Research Article

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# The virtual water content of major grain crops and virtual water flows between regions in China

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## Abstract

**BACKGROUND: The disproportionate distribution of arable land and water resources has become a bottleneck for guaranteeing food security in China. Virtual water and virtual water trade theory have provided a potential solution to improve water resources management in agriculture and alleviate water crises in water-scarce regions. The present study evaluates the green and blue virtual water content of wheat, maize and rice at the regional scale in China. It then assesses the water-saving benefits of virtual water flows related to the transfer of the three crops between regions.**

**RESULTS: The national average virtual water content of wheat, maize and rice were 1071 m$^3$ per ton (50.98% green water, 49.02% blue water ), 830 m$^3$ per ton (76.27% green water, 23.73% blue water) and 1294 m$^3$ per ton (61.90% green water, 38.10% blue water), respectively. With the regional transfer of wheat, maize and rice, virtual water flows reached 30.08 Gm$^3$ (59.91% green water, 40.09% blue water). Meanwhile, China saved 11.47 Gm$^3$ green water, while it consumed 7.84 Gm$^3$ more blue water than with a no-grain transfer scenario in 2009.**

**CONCLUSION: In order to guarantee food security in China, the government should improve water productivity (reduce virtual water content of crops) during the grain production process. Meanwhile, under the preconditions of economic feasibility and land-water resources availability, China should guarantee the grain-sown area in southern regions for taking full advantage of green water resources and to alleviate the pressure on water resources.**


**Keywords:** virtual water content; green water; blue water; virtual water flows; water saving; China

## INTRODUCTION

The amount of water consumed in the production process of a product is defined as its virtual water content (VWC).[1,2] Virtual water flow represents the volume of water that is embedded in traded commodities.[3] Countries or regions with scarce water resources could import water-intensive products to decrease the pressure on their own water resources. Meanwhile, the virtual water trade could save water globally if a water-intensive product is traded from a region where it is produced with high water productivity to a region with lower water productivity.[4] Therefore, the virtual water flow process may prove significant for improving global water use efficiency and alleviating pressure on local water resources.[2,5]

Since the 1990s, several researchers have estimated the virtual water flows embedded in the importing or exporting of agricultural products between countries or regions.[2,6,7] Meanwhile, other studies have stressed that the virtual water trade could alleviate local water scarcity and improve global water use efficiency by importing high water-intensive commodities (like grains) from a country or region that has a low VWC for commodities or abundant water resources.[4,5,8–10] Hitherto, most studies of virtual water and virtual water trade have generally been carried out at a global or national scale, thus concealing the regional differences of countries that consist of a wide range of agro-climatic areas.[11] At the same time, few studies focus on distinguishing green water (rainwater consumed during the crop production process) and blue water (surface or ground water consumed in crop production) in crop VWC.[12–14] The emphasis has been given to blue water in conventional water resources planning and management. However, the use of blue water is restricted by its scarcity, high opportunity cost and large influence on the environment. Meanwhile, this becomes the limiting factor to socio-economic development in water-scarce areas. Green water has sustained the terrestrial ecosystem and rain-fed agriculture worldwide.[15,16] In addition, green water generally has a lower opportunity cost and smaller environmental impact.[17] Therefore, the significance of green water for agriculture and ecosystem has triggered

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concerns among scholars.[15,17–19] In this context, determining how to reduce blue water consumption in agricultural production and divert the blue water to other sectors has become the target of countries and regions worldwide.[17] In order to achieve this purpose, it is important to quantify the amount and proportion of blue and green water in crop production.

Agriculture, as the primary consumer of water around the world, is increasingly squeezed by the demands from other sectors and threatened by climatic change.[20] Matters of food security in China have attracted much attention around the world. However, the uneven distribution of arable land and water resources has become a bottleneck for guaranteeing food security in China. Arable land is mainly located in the northern regions, while water resources are concentrated in the southern regions.[21] The total arable land in northern regions was $73.03 \times 10^6$ ha, which accounts for about 60% of total arable land of China, while the water resources in northern regions is only 19% of total quantity of China. In contrast, the cultivated land in southern regions accounts for 40% of total arable land of China; however, the water resources in southern regions make up over 81% of total water resources in China.[22] By virtue of favorable climatic conditions and water resources, the southern regions have traditionally been overwhelmingly superior in food production; hence the southern regions used to be the major grain 'export' regions. Since the 1990s, however, this situation has changed. Owing to the influence of economic, social and other factors, the arable land and grain production of southern regions have been decreasing over the last 20 years, and the southern regions have turned into the grain 'importer'.[23] This shift will have a significant effect on the redistribution of arable land and water resources in China. The transfer of grain from north to south will cause water resources diversion from northern to southern regions. This diversion brings up several issues that need to be considered: (1) the regional differences of green and blue VWC for the major grain crops; (2) the amount of virtual water flows related to the grain transfer process; and (3) any water saving benefits related to grain transfer between regions.[24]

In order to explore the foregoing problems, the present paper takes wheat, maize and rice as the research objects which are major grain crops in China and account for more than 86% of the total national grain output.[23] The present paper first provides a more detailed analysis of the green and blue VWC of wheat, maize and rice at the regional scale in China. It then evaluates the virtual water flows and volume of water savings related to the transfer of the three crops between regions.

## DATA AND METHODS

### Study area

The study region contains 31 provinces, autonomous regions and municipalities in mainland China. They are divided into two primary regions and eight sub-regions according to geographical location, climatic conditions and agricultural production conditions. The northern regions include North China, Northeast China, Huang-huai-hai Region and Northwest China. The southern regions contain Southeast China, the Middle–Lower Reaches of the Yangtze River, South China and Southwest China[25] (Fig. 1).

### Data

The model and data used in the study include the following:

*FAO Cropwat8.0 model*

CROPWAT is a decision support tool developed by the Land and Water Development Division of the Food and Agriculture Organization (FAO). It can help agricultural meteorologists, agronomists and irrigation engineering personnel to calculate crop water requirements and irrigation requirements based on soil, climate and crop data.[26,27]

*Climate data*

Climate data were taken from the CLIMWAT database,[28] including monthly average maximum temperature, monthly average minimum temperature, relative humidity, wind speed, sunshine hours and precipitation.

*Agricultural data*

The agricultural data, including crop yield, sown area and agricultural inputs (fertilizers, pesticides, agricultural machinery, etc.) (Table 1), were taken from the *China Statistical Yearbook* and Chinese agricultural statistics data.[23,29]

### Methods

The components of crop VWC are the type of water resources used in the crop growth process, including blue water (surface water or groundwater) and green water (effective precipitation). Under a rain-fed scenario, green water is equal to the total VWC of the crop. The VWC of primary crops can be calculated according to the methodology developed by Hoekstra and Hung[2] as follows:

$$\mathrm{VWC} = \frac{\mathrm{CWR}}{Y} \tag{1}$$

where VWC denotes the virtual water content ($m^3$ per ton) of crop, CWR is the crop water requirement ($m^3$ $ha^{-1}$) and $Y$ is the crop yield per unit area (tons $ha^{-1}$).

The CWR is calculated from the accumulated evapotranspiration ($ET_{c.}$) over the crop-growing period:[2]

$$\mathrm{CWR} = 10 \times \sum_{d=1}^{\log p} \mathrm{ET_c} \tag{2}$$

where the factor 10 is intended to convert water depth (mm) into water volume per land surface ($m^3$ $ha^{-1}$); evapotranspiration over the crop-growing period (mm) is calculated as follows:[27]

$$\mathrm{ET_c} = K_c \times \mathrm{ET_0} \tag{3}$$

where $K_c$ is the crop coefficient; $ET_0$ is the reference crop evapotranspiration (mm) and is calculated according to the FAO Penman–Monteith equation as follows:[27,30]

$$\mathrm{ET_0} = \frac{0.408\Delta\,(R_n - G) + \gamma \times \frac{900}{(T+273)} \times U_2 \times (e_s - e_a)}{\Delta + \gamma\,(1 + 0.34U_2)} \tag{4}$$

where $\Delta$ is the slope of the vapor pressure curve (kPa °$C^{-1}$), $R_n$ the net radiation at the crop surface (MJ $m^{-2}$ $d^{-1}$), $\gamma$ the psychrometric constant (kPa °$C^{-1}$), $T$ the average air temperature (°C), $U_2$ the wind speed measured at 2 m height (m $s^{-1}$), $e_s$ the saturation vapor pressure (kPa) and $e_a$ the actual vapor pressure (kPa).

The green and blue VWC for a crop is calculated as the green and blue water in crop water use (CWU) divided by the crop yield per unit area. The values for green and blue water in CWU are calculated



  


**Figure 1.** Study area partition. *Note:* because of limited data availability the study did not include Hong Kong, Macao and Taiwan.

**Table 1.** Sown area, yield of the three crops and agricultural inputs of each region

| | Sown area ($10^3$ ha) | | | Yield ($10^3$ tons) | | | Agricultural inputs | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sub-regions | Wheat | Maize | Rice | Wheat | Maize | Rice | Chemical fertilizer ($10^3$ tons) | Pesticide ($10^3$ tons) | Power of agricultural machinery ($10^3$ kW) | Irrigation applied ($10^9$ $m^3$) |
| North China | 869 | 1685 | 17 | 3 382 | 8 551 | 109 | 1 429 | 32 | 3 426 | 5.7 |
| Northeast China | 707 | 10741 | 3 806 | 2 502 | 65 047 | 26 731 | 6 274 | 175 | 12 375 | 51.3 |
| Huang-huai-hai Region | 13 548 | 9240 | 3 036 | 74 750 | 52 312 | 19 926 | 16 978 | 2 050 | 61 663 | 58.6 |
| Northwest China | 3 088 | 2511 | 281 | 11 722 | 13 260 | 1 943 | 4 391 | 70 | 5 228 | 73.1 |
| Southeast China | 103 | 67 | 1 907 | 409 | 268 | 12 585 | 2 260 | 131 | 3 966 | 21.5 |
| M&L of Yangtze River | 3 098 | 1126 | 11 399 | 13 325 | 5 640 | 76 957 | 10 249 | 442 | 26 753 | 77.2 |
| South China | 5 | 651 | 4 376 | 7 | 2 777 | 22 547 | 4 948 | 195 | 7 655 | 46.6 |
| Southwest China | 2 200 | 3844 | 4 419 | 6 367 | 18 060 | 31 096 | 5 863 | 139 | 9 118 | 32.3 |

Because of limited data availability the study did not include Hong Kong, Macao and Taiwan.
M&L, Middle–Lower Reaches.

by computing the accumulation of daily evapotranspiration over the crop growing period:[2]

$$VWC_{green} = \frac{CWU_{green}}{Y} = 10 \times \frac{ET_{green}}{Y} \quad (5)$$

$$VWC_{blue} = \frac{CWU_{blue}}{Y} = 10 \times \frac{ET_{blue}}{Y} \quad (6)$$

where $VWC_{green}$ and $VWC_{blue}$ are the green and blue components, respectively, of VWC for a crop ($m^3$ per ton), $CWU_{green}$ and $CWU_{blue}$ are green and blue water consumption over the crop-growing period ($m^3$ $ha^{-1}$), and $ET_{green}$ and $ET_{blue}$ are green and blue water evapotranspiration over the crop growing period (mm).

$ET_{green}$ and $ET_{blue}$ during the crop-growing period can be estimated using the Food and Agriculture Organization's CROPWAT model:[27,31]

$$ET_{green} = \min\,(ET_c, P_{eff}) \quad (7)$$

$$ET_{blue} = \max\,(0, ET_c - P_{eff}) \quad (8)$$

where $P_{eff}$ is the effective rainfall over the crop-growing period (mm).

By using the CROPWAT model combined with CLIMWAT database, the crop water requirement (CWR), effective rainfall and irrigation requirements of wheat, maize and rice were calculated for each sub-region. Subsequently, according to the yield of the three crops in the producing region, the green and blue VWC of wheat, maize and rice were calculated. In order to further analyze

  

**Table 2.** The green and blue virtual water content (VWC) of each crop in sub-regions ($m^3$ per ton)

| Sub-region | Wheat VWC | Wheat $VWC_{green}$ | Wheat $VWC_{blue}$ | Maize VWC | Maize $VWC_{green}$ | Maize $VWC_{blue}$ | Rice VWC | Rice $VWC_{green}$ | Rice $VWC_{blue}$ |
|---|---|---|---|---|---|---|---|---|---|
| North China | 1362 | 340 | 1022 | 819 | 599 | 220 | 1390 | 521 | 869 |
| Northeast China | 1538 | 531 | 1007 | 883 | 605 | 278 | 1285 | 527 | 758 |
| Huang-huai-hai Region | 960 | 512 | 448 | 759 | 656 | 103 | 1311 | 805 | 506 |
| Northwest China | 1408 | 327 | 1081 | 1007 | 446 | 561 | 1373 | 351 | 1022 |
| Southeast China | 1103 | 1060 | 43 | 1050 | 988 | 62 | 1336 | 974 | 362 |
| M&L of Yangtze River | 1025 | 839 | 186 | 665 | 659 | 6 | 1293 | 855 | 438 |
| South China | 1184 | 968 | 16 | 919 | 900 | 19 | 1472 | 1085 | 387 |
| Southwest China | 1450 | 827 | 623 | 762 | 758 | 4 | 1131 | 627 | 504 |
| National average | 1071 | 546 | 525 | 830 | 633 | 197 | 1294 | 801 | 493 |
| SD | 214.15 | 284.03 | 447.84 | 131.58 | 174.70 | 192.36 | 99.07 | 252.08 | 245.37 |
| CV | 0.17 | 0.42 | 0.80 | 0.15 | 0.25 | 1.22 | 0.07 | 0.35 | 0.41 |
| Hoekstra and Hung (2002) | 690 | — | — | 801 | — | — | 1321 | — | — |
| Liu (2007) | 975 | — | — | 844 | — | — | 1190 | — | — |

SD, standard deviation; CV, coefficient of variation; M&L, Middle–Lower Reaches.

the regional differences of VWC for the three crops, meteorological and yield data from more than 100 sites in the producing provinces were used to calculate the VWC of wheat, maize and rice. Kriging interpolation technology was used for generating the spatial distribution map of VWC for wheat, maize and rice respectively.

## RESULTS

### VWC of wheat, maize and rice

Table 2 shows the green and blue VWC of wheat, maize and rice in each region. Owing to the differences in climatic condition, crop yields and crop management between regions, the regional differences of VWC for wheat, maize and rice were significant. The coefficient of variation (CV) of wheat VWC reached 0.17, and the highest value (1538 $m^3$ per ton) was approximately 1.60 times that of the lowest value (960 $m^3$ per ton). The CV of maize (0.15) took second place, followed by VWC of rice (0.07). The national average VWC of wheat, maize and rice were as follows: wheat (1071 $m^3$ per ton), maize (830 $m^3$ per ton) and rice (1294 $m^3$ per ton). These results are approximately consistent with the results of former studies.[2,13]

Figure 2(a) shows that the regional differences of VWC for wheat were significant. The VWC of wheat was relatively low in the eastern part of Northeast China, Huang-huai-hai region, parts of the Middle–Lower Reaches of the Yangtze River and Sichuan province being less than 1000 $m^3$ per ton. The high values of VWC for wheat were mainly distributed in Northwest China, the west of Inner Mongolia, the south of the Middle–Lower Reaches of the Yangtze River and the south of Southwest China, and were more than 1800 $m^3$ per ton. The VWC of maize was between 583 and 1341 $m^3$ per ton, and the spatial distribution was slightly different from that of wheat. The low values, less than 800 $m^3$ per ton, were located in the eastern part of Northeast China, Huang-huai-hai region, the western part of the Middle–Lower Reaches of the Yangtze River and Southwest China. In contrast, the high values of VWC for maize reached more than 1000 $m^3$ per ton, and these values were mainly located in Northwest China, the western part of Inner Mongolia and most parts of Southeast China (Fig. 2b). As rice production needs more water and heat resources than wheat and maize, the sown area of rice was not as extensive as that of wheat and maize. The VWC of rice was relatively low (less than 1200 $m^3$ per ton) in the eastern part of Northeast China, Middle–Lower Reaches of the Yangtze River and the eastern part of Southwest China. In contrast, the high values of VWC for rice were located in the west of Inner Mongolia and south of Xinjiang Uygur Autonomous Region (Fig. 2c), which were more than 1600 $m^3$ per ton.

### The green and blue VWC of wheat, maize and rice

The analysis of green and blue VWC for wheat, maize and rice showed that the green water proportion in each crop increased gradually from northern to southern regions. For example, the proportion of green water in wheat VWC was 18.62% in Beijing, while it was more than 80% in most of southern regions (Fig. 3). The regional variability of green water proportions in VWC was in accordance with the distribution of precipitation in China (Fig. 3a). The regions with abundant precipitation usually have a high proportion of green water in crop VWC. Precipitation in southern regions is far greater than that in northern regions. According to the *China Water Resources Bulletin*,[21] the precipitation in northern regions only accounted for 31.51% of total precipitation of the whole country. In contrast, precipitation in southern regions accounted for 68.49% of total precipitation in China. Consequently, the green water proportion of crop VWC in southern regions would be higher than that in northern regions.

The national average green water proportion of VWC for wheat, maize and rice showed that the highest share of green water was in maize VWC (76.27%), followed by rice (61.90%) and wheat (50.98%). This suggests that the growth of maize mainly relies on green water in China. Rice took second place and wheat ranked last. Such variability was mainly caused by the non-uniform seasonal distribution of precipitation. Precipitation is concentrated mostly in summer and autumn (from May to October), and it coincides with the growing period of maize in most regions of China. Thus the green water proportion in maize VWC was higher. On the contrary, due to the limited rainfall during the growing period for wheat (particularly for winter wheat), the green water proportion of wheat VWC was much smaller than that of maize (Fig. 3).



  

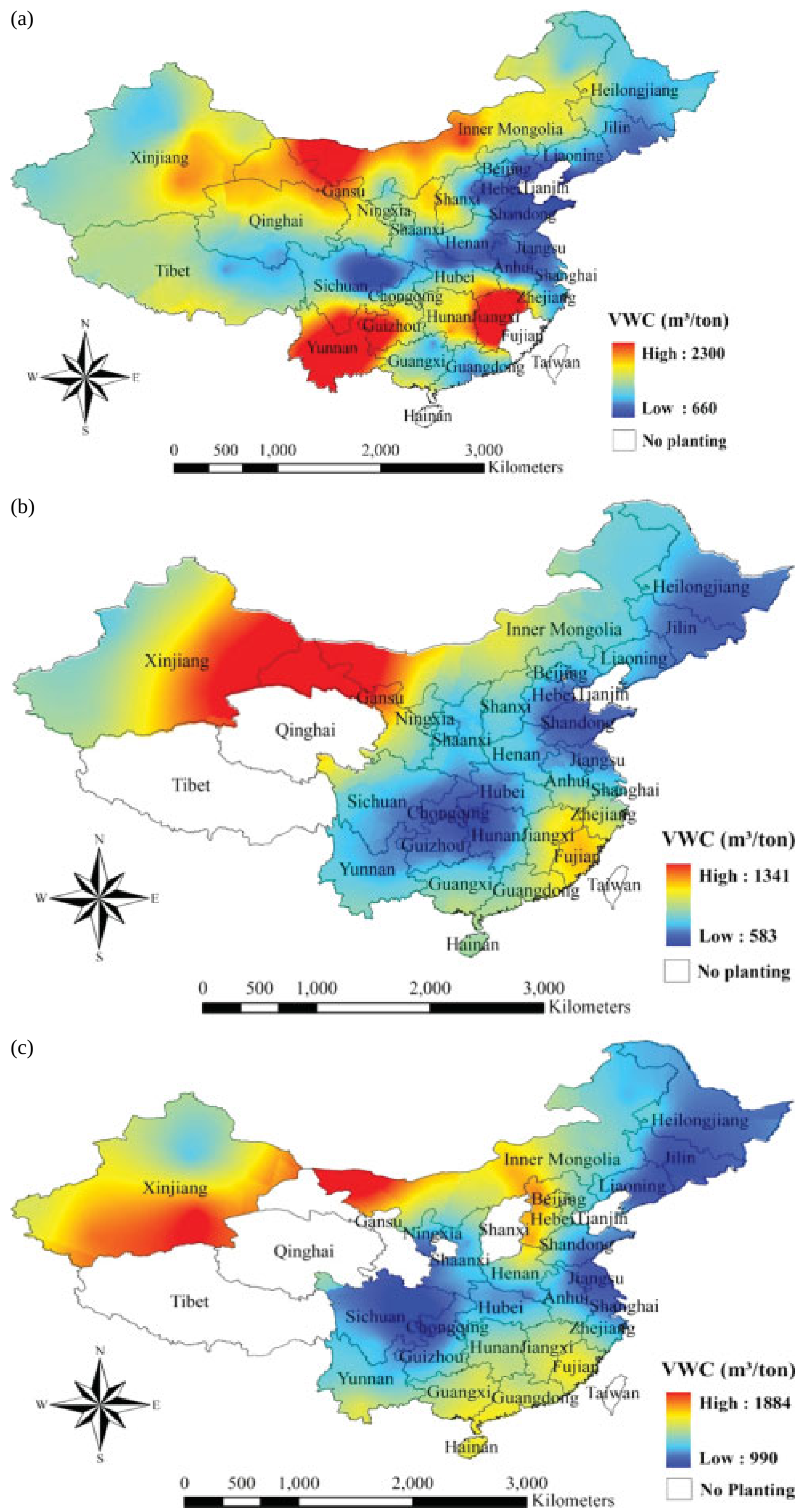


**Figure 2.** Spatial distribution of VWC of wheat, maize and rice ($m^3$ per ton): (a) wheat; (b) maize; (c) rice. *Note:* the region where the sown area was less than $10 \times 10^3$ ha and is deemed 'no planting'.

**Virtual water flows related to grain transfer between regions**

The imbalance between grain supply and demand will lead to grain transfer between regions. As can be seen from Fig. 4, grain production in northern regions has increased substantially over the past 60 years, such as in Northeast China and Huang-huan-hai region, whereas there has been an obvious downtrend in southern regions since 1990, such as South China and Southeast China. Since the beginning of the current century, the major grain production regions were located in Northeast China, Huang-huan-hai region and the Middle–Lower Reaches of the Yangtze River. According to information provided by the China National Grain and Oil Information Center,[32] the regions where wheat



  

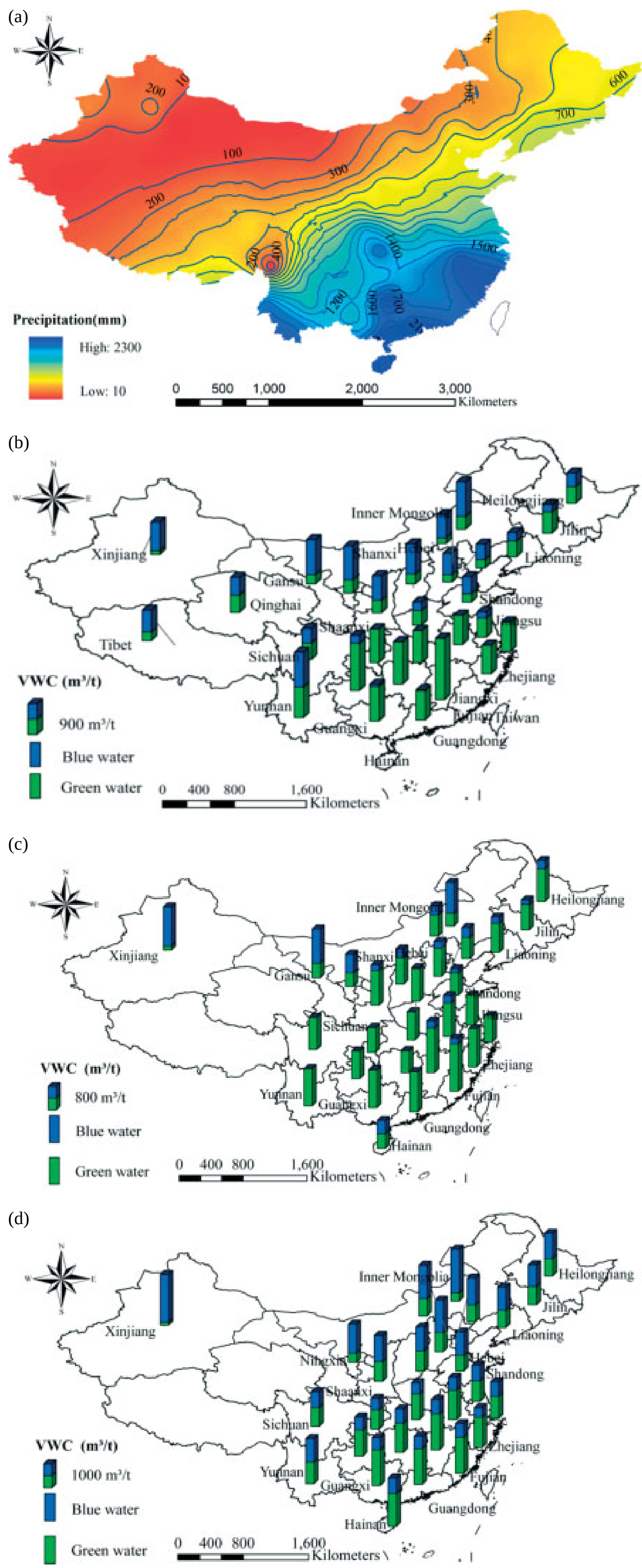


**Figure 3.** Distribution of precipitation and green/blue water components of VWC: (a) precipitation distribution; (b) wheat; (c) maize; (d) rice.



  

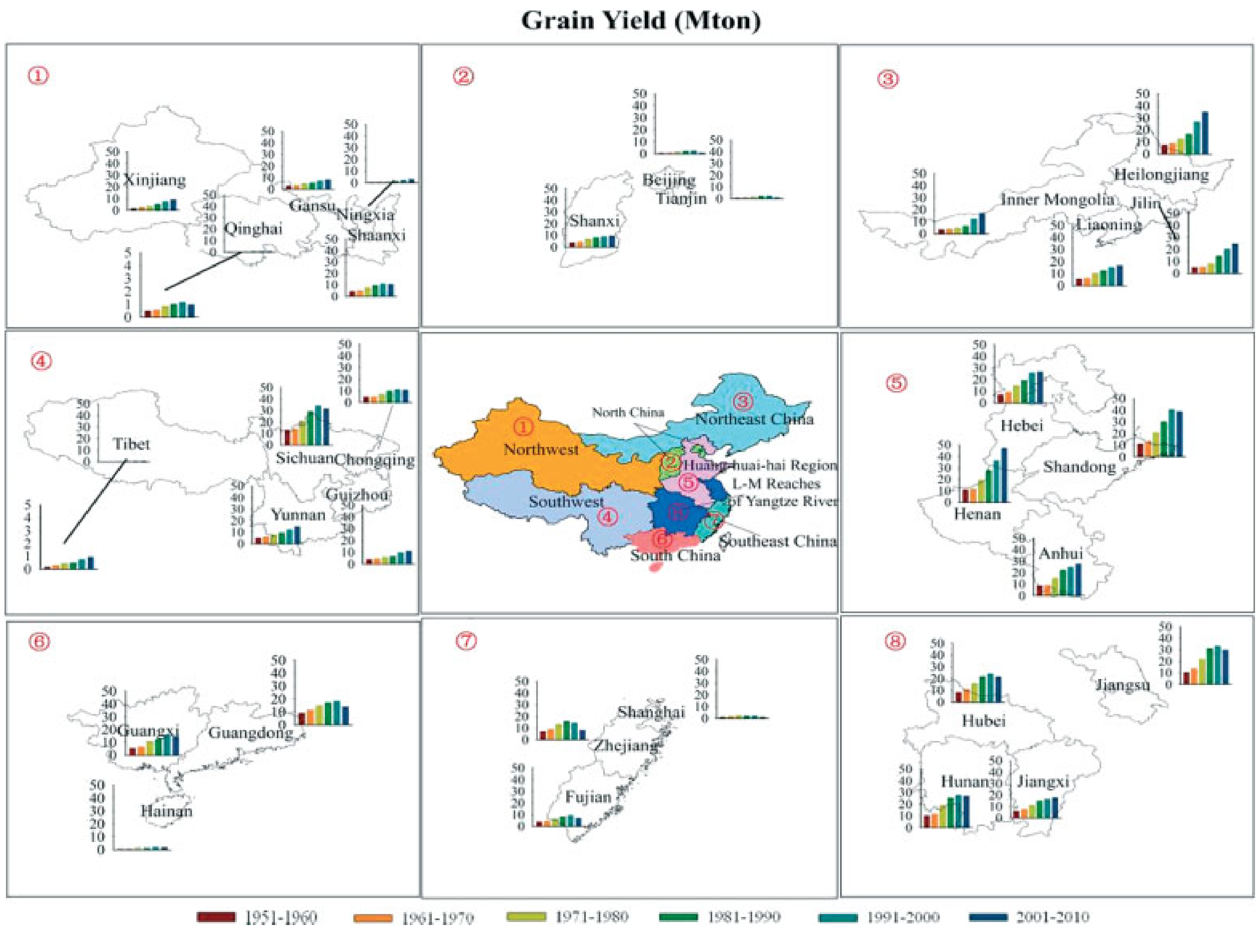


**Figure 4.** Grain production of China in different periods (megatons).

output exceeds demand were mainly located in Huang-huai-hai region, Northwest and Southwest China; For maize, the oversupply regions were distributed in North China, Northeast China, Huang-huai-hai region, Northwest China and Southwest China. For rice, the surplus regions were distributed in Northeast China, Middle–Lower Reaches of the Yangtze River and Southwest China (Fig. 5). Based on the calculation results of VWC for wheat, maize and rice above, virtual water flows related to grain transfer can be obtained (Table 3).

As can be seen from Table 3, northern regions were the major grain-'exporting' regions in China. The volume of virtual water flows related to the transfer of wheat from north to south was 9.98 $Gm^3$. The Huang-huai-hai region was the primary wheat-'exporting' region (Fig. 6a). Northeast China was the major maize-exporting region. The volume of virtual water flows related to maize 'export' from Northeast China was 13.30 $Gm^3$, of which 68.57% was green water (Fig. 6b). Rice was mainly planted in the southern regions, so it was usually transferred from southern to northern regions. During this process, the amount of virtual water flows was 1.2 $Gm^3$, and the Middle–Lower Reaches of the Yangtze River was the major 'exporting' region (Fig. 6c).

The above results showed that with the regional transfer of wheat, maize and rice in 2009, the volume of virtual water flows reached 30.08 $Gm^3$, which occupied 11.47% of total water supply in northern regions.[21] Agriculture is a high water-consuming sector; the production of grain would consume large quantities of water and put pressure on water resources of northern regions.

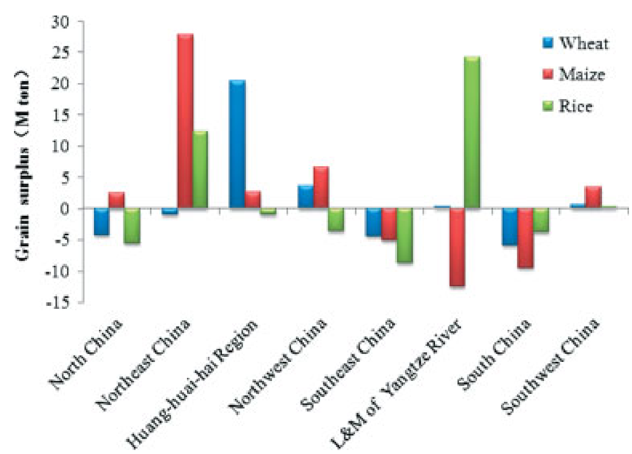


**Figure 5.** Demand and supply analysis of wheat, maize and rice in China (megatons) (2009).

Therefore, the transfer of grain from northern to southern regions would have a significant impact on the water resources situation in northern regions.

## Water savings related to grain transfer between regions in China

Through 'importing' virtual water embodied in grain, a nation or region could save the water required to produce those grains

**Table 3.** Virtual water flows related to grain transfer between regions ($Gm^3$)

| Sub-region | Wheat | | | Maize | | | Rice | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VWC | $VWC_{green}$ | $VWC_{blue}$ | VWC | $VWC_{green}$ | $VWC_{blue}$ | VWC | $VWC_{green}$ | $VWC_{blue}$ | VWC | $VWC_{green}$ | $VWC_{blue}$ |
| North China | 4.05 | 2.16 | 1.89 | — | — | — | 7.24 | 2.97 | 4.27 | 11.29 | 5.13 | 6.16 |
| Northeast China | 0.90 | 0.48 | 0.42 | −13.30 | −9.12 | −4.18 | −12.04 | −4.93 | −7.11 | −19.64 | −11.61 | −8.03 |
| Huang-huai-hai Region | −14.93 | −7.97 | −6.96 | −1.95 | −1.69 | −0.26 | 1.20 | 0.79 | 0.41 | −15.68 | −8.86 | −6.82 |
| Northwest China | — | — | — | −6.05 | −2.68 | −3.37 | 4.80 | 1.96 | 2.84 | −1.25 | −0.72 | −0.53 |
| Total of Northern Region | −9.98 | −5.33 | −4.65 | −21.30 | −13.48 | −7.82 | 1.20 | 0.79 | 0.41 | **−30.08** | **−18.02** | **−12.06** |
| Southeast China | 4.27 | 2.28 | 1.99 | 4.17 | 3.21 | 0.96 | 11.34 | 7.50 | 3.84 | 19.78 | 12.98 | 6.80 |
| M&L of Yangtze River | — | — | — | 11.08 | 7.60 | 3.48 | −17.56 | −11.61 | −5.95 | −11.27 | −5.97 | −5.30 |
| South China | 5.71 | 3.05 | 2.66 | 8.70 | 5.31 | 3.39 | 5.01 | 3.31 | 1.70 | 19.42 | 11.66 | 7.74 |
| Southwest China | — | — | — | −2.66 | −2.64 | −0.02 | — | — | — | −2.66 | −2.64 | −0.02 |
| Total of Southern Region | 9.98 | 5.33 | 4.65 | 21.30 | 13.48 | 7.82 | −1.20 | −0.79 | −0.41 | **30.08** | **18.02** | **12.06** |

'—'denotes no virtual water flows; '−' denotes virtual water output; M&L, Middle−Lower Reaches.

in their own country or region. For instance, the VWC of rice in Southwest China was 1131 $m^3$ per ton, of which 44.56% was blue water. In the Middle−Lower Reaches of the Yangtze River, the VWC for rice was1293 $m^3$ per ton, of which 33.87% was blue water. Southwest China could save 1131 $m^3$ water by 'importing' 1 ton of rice from the Middle−Lower Reaches of the Yangtze River region. At the national scale, however, when rice was transferred from the Middle−Lower Reaches of the Yangtze River region to Southwest China, there were no water saving benefits because rice production in the Middle−Lower Reaches of the Yangtze River region needed more water than that in Southwest China. The diversion of rice from the Middle−Lower Reaches of the Yangtze River region to Southwest China would lead to 162 $m^3$ of water loss per ton at the national scale. However, if the focus is only on blue water, transfer of rice from the Middle−Lower Reaches of the Yangtze River region to Southwest China would save 66 $m^3$ of blue water per ton of rice at the national scale.

Based on the principle mentioned above, an analysis was conducted to determine whether there were any water savings benefits of virtual water flows related to grain transfer between regions from the national perspective. The results are shown in Table 4. Through wheat transfer between regions, 3.01 $Gm^3$ of water was saved at the national scale. However, if we look at blue water only, 1.42 $Gm^3$ more blue water was consumed than with a no-grain transfer scenario. For maize, the virtual water flows embedded in maize transfer between regions resulted in a considerable net national water loss of 1.55 $Gm^3$; although it saved 5.71 $Gm^3$ of green water, it used 7.26 $Gm^3$ more blue water. The transfer of rice between regions saved 2.17 $Gm^3$ of water (1.33 $Gm^3$ green water and 0.84 $Gm^3$ blue water).

In summary, the virtual water trade for wheat, maize and rice between regions had saved 3.63 $Gm^3$ water in China. From the perspective of proportions of green and blue water, it saved 11.47 $Gm^3$ of green water, while consuming 7.84 $Gm^3$ more blue water than with a no-grain transfer scenario.

## DISCUSSION

The dominant challenge for agricultural water resources management for coming generations is how to secure water to meet food demands of the rapidly expanding world.[16] The growth of population and climate change may further increase water requirements for grain production in the future.[33,34] Virtual water and virtual water trade theory provide a feasible solution to improve global water use efficiency for agricultural production and to alleviate the pressure on water resources in water-scarce countries or regions.[35]

According to the virtual water theory, the VWC of a crop depends on the crop water consumption (blue water and green water) over the crop-growing period and the crop yield per unit area.[2] Crop water consumption mainly depends on the local agro-meteorological condition and irrigation system. On the other hand, crop yield per unit was influenced not only by the local agro-meteorological condition but also by the agricultural production level, such as agricultural inputs. The crop evapotranspiration ($ET_c$) of wheat in the Huang-huai-hai region was 529.67 mm, while it was 583.82 mm in Northwest China due to sparse rainfall and intense evaporation. For the yield of wheat, it was 5517.42 kg $ha^{-1}$ in Huang-huai-hai region and 3795.98 kg $ha^{-1}$ in Northwest China. Therefore, regional differences in VWC for wheat were caused mainly by the diversities of climate condition and crop yields among regions.

Although the virtual water trade for the three crops between regions in China saved 3.63 $Gm^3$ water, it resulted in a considerable net national blue water loss of 7.84 $Gm^3$ compared with a no-grain diversion scenario in 2009. The 'importing' country or region would not be concerned with whether the grain has been produced by using green or blue water in the exporting country or region, but nevertheless this has significant implications from a global or national perspective [9,18,36]. Green water generally has a lower opportunity cost and smaller environmental impact. Thus we are committed to increasing the proportion of green water in crop VWC and reducing blue water consumption. At the national level, however, the transfer of grain from northern regions to southern regions will increase the consumption of blue water. As mentioned above, the southern regions have abundant green water resources, and the proportion of green water in crop VWC is much higher in southern regions than that in northern regions. Thus the transfer of grain from south to north will reduce blue water consumption. Therefore, under the precondition of economic feasibility and land−water resources availability, China should guarantee the grain-sown area in southern regions to take full advantage of green water resources. Meanwhile, the green VWC of a crop is also influenced by the soil characteristics, conservation practices and crop species. The crop and soil properties have a significant influence on surface



  

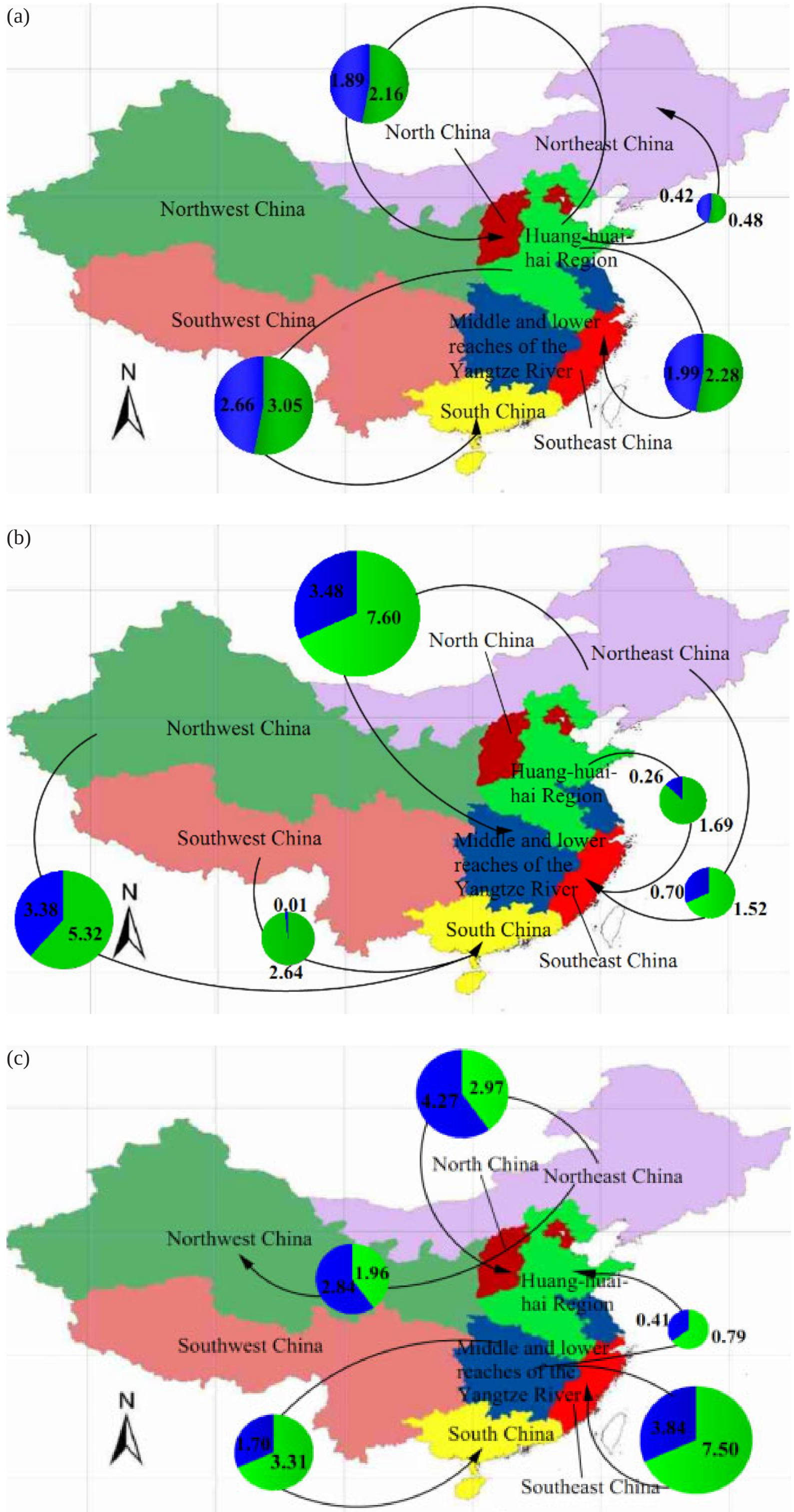


**Figure 6.** Virtual water flows related to grain transfer between regions (Gm$^3$): (a) wheat; (b) maize; (c) rice.

runoff, transpiration, evaporation and potential groundwater recharge. Good husbandry of soil, water and crops (green water management) would increase groundwater recharge and stream base flow. Several studies showed that, besides the positive effect on erosion, mulching is able to reduce soil evaporation significantly – in some cases up to 40%.[37] Therefore, better green water management would contribute to the improvement of green water use efficiency by maximizing the productive flow of water as plant transpiration and minimizing non-productive water flows, including soil evaporation, runoff and percolation beyond the root zone.[38]

Currently, most of the studies related to virtual water focus on fresh water availability. However, in countries with limited water resources, reclaimed water may contribute considerably to the



  

**Table 4.** The volume of water savings related to grain transfer between regions ($Gm^3$)

| | Wheat | | | Maize | | | Rice | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sub-region | VWC | $VWC_{green}$ | $VWC_{blue}$ | VWC | $VWC_{green}$ | $VWC_{blue}$ | VWC | $VWC_{green}$ | $VWC_{blue}$ | VWC | $VWC_{green}$ | $VWC_{blue}$ |
| North China | −1.70 | 0.72 | −2.42 | — | — | — | −0.58 | 0.04 | −0.62 | −2.28 | 0.76 | −3.04 |
| Northeast China | −0.54 | −0.02 | −0.51 | — | — | — | — | — | — | −0.54 | −0.02 | −0.52 |
| Huang-huai-hai Region | — | — | — | — | — | — | −0.02 | 0.05 | −0.07 | −0.02 | 0.04 | −0.06 |
| Northwest China | — | — | — | — | — | — | −0.30 | 0.65 | −0.95 | −0.30 | 0.66 | −0.96 |
| Southeast China | −0.63 | −2.43 | 1.80 | −1.17 | −1.81 | 0.64 | −0.38 | −1.04 | 0.66 | −2.18 | −5.29 | 3.11 |
| M&L of Yangtze River | — | — | — | 2.74 | −0.67 | 3.41 | — | — | — | 2.74 | −0.67 | 3.41 |
| South China | −0.14 | −2.71 | 2.57 | −0.02 | −3.22 | 3.20 | −0.89 | −1.03 | 0.14 | −1.05 | −6.95 | 5.90 |
| Southwest China | — | — | — | — | — | — | — | — | — | — | — | — |
| Total | −3.01 | −4.43 | 1.42 | 1.55 | −5.71 | 7.26 | −2.17 | −1.33 | −0.84 | **−3.63** | **−11.47** | **7.84** |

'—'denotes there is no grain transfer; '–' means with grain transfer between regions, this will save water at the national scale.

water budget and alleviate stress on fresh water resources.[39] The use of wastewater for irrigation is one of the methods currently widely used. It is particularly important in arid regions.[40,41] China is one of the countries that suffer a serious water shortage, for which providing sufficient water for different sectors is a challenging issue. The annual discharge of domestic wastewater is 41.4 $Gm^3$ in China.[42] While the inefficient treatment and recycling of wastewater result in the pollution of water areas and the aggravation of water crisis, there is a great water-saving potential through improving domestic wastewater centralized treatment rate and reclaimed water utilization rate in China. Although irrigation with treated wastewater can mitigate the utilization of natural water resources, it may also result in environmental problems. One particular concern is the long-term sustainability issue (e.g. the increase of salinity and sodium content in soil).[43] The study conducted by Gross[44] found evidence that long-term irrigation of arid loess soil with wastewater may result in accumulation of salts and surfactants in the soil, causing changes in soil properties and toxicity to plants. Therefore, wastewater needs to be properly treated before reuse for the purposes of irrigation. Meanwhile, how wastewater is involved in crop virtual water content and virtual water flows needs to be studied in future.

In addition, the virtual water metaphor is not sufficiently broad in scope to be considered the same concept as comparative advantage. In particular, virtual water discussions and calculations do not consider opportunity costs, which must be considered to determine the optimal allocation of scarce resources.[45] For example, the present paper focuses solely on the physical efficiency of water use in different regions in China and does not take into account the regional differences of economic efficiency; this is a limitation of the present study and further research is needed. To make reasonable decisions about the use of water resources, not only the technical efficiency of water use, but also the economic value of water in different regions, should be considered.[46]

## CONCLUSION

Food security has significant implications for China, especially as water resources become increasingly scarce. The issues we need to be concerned with are whether the water resources meet the demand for grain production and whether the distribution of grain planting is reasonable. Thus to determine the green and blue VWC of crops and the virtual water flows between regions is important for providing references for decision making for the government in agricultural water resources management. Grain diversion from northern regions to southern regions was disproportionate to the distribution of water resources in China. Therefore, in order to guarantee food security in China, the government should improve water use efficiency (reduce VWC of crops) during grain production through the application of water-saving irrigating techniques and better management of all agricultural inputs. Meanwhile, it is necessary to alleviate the pressure on blue water resources through stabilizing grain-sown areas in southern regions under the precondition of economic feasibility and land–water resources availability.

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