Sustainability of water resources for agriculture considering grain production, trade and consumption in China from 2004 to 2013

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Abstract: China is a country with a serious water shortage. Irrigation water accounts more than 60% of total water use. With the nation's population forecasted to peak approximately 2030, however the production of food for additional people will require more water resources, which exacerbates water shortages. North China is a typical case for studying water-food nexus because water shortage has become a primary factor in restricting food production. From the perspective of virtual water, the study calculates the changing trend of the virtual water (VW) flow related to grain transfer in China, for which three primary crops of China, including rice, wheat and maize, are considered. The results demonstrate the impact of changing the spatial patterns of grain production on water resource utilization is large, and water resources are redistributed related to grain trade. Northern China imports water-intensive products from southern China and exports water-extensive products, and the VWVW flow from North to South from 2004 to 2013 was approximately 42.6 billion m³ per year. Although the South–North Water Diversion Project, a mega-engineering scheme constructed from the Yangtze River Basin to the Huang-Huai-Hai River Basins, alleviates water pressure on the North to a certain extent, it is insufficient for exporting to provinces, and water resources for meeting grain production in the North is problematic. Based on the results, this paper suggests that virtual water flow among provinces should be linked to water resource management. The next step in water management should focus on water supply management, rather than increasing crop trade from the North to the South, which is governed by governmental policies and economy.

Keywords: grain trade, virtual water, water footprint, water stress, water management

1 Introduction

Sustainable water supply is important for grain production, and the agricultural sector is the primary freshwater consumer; approximately 70% of the total freshwater withdrawal in the world is for irrigation (Gheewala et al., 2014). According to report on China population development, published by the China Development Research Foundation (2012), the Chinese population is forecast to peak at 1.51 billion by 2027 and 1.54 billion by 2044, the rate of population increase is approximately 11% in next decades. Due to the population and grain consumption, China's food security is not only significant to economic development and social stability in China but also important to global grain patterns (Wang et al., 2015). To ensure food security, the Chinese government pursues self-sufficiency in major staple foods, such as wheat, rice and maize (Zhuo et al., 2016a); however, geographic mismatch between its arable land and water availability has led to unsustainable agricultural expansion (Dalin et al., 2015). The Chinese crop production system is facing enormous challenges, including increasing food demand derived from the ascending population, decreasing and degrading of arable land (Zhang et al., 2016) and severe water scarcity

(Jiang, 2009). Concurrently, the “three red lines” policy was fully implemented in 2012, which sets targets of total maximum blue water consumption (670 billion m³ in 2020) (SCPRC, 2010), this is a resource constraint for agricultural water management in China.

Virtual water (VW) flow related to grain transfer could redistribute water-intensive products, which is traded from a region with lower water productivity (Oki and Kanae, 2004) and alleviate pressure on local water resources (Hoekstra and Hung, 2002; Yang and Zehnder, 2002). There have been several studies that analyzed the structure of global VW trade associated with the international food trade (Konar et al., 2011; Liu et al., 2016; Wichelns, 2015) and China’s international VW imports and exports related to crop trade (Dalin et al., 2015; Shi et al., 2014; Zhang et al., 2016), which show that VW is important for providing references for agricultural water resources management (Sun et al., 2013). The water footprint (WF), introduced by Hoekstra (Hoekstra, 2003), measures water use in relation to production or consumption. In agricultural sector, green and blue WFs of a crop are calculated by dividing the total green and blue water over the crop-growing period by the crop yield (Hoekstra et al., 2011). Substantial literature on green WF in rain-fed agriculture estimates spatial and temporal variation of evaporation (García Morillo et al., 2015; Huang et al., 2015), and blue WF lead to a reassessment of water resources (Duan et al., 2015; Veetil and Mishra, 2016). Some studies have incorporated green and blue WFs to harmonize water consumption for quantifying the volume of VW based on virtual water theory (Jiang et al., 2015; Sun et al., 2016; Zhao et al., 2015; Zhuo et al., 2016b).

These studies have mainly focused on calculating the WF of crops over long-term changes; by quantifying the intra-annual variability of virtual water trade pattern, they have shown that China has a large WF related to crop consumption and production (Hoekstra and Chapagain, 2007; Lu et al., 2016; Zhuo et al., 2016a). Furthermore, crop trade could save water when a region imports water-intensive crops rather than locally producing them. However, these literatures lack an analysis of the impact of virtual water flow on water resources in exporting regions, and do not consider irrigation management or efficiency of water used. In addition, agriculture water management practices are primarily aimed at, for instance, creating and adopting new technologies, shifting cropping patterns, and developing different cultivars (Smidt et al., 2016), and emphasizing water consumption at farm level and on-site studies (González Perea et al., 2016). These studies have shortcomings linking virtual water and water management and the impact of current food policy on water scarcity. This study links WF and VW to water management for researching water and food issues. Implementing a political plan to attain water and food security is an important problem for China (Vanham et al., 2015).

According to Bureau Statistics of China, China’s population has been more than 1.3 billion since 2004, and grain production has increased by 29% with an increase of only 1.7% in total harvested area but a 28.8% growth in irrigated area. The expansion of irrigation area mainly occurred in the North (approximately 70.4%), which accounts for 60% of cultivated land but whose share in water resources accounts is only 17% (Jia et al, 2004; Zhang et al, 2009). Despite this disparity, Northern agriculture has been exporting since 1900 (Wang et al., 2014). Given present increasing trends in population and grain, the output of grain will reach to 0.63 billion ton in 2020 (Chongqing, 2015). If 65% of this target could be taken by the North (Wu et al, 2010), the North will produce 0.41 billion ton. However, approximately 64% of China’s total population will face severe blue water scarcity (Mekonnen and Hoekstra, 2016), mainly in the North, as a result water shortage is one of the important limiting factors for agricultural development in China (Yu et al.,

2016), and it is an important challenge for water management in agriculture.

To analyze the pattern of crop trade from North to South comprehensively, this study assesses the inter-annual variability of green and blue water footprint of rice, wheat and maize, and virtual water flow related to crop trade in China. We focus on evaluating provincial water stress and impact of detailed interprovincial trade on local water conditions, discussing the SNWDP in terms of alleviating water scarcity and the influence of food policies on water resource management. Our findings will provide important insights to water management with the development of agriculture.

2 Method and Data

2.1 Study area

The Chinese mainland consists of 31 provinces, autonomous regions and municipal cities (Fig 1). China can be roughly divided into two part, south and north by isohyet 400 mm. According to Chinese multi-regional input-output models, the provinces are categorized into eight regions that have similar features in natural resources, close economic ties and adjacent geographical location (Zhang Y., 2007), including Northeast, Jing-Jin, North Coast, Northwest, Central, East Coast, South Coast, and Southwest. Next, the former four regions are classified as the north, while the latter 4 regions are belong to the south, except Shanxi and Henan.

Fig 1 Provinces and eight regions of Mainland China

2.2 Data

The data sources used in this paper are be divided into four categories, including

(1) Climate data, acquired from 820 meteorological stations of the Chinese ground climate data. The majority of the stations have complete record of climatic variables from 2004 to 2013, such as maximum and minimum air temperature at 2 m height, precipitation, relative humidity, wind speed and sunshine duration at a daily time step, which is required for green and blue water estimate.

(2) Although evapotranspiration is defined as the water lost as vapor by an unsaturated vegetative surface and it is the sum of evaporation from soil and transpiration by plants (Choudhury and Singh, 2016), crop water demand considers the crop coefficient (K_C) in order to avoid underestimation or overestimation. FAO suggests different K_C values for different crops based on various field experiments, which were conducted based on the literature surveys (Gao et al., 2014; Work, 1993; Yang et al., 2016; Zhao et al., 2015).

(3) The agricultural yield of different crops and total population in the nation and regions were obtained from statistical yearbooks, such as the China Agricultural Statistical Yearbook and China Statistical Yearbook. Rice, wheat and maize are the main crops in China, and the yield of the three types accounts for approximately 87% of the total grain producing in China from 2004 to 2013. These three crops plays a crucial role in the national grain production, as a result, this study focuses on analyzing rice, wheat and maize production and spatial distribution.

(4) This study collected water use, irrigation area and freshwater availability from the Water Resources Bulletin, which is issued by China Ministry of Water Resources, and can be used for calculating irrigation water and water stress index.

2.3 Method

2.3.1 Net transfer amount of grain

The trade balance of a crop in the province is estimated as the provincial crop production minus the total provincial amount of crop for utilization. This paper assumes that grain production could be consumed completely in a year, and exported crops are related to provinces with crop surpluses, while imported crops are related to provinces with crop deficits. Moreover, we assume that crop-deficit provinces primarily receive from the nearest crop-surplus provinces, there is the same per capita consumption in different provinces of China and values of grain consumption are equivalent to the national average.

$$\Delta A_{i,j} = T_{i,j} - P_j \times \frac{T_{i,c}}{P_c} \quad (1)$$

where ΔA_j is the net transfer amount of crop i (such as rice, wheat and maize) in province j , a positive value means grain export while a negative value means import, ton; $T_{i,j}$ and $T_{i,c}$ are the crop i production of province j and the nation, respectively, ton; P_j and P_c are the population of province j and the national population, capita.

2.3.2 Water footprint (WF) estimation

This paper excludes gray WF and only calculates green and blue components of WF because this study focuses on inter-annual variability of water resources and discusses water availability. The WF of grain production represents the water consumption per ton, and equals the sum of WF_{green}, WF_{blue} in the agricultural system with a unit of m³/ton. These values are calculated as follow:

$$WF_{i,j} = WF_{i,j, \text{green}} + WF_{i,j, \text{blue}} \quad (2)$$

$$WF_{i, \text{total}} = \frac{\sum_{j=1}^{31} WF_{i,j} \times W_{i,j}}{\sum_{j=1}^{31} W_{i,j}} \quad (3)$$

where $WF_{i,j}$ is WF of crop i in province j , m³/ton; $WF_{i, \text{total}}$ is WF of crop i in the whole country, m³/ton; $W_{i,j}$ is output of crop i in province j , ton.

This paper takes a complete plant-growing season into account based on the FAO program CROPWAT model to calculate crop water demand. The core of CROPWAT is the Penman-Monteith method, which is hypothesized to estimate potential evapotranspiration more realistically than other methods (Xu et al., 2014). The formula of the Penman-Monteith method is

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \times \frac{900}{(T + 273)} \times U_2 \times (e_s - e_n)}{\Delta + \gamma(1 + 0.34U_2)} \quad (4)$$

where ET_o is reference evapotranspiration (mm), Δ is the slope of the vapor pressure curve (kPa/°C), γ is the psychrometric constant (kPa/°C), R_n is the net radiation at the crop surface (MJ/m²d), T is the average air temperature (°C), U_2 is wind speed measured at 2 m height (m/s), e_s is saturation vapor pressure (kPa) and e_n is actual vapor pressure (kPa), and P is gross monthly rainfall.

The total crop water demand (CWR) should compensate the evapotranspiration loss from the cropped field (FAO, 1998), which associated with reference crop evapo-transpiration (ET_o) and is estimated by Penman-Monteith model and crop coefficient (K_c). In the CROPWAT model, Effective Rain (P_{eff}) can be calculated using the US-DA, SCS model.

$$CWR = ET_o \times K_c \quad (5)$$

$$P_{eff} = \begin{cases} P \frac{(125 - 0.2P)}{125} & P \leq 250 \text{ mm/m} \\ 125 + 0.1P & P > 250 \text{ mm/m} \end{cases} \quad (6)$$

As usual the irrigation water requirements basically represent the difference between the CWR and P_{eff} . When P_{eff} is more than CWR, the crop water demand could be completely met by rainfall, with no need for irrigation.

$$WF_{i,j, \text{green}} = CWR \times A_{i,j} / W_{i,j} \quad (7)$$

When P_{eff} is less than CWR, the crop needs surface water and groundwater for irrigating.

$$WF_{i,j, \text{green}} = P_{eff} \times A_{i,j} / W_{i,j} \quad (8)$$

In practical operation, crops are under the condition of insufficient irrigation most of the time. When actual irrigation is more than the difference between CWR and P_{eff} :

$$WF_{i,j, \text{blue}} = (CWR - P_{eff}) \times A / W_{i,j} \quad (9)$$

When the actual irrigation is less than the difference between CWR and P_{eff} :

$$IR_{i,j} = IR_{total} \times \frac{A}{Y} \quad (10)$$

$$WF_{i,j, \text{blue}} = (CWR - P_{eff}) \times A / W_{i,j} \quad (11)$$

When the actual irrigation is less than the difference between CWR and P_{eff} :

$$WF_{i,j, \text{blue}} = IR \times A / W_{i,j} \quad (12)$$

$$WF_{i,j, \text{blue}}$$

$$VW_{j, \text{blue}} = \sum_{i=1}^3 \Delta A_{i,j} \times$$

$$(13)$$

where A is the crop planning area of crop i in province j , ha. IR is the amount of actual irrigation water, m³.

2.3.3 Net transfer amount of virtual water

VW flow among regions related to crop trade are calculated by multiplying the net transfer amount of grain (ton) with the WF of grain (m³/ton) in the exporting region.

$$VW_j = i = 1 n \Delta A_{i,j} \times$$

$$i = 1$$

$$n$$

$$\begin{aligned}
& \Delta A \\
& i, j \\
& \times \\
& itotal,
\end{aligned}
\tag{8}$$

where VW_j is virtual water flow related to grain transfer in province j , a positive value represents virtual water export while a negative value represents import, m^3 .

2.3.4 Water Stress Index

The Water Stress Index (WSI) refers to water stress arising from water withdrawal from available local water sources (Q) (Zhao et al., 2015), which reflects water scarcity and the limits of freshwater availability for human use (Smakhtin et al., 2004). WSI only refers to blue water because green water is not useful during times of water scarcity. WSI is expressed as follow:

$$WSI_j = \frac{WW_j}{Q_j} = \frac{WU_j - PW_{net,im,j}}{Q_j} \tag{14}$$

where WSI_j is the index of blue water stress in province j ; WW_j is the local water withdrawal in province j (m^3), including industrial, agricultural, and domestic water withdrawal and is equal to water use (WU_j) minus net physical water import of province j . $PW_{net,im,j}$ is the total volume of water use from transit river and water use by interbasin water transfer in province j , m^3 . The values of WSI have been classified into 4 levels of water scarcity: No stress ($WSI \leq 20\%$), moderate ($20\% < WSI < 40\%$), severe ($40 \leq WSI \leq 100\%$) and extreme water stress ($WSI > 100\%$).

3 Result

3.1 Grain production, consumption and trade in China from 2004 to 2013

Grain productivity has risen substantially from 469 million tons in 2004 to 601 million tons in 2013. There are different crop patterns among different regions due to variable climate, soil, and dietary patterns; the most important crop is rice in the Southern China while the main crop in the Northern China is maize. Food security mainly relies on the major grain production areas, where the total land area accounts for approximately 40% of China's land area; the percentage of grain output in major grain production area has remained steady at approximately 75%. As shown in Fig 2, the total grain production in Northern China has surpassed Southern China for the first time since 2004, the output of grain in the North occupied 51% of total grain output in the nation in 2004, increasing to 56% in 2013, and the net transfer grain in 2004 is 30 million ton while the net transfer grain in 2013 is 83 million ton; more and more grain is transferred from North to South.

Fig 2 Net transfer amount of grain in North and South China

3.2 Water footprint of crop production

The total green water and blue water in China increased 20% and 10%, respectively, while the total production of those crops grew 29%. As a result, the WFs of rice, wheat and maize have slightly decreased (Fig 3). On a national scale, crops with high yield have small WF, while crops with low yield have high WF. As a result, average WF of rice is the largest of the three crops, and decreased by 4%, from 1219 m³/ton (367 m³/ton blue WF) in 2004 to 1165 m³/ton (365 m³/ton blue WF) in 2013. The WF of maize is the lowest, decreasing by 12%, from 1019 m³/ton (239 m³/ton blue WF) to 892 m³/ton (219 m³/ton blue WF). The total water consumption for rice, wheat and maize production (green water and blue water) grew from 458 billion m³ (29% of blue water) in 2004 to 553 billion m³ (30% of blue water) in 2013; however, blue water used for crop production increased from 133 billion m³ to 165 billion m³.

Fig 3 National average WF of crops (rice, wheat and maize) from 2004 to 2013 in China

3.3 Inter-regional virtual water flows in China

VW flow within China transferred from North to South experienced a sharp increase from 25.7 billion m^3 in 2004 to 65.7 billion m^3 in 2013, and VW is approximately 42.6 billion m^3 per year (24% blue water) (Fig 4). However, the North imports rice from the South, while VW declined from 58.3 billion m^3 (30% blue water) in 2004 to 50.4 billion m^3 (31% blue water) in 2013. While the South imports wheat and maize from the North, the VW related to wheat transfer slightly declined from 33.9 billion m^3 (33% blue water) in 2004 to 35 billion m^3 (35% blue water) and VW related to maize transfer significantly increased from 50 billion m^3 (24% blue water) in 2004 to 81 billion m^3 (24% blue water) in 2013.

Fig 4 Virtual water transfer from North to South China resulting from inter-regional crop trade, (a) blue water virtual flow, and (b) the sum of green and blue virtual flow.

Table 1 presents the net virtual trade balance of eight regions between 2004 and 2013, and the Northeast and Central have always been the major grain exporting regions. The Northeast is the major maize and rice exporting region, almost exporting VW 26 billion m^3 (21% blue water) in 2004, and the total net VW export increased to 61 billion m^3 (26% blue water) in 2013, which accounts for more than 93% of VW export in the North. Central China only exports rice and wheat, with VW export increasing from 25 billion m^3 (35% blue water) to 31 billion m^3 (38% blue water). The Jing-Jin, East Coast, South Coast and Southwest are all VW importers, and Northwest has changed from VW importer (1.27 billion m^3 blue water) in 2004 to exporter (0.25 billion m^3 blue water) in 2013. The North Coast is one of the primary wheat-exporting regions, and imports intensive-water rice crop, which consume more green water (almost 81% green water and 19% blue water) export extensive-water crop of wheat (63% green water and 37% blue water) and maize (79% green water and 21% blue water).

Table 1 Virtual water flow related to grain between regions (billion m^3)

Region	Year	Rice			Wheat			Maize			Total		
		VW	VW _G	VW _B	VW	VW _G	VW _B	VW	VW _G	VW _B	VW	VW _G	VW _B
NE	2004	5.83	4.07	1.76	-7.79	-5.17	-2.62	27.97	21.39	6.58	26.01	20.29	5.71
	2013	19.13	13.12	6.00	-9.38	-6.05	-3.33	51.63	38.94	12.69	61.38	46.01	15.37
Jing-Jin	2004	-4.12	-2.88	-1.24	-1.41	-0.94	-0.47	-1.45	-1.11	-0.34	-6.98	-4.92	-2.06
	2013	-6.13	-4.20	-1.92	-9.38	-6.05	-3.33	-3.58	-2.70	-0.88	-19.08	-12.95	-6.13
NC	2004	-25.38	-17.72	-7.66	17.42	11.56	5.86	10.62	8.12	2.50	2.66	1.96	0.71
	2013	-27.98	-19.20	-8.79	20.53	13.24	7.28	8.21	6.19	2.02	0.75	0.24	0.52
EC	2004	5.69	3.98	1.72	-3.53	-2.34	-1.19	-12.24	-9.36	-2.88	-10.07	-7.72	-2.35
	2013	2.42	1.66	0.76	-2.77	-1.79	-0.98	-20.61	-15.55	-5.07	-20.97	-15.68	-5.29
SC	2004	-0.64	-0.44	-0.19	-11.11	-7.37	-3.74	-13.11	-10.02	-3.08	-24.85	-17.84	-7.01

	2013	-7.04	-4.83	-2.21	-13.65	-8.81	-4.84	-21.02	-15.86	-5.17	-41.71	-29.49	-12.22
Central	2004	24.71	17.26	7.45	13.24	8.79	4.46	-13.44	-10.28	-3.16	24.52	15.77	8.75
	2013	31.10	21.33	9.76	19.56	12.62	6.94	-19.38	-14.62	-4.76	31.27	19.33	11.94
NW	2004	-16.92	-11.81	-5.10	4.99	3.31	1.68	9.16	7.00	2.15	-2.77	-1.50	-1.27
	2013	-18.35	-12.59	-5.76	3.77	2.43	1.34	19.01	14.34	4.67	4.43	4.18	0.25
SW	2004	10.82	7.56	3.26	-11.81	-7.84	-3.98	-7.52	-5.75	-1.77	-8.52	-6.04	-2.48
	2013	6.85	4.70	2.15	-15.61	-10.07	-5.54	-14.24	-10.74	-3.50	-23.01	-16.12	-6.89

3.4 Impact VW flow on water resources at the provincial level

There are 11 provinces that were the blue VW exporters in 2013, seven of those provinces are located in the North (Fig 5). Heilongjiang and Guangdong are the biggest exporter and importer, respectively, where Heilongjiang exports 10.64 billion m³ blue VW, which accounts for 69% of blue water flow in the Northeast region, and Guangdong imports 8.98 billion m³ blue VW, which is approximately 73% of blue water flow in the South CoastCoast. Water stress in China was 21.3% on average in 2013, which belongs to the moderate water stress category. As shown in Fig 6, 13 of 31 provinces have at least severe water scarcity (WSI>40%), with 5 provinces showing extreme water stress (WSI>1). Water is more scarce in the North than in southern China; WSI in northern China reaches 45% while WSI in southern China it is 17%, Chinese water-scarcity areas are primarily in northern China, such as Beijing, Hebei, Ningxia, and Xinjiang, and 10 of 16 provinces in the South show no water stress. As a high water-consuming sector, agriculture consumes large quantities of water and more grain production in the North will put pressure on water resources of the northern regions.

Fig 5 Blue VW related to grain transfer and WSI in eight regions of China in 2013

4 Discussion

4.1 Uncertainty

The current study provides WF for grain production in China, this paper compares the national average WF of rice, wheat and maize as estimated in the current study with four previous studies (Table 2). Out estimates match well with Mekonnen et al. with an R^2 value of 0.88, and the comparison with Zhuo et al. also show a good agreement with an R^2 value of 0.95. The difference between our estimates and Sun et al. and Shi et al. are within $\pm 10\%$.

Table 2 Comparison between results from previous studies

Source	Study period	Study area	Rice (m^3 / ton)			Wheat(m^3 / ton)			Maize(m^3 / ton)		
			WF _{total}	WF _{green}	WF _{blue}	WF _{total}	WF _{green}	WF _{blue}	WF _{total}	WF _{green}	WF _{blue}
(Mekonnen and Hoekstra, 2011)	1996-2005	Global	1487	1146	341	1619	1277	342	108	947	81
(Zhuo et al., 2016b) (2016)	1978-2008	China	1345	961	384	1151	839	312	754	66	819
Sun (2013)	1999-2007	China	1294	801	493	1071	546	525	830	633	197
(Shi et al., 2014) (2014)	1986-2008	China	1333	-	-	1171	-	-	850	-	-

Because there are not records indicating per capita crop consumption in different provinces, this paper assumes crop consumption per capital in different provinces is equal to the national average and crop trade from surplus regions to deficit regions were determined using the nearest rule. These assumptions provide some uncertainties in the result. However, the purpose of this paper is to understand water usage efficiency of different crops and calculate VW flows among regions based on population change, which is useful for illustrating spatial and temporal variability. This generalization principle could obtain trade flow without affecting result analysis.

4.2 Impact of SNWDP on agricultural water resources

To mitigate drought, China's South-North Water Diversion Project (SNWDP) transfers water from the humid Yangtze River basin to the dry northern plains of the Huang-Huai-Hai River Basin. SNWDP in China will ultimately transfer 44.8 billion m^3 annually, of which 14.8 billion m^3 is for

the East Route, 13 billion m^3 is for the Middle Route and 17 billion m^3 is for West Route (Liu et al., 2013). However, the West Route is still in the research stage. Approximately 60% of water diversion from the East Route and 35% of water diversion from the Middle Route supply agriculture water and zoology water, approximately 14 billion m^3 ; water receiving provinces of East and Middle Route are Jing-Jin, Hebei, Shandong, Henan and Anhui. The VW-exporting provinces in the North, including Heilongjiang, Jilin, Xinjiang and Inner Mongolia, are not water receiving areas, therefore they will have to increase their WSI to produce more grain. In addition, the water exporting provinces of SNWDP are Hubei and Jiangsu, which are also VW exporting, combined, this will result in increasing water stress. Consequently, SNWDP has a limited impact in mitigating water resource shortages caused by developing grain production. Apart from establishing the diversion project and implementing water-saving policy to manage agricultural input, the Chinese government also takes into full account both the domestic and international markets to adjust pressure on agricultural and water resources.

4.3 Water resources management in the future

If the grain output reaches 0.634 billion tons, and rice, wheat and maize produce 0.211 billion tons, 0.13 billion tons and 0.24 billion tons in 2020, respectively, the VW of grain production will total 642 billion m^3 , and will consume 173 billion m^3 in blue water. The VW of these crops will reach 407.5 billion m^3 and blue water consumption 108.9 billion m^3 in the North, which accounts for 40.3% of the limit value placed on total water consumption in the North by 2020 according to Three Red Lines policies. Chinese government has formulated a series of policies and regulations to improve the production capacity of cropland and the entire agricultural system, which has become essential to food security. Grain production is governed by market orientation for the best possible economic returns, therefore, main grain producing areas, Liaoning, Hebei, Shandong, Jilin, Jiangsu, have a very important status in agricultural development. At the same time, these provinces are facing water scarcity (Fig 6), and agricultural expansion may worsen the water scarcity in these provinces. Policy makers should link virtual water resources among provinces and regions to water management, instead of only focusing on water demand management and water use efficiency in a region. The scale of grain development production should be defined from available water resource supply at the planning level. In addition, developing water-saving irrigation and improving water use efficiency should be accelerated in the North, while the grain production capacity of South Coast should be recuperated and sown area of rice with high water consumption could be increased in the South.

5 Conclusions

WF is the key tool to assess the water redistribution related to grain trade, which is closely related to sustainable utilization of water resources. VW will also provide a new perspective for calculating water resource carrying capacity. Without considering the factor of VW related to grain trade, the planning link of VW to water management will provide a good theoretical method for sustainable agriculture development in arid and semi-arid areas. This paper assesses the nexus between food and water resources based on virtual water and is important for providing references for decision making to alleviate water shortages in the North from the produce structure's improvement and agriculture resources' disposition.

By calculating the agricultural water consumption of green and blue in China, this paper shows that irrigation water amount in the North has increased from 167 to 189 billion m^3 , while blue VW related to grain trade graduate increased from 55.71 billion m^3 in 2004 to 1515.37 billion

m³ in 2013; approximately 8% of irrigation water was transferred from the North to the South. VW flow related to regional transfer of rice, wheat and maize was approximately 42.6 billion m³ per year (24% blue water) over the period of 2004 to 2013, and reached 66 billion m³ in 2013, consuming 10% of total water resources in North China. Increasing agricultural water use and exporting VW reduce water for the development of secondary and third industry with higher added economic value, which weakens water resource carrying capacity in the North. At aregional scale, the Northeast isis always the major VW exporting regions which contributes approximately 93% VW transferred in the North, however the region is under severe water stress. Concurrently, the South Coast and Southwest are all-time VW importers, having no water stress. According to the results, agricultural development planning is not aligned with water resource planning and management. If these trends continue, this will put increasing pressure on these regions' already limited water resources.

InOn a provincial scale, Heilongjiang is the biggest exporting province, accounting for 69% of blue water flow in the Northeast region. Although SNWDP may alleviate the water pressure of provinces in the North to a certain extent (such as Beijing, Tianjin, Hebeiwhich , etc.), itis less than the VW transported from North to South. Provinces in the North, such as Heilongjiang, Shandong, Henan and Xinjiang Province are both major exporters have severe water scarcity. SNWDP does not provide relief to these VW-exporting provinces, instead it also increases water pressure on Hubei and Jiangsu. In addition, water resource policy places emphasis on both the development and conservation of water at present, but the future potential of water conservation is limited because high-efficiency water conservation projects have already been implemented in the North.

Sustainability of grain production has been a top-priority issue in China, however, the associated pressure on water resources continues to increase. China is in urgent need of collaborative efforts to develop water resources and other industries from the perspective of VW. This paper suggests that current grain production and trade pattern, governed by economics and governmental policies, will worsen the water scarcity in the North. In addition to developing water-saving irrigation and improving water use efficiency in the North, and increasing rice production areas in the South, water management should consider the impact of virtual water flow among different regions. Furthermore, agricultural development planning should be based on the local water resource condition, and water resources planning should be determined by water supply-orientation. Addressing severe water stress will alleviate the pressures on water resources and ensure food security.

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