainable virtual blue water increased to 17, with a total loss of 1.1 Gm³ H₂O-eq y⁻¹, accounting for 8% of inter-provincial SVW flow.

4. Discussion

4.1. Non-Negligible and Intensive WF and VW Flows Related to Feed for Pork

For the first time, we clarified the contribution of feed production to both animal product-related WF and inter-provincial VW flows alongside the associated sustainability in the case for pork in China. The quantitative results demonstrate that the WF of pork production has apparent temporal and spatial differences. The northern areas with greater WS are mainly responsible for the supply of pig feed, and the feed-related VW flows from the northern areas to the southern areas with lower WS. From the perspective of water resources and economic costs, the current situation is unreasonable. China’s population is projected to reach a peak of 1.47 billion in 2032 (DESA, 2019). China’s demand for pork will continue to increase in the future. If the previous pig feeding model continues, it will undoubtedly aggravate the water crisis in the north. The most fundamental way to reduce the WF of pork is to reduce the WF of feed crops (Hoekstra & Mekonnen, 2012). Therefore, improving crop water use efficiency, vigorously developing agricultural water-saving technologies, and adjusting crop planting structures are still the primary solutions. Zhuo et al. (2019) divided the VW flow in the production and consumption of animal products into two stages: approximately 10% of the water embodied in maize exports from north to south China returns in the form of pork. However, they only considered maize, because regarding animal products. To fully track the water consumption in the pork production process, we considered the raw materials of pig feed crops more comprehensively and found that at least approximately 20% of the water embedded in feed exports from north to south returned in the form of pork.

The shown large amount of unsustainable blue WF for pork production and intensive pressure on already water scarce regions by pork production and consumption is mainly at the cost of growing feed crops in high water stressed areas. Therefore, optimization of planting structure is needed, and improvement can be conducted by placing water-intensive feed crops in low WS areas. There is also a need to restructure the feed trade, with considerably reductions in feed imports from areas of high WS. Instead, using more locally produced feed crops or import from areas of relative lower WS. In addition, regions on the two sides of pork trade generating more severe environmental impacts (e.g., Liaoning–Heilongjiang, Yunnan–Shaanxi), need to improve their productivities in respective local pork production especially exporters, or importers from other regions where the WFs of pork production and WS are both lower than their own especially to the importers.

4.2. WFN Versus LCA Framework in Assessing Impacts on Water Resources

We used the WSF of the LCA-based assessment framework to evaluate the impact of water consumption of pork production and consumption on water scarcity in China. The shown regional distributions of the consumption of scarce water resources for pork production in China obtained by evaluating unsustainable blue WF and WSF were consistent. Moreover, the WSF and the unsustainable blue WF of pork production in areas with low WS both accounted for one-third of the total values in China. The unsustainable blue WF based on WFN not only evaluates the environmental impact caused by water consumption but can also bring people more intuitive water resources management information based on the volume of water. The evaluation method based on LCA expresses more of an environmental impact degree, WF weighted by WS can describe this degree of strength and make up for the shortcomings of the unsustainable blue WF in this respect. With different indicators in different units,
Table 1
WSF of Pork Weighted by WS and CF \textsubscript{AWARE}

| Province | WS | 2017 Blue WF (m\textsuperscript{3}/kg) | WSF weighted by WS (m\textsuperscript{3} H\textsubscript{2}O-eq/kg) | CF | WSF weighted by CF (m\textsuperscript{3} world-eq/kg) |
|----------|----|----------------------------------------|-------------------------------------------------|----|--------------------------------------------------|
| Hunan    | 0.05 | 0.64 | 1.41 | 0.37 | 15 |
| Jiangxi  | 0.05 | 0.29 | 0.28 | 0.18 | 1 |
| Fujian   | 0.13 | 0.30 | 0.53 | 6.15 | 6 |
| Zhejiang | 0.15 | 0.93 | 3.31 | 15.20 | 69 |
| Tibet    | 0.45 | 2.33 | 6.53 | 1.41 | 133 |
| Heilongjiang | 0.48 | 0.94 | 2.99 | 1.83 | 54 |
| Guangdong | 0.55 | 0.55 | 1.18 | 2.08 | 6 |
| Qinghai  | 0.80 | 1.52 | 4.45 | 71.31 | 169 |
| Chongqing | 0.83 | 0.76 | 2.31 | 0.70 | 33 |
| Hubei    | 0.84 | 0.39 | 0.80 | 0.26 | 9 |
| Guizhou  | 0.84 | 0.45 | 1.21 | 0.58 | 16 |
| Sichuan  | 0.88 | 0.56 | 1.35 | 0.72 | 16 |
| Shanghai | 0.98 | 0.32 | 0.76 | 48.56 | 14 |
| Jilin    | 0.99 | 1.01 | 3.81 | 9.10 | 68 |
| Guangxi  | 1.06 | 0.47 | 1.14 | 0.79 | 11 |
| Liaoning | 1.37 | 1.03 | 3.31 | 35.87 | 69 |
| Yunnan   | 1.73 | 0.57 | 1.39 | 1.56 | 12 |
| Anhui    | 1.95 | 0.30 | 0.63 | 1.39 | 2 |
| Shaanxi  | 2.54 | 0.49 | 1.19 | 76.47 | 34 |
| Jiangsu  | 2.62 | 0.48 | 1.29 | 37.30 | 18 |
| Gansu    | 2.65 | 1.36 | 3.61 | 68.57 | 90 |
| Inner Mongolia | 2.76 | 1.58 | 4.51 | 60.30 | 101 |
| Ningxia  | 3.05 | 1.75 | 5.24 | 89.65 | 141 |
| Xinjiang | 3.17 | 2.84 | 8.85 | 73.59 | 204 |
| Hainan   | 3.22 | 0.49 | 1.47 | 14.46 | 13 |
| Henan    | 3.38 | 0.60 | 1.92 | 35.22 | 20 |
| Hebei    | 3.61 | 0.98 | 3.24 | 89.47 | 78 |
| Shanxi   | 3.79 | 0.90 | 2.94 | 92.00 | 69 |
| Shandong | 4.31 | 0.86 | 3.49 | 84.35 | 66 |
| Beijing  | 4.49 | 0.87 | 3.05 | 95.44 | 62 |
| Tianjin  | 4.50 | 1.12 | 4.45 | 96.71 | 87 |
the dimensions of the two frameworks are for sure not comparable (Vanham & Mekonnen, 2021). The current results verify the views of Boulay et al. (2013), Fang and Heijungs (2015), Pfister et al. (2017), Bai et al. (2018), and Borsato et al. (2019). The two methods can realise the evaluation of WF synergistically, providing complementary information.

4.3. Uncertainty of Accessing WS Footprint

The selection of different water scarcity indicators may introduce uncertainty to the results of WSF. The CF\textsubscript{AWARE} (Boulay et al., 2018) is another widely acknowledged WS indicator which has been developed by the Water Use in Life Cycle Assessment (WULCA), and is the midpoint indicator recommended by the United Nation Environmental Program for assessing a WSF (Frischknecht & Jolliet, 2016). Therefore, we compared the current WSF values weighted by WS from Mekonnen and Hoekstra (2016) with the CF\textsubscript{AWARE} weighted WSF of pork production (Table 1). Most of the relative distribution of the WSF calculated by the two indicators is consistent. The exception is Qinghai, measured by WS (0.8), belongs to areas with low water stress, while the CF (71.31) is a high-water stress area. Differences in blue water data sources and calculation methods of different indexes, resulting in different water stress levels in the same area.

By definition, a CF\textsubscript{AWARE} value greater than or equal to 100 means that there is not available water to meet the demand. Data from Boulay and Lenoir (2020) displayed that the CF\textsubscript{AWARE} value of each province in China was less than 100, which does not conform to the actual situation in China. For example, as displayed in the China Water Resources Bulletin issued by the Ministry of Water Resources, the demand for blue water in Beijing and Tianjin is greater than the available blue water in the local area (MWR, 2008, 2017, 2020). Therefore, it is highly recommended again to adjust the CF\textsubscript{AWARE} by local water endowments in application for sensitive regions to the approach for setting the environmental flow requirements and blue water availability (Boulay et al., 2018).

4.4. Limitations

There are three main limitations to the current analysis. First, this study focuses on blue water sustainability. There are also corresponding evaluation indicators of scarcity for green water and gray water, but the evaluation indicators for green water resources have not yet been unified (Quinteiro et al., 2018; Schyns et al., 2019). Second, the spatial scale of this study was at the provincial level. The WS was an aggregation of grid scales. The distribution of water stress degree within provinces with high water stress was different, and the water consumption of these provinces was not completely affected by the average water stress. It may result in over- or underestimation of the scarce water consumption of pork products. However, to date, the WF related to pig and pork at finer spatial resolution is not possible for the current case because of data limitations. Third, the analysis focus on one type of livestock product, even though representing the majority of the China’s case. But in a smaller scale, or localized implementations, the focuses on other water-intensive animal products is highly recommended.

5. Conclusions

The current study examined the VW flow induced by pork product consumption and its intrinsic relationship with the production WF of related feed crops and the VW flow induced by consumption, through the case for China. The results display that the distribution of pig feeding scales mainly manifests the spatial difference in WF pork production across the country. The spatial distribution of the environmental impact caused by the water consumption of pork production derived from the two frameworks of LCA and WFN is consistent, and the performance is more apparent in hot spots. On the responsibility transfer caused by VW flow, the results obtained by each framework are slightly different, but the overall trend is the same. Due to pork production in China, the pressure on water resources in the north continues to rise. The north not only provides large quantities of water for pork production in the south but also bears more than 80% of the environmental impact caused by national pork water consumption (in term of blue water). Simultaneously, more than 80% of the national blue WF of pork production is unsustainable. The scarce water consumption (unsustainable blue WF and WSF) of pork production in low water stress areas should not be underestimated. We must focus our attention on improving the efficiency of crop water use, vigorously developing agricultural water-saving technologies, adjusting crop planting struc-
ture, and effectively and reasonably altering the trade structure to avoid water loss and unnecessary ecological and environmental impacts.

Data Availability Statement
The data on reference provincial water footprint of feed crop production used for water footprint accounting for feed in the study is available at WaterStat Data set (Mekonnen & Hoekstra, 2011). The data on blue water scarcity index used for sustainability assessments of blue water footprints and virtual water flows in the study can be obtained from Mekonnen and Hoekstra (2016). The statistical data on annual provincial production, yield of each considered feed crop, and the pork production and head of slaughtered pigs used in the study is available at the National Data Set (NBSC, 2020).

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