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Virtual water output intensifies the water scarcity in Northwest China: Current situation, problem analysis and countermeasures

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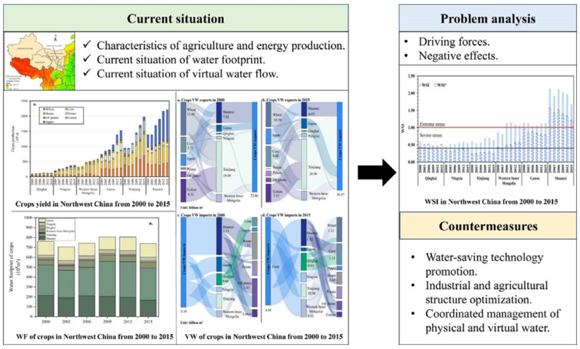
HIGHLIGHTS

- The Northwest region is a net virtual water exporter.
- The increase of virtual water export aggravates the local water resource pressure.
- We revealed the driving factors behind the virtual water transfer.
- Important insights about coordinating food and energy trade with sustainable water use

GRAPHICAL ABSTRACT



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ABSTRACT

With 80% water resources in the south and 65% arable land in the north, China is facing a rigorous challenge due to the spatial mismatch between water distribution and food & energy production to make a balanced development of economy and ecosystem. In the past decades, the northwest has played a prominent role in maintaining national food and energy security. However, the lack of water resources in this region poses a great threat to sustainable development. Based on this, this study quantitatively analyzed the evolution trend of water footprint (WF) of major crops and energy products in Northwest China from 2000 to 2015 and revealed the virtual water (VW) transfer pattern with commodity trade and its water resource stress caused by the virtual water output. The results show that, although the improvement of technology has greatly reduced the WF per unit production, the northwest region is still a net VW output area, whose net VW output associated with food and energy trade is increasing sharply from 287.2×10^8 m^3 (2000) to 328.5×10^8 m^3 (2015) with a growth rate of 14.4%, seriously aggravating the local water resource pressure. To ensure the water, food and energy safety of the northwest, we proposed countermeasures and suggestions on technological development and strategic planning, including water-saving technology promotion, industrial and agricultural structure optimization, and the coordinated management of physical and virtual water. The above findings provide a scientific reference to ensure the sustainable development of Northwest China.

1. Introduction

Water, energy, and food (WEF) are the fundamental factors and strategic supporting elements for human beings and society (Chang et al., 2016). However, the past decades saw great increasing population, accelerated urbanization and remarkable climate change, which increased the

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global demand for WEF (Gerbensleenes et al., 2009). According to UN statistics, the population of the world is expected to be 10 billion in 2050, and 40% of them will be in water-deficient areas (UN DESAPD, 2011). Accordingly, the global demand for food and energy is estimated to be up to 60% and 80%, respectively (Flammini et al., 2014). Water, the most critical constraint for food and energy production, is projected to increase by 50% in developing nations and by 18% in developed nations by 2025 (Hoekstra and Mekonnen, 2012; Okadera et al., 2014). To balance the relationship of WEF nexus, it is particularly necessary to further enhance the interaction between water for food and water for energy and strengthen water security measures in areas with water shortage.

China is one of the world's largest water users, occupying 13% of the global water consumption (Shang et al., 2016; He et al., 2019). It is estimated that the gap between water resources supply and demand in China will reach 46 × 10^8 m^3 in 2030 (China's Development and Reform Commission, 2009). In addition, China's water resources are unevenly distributed, with 82% in the south and only 18% in the north. (China Ministry of Water Resources, 2018). The spatial mismatch of land and energy undoubtedly aggravates the water scarcity in Northern China. More seriously, Northwest China has 2168 × 10^8 $m^3$of water, only accounting for 8% of the national total (Bao and Zou, 2017). However, Northwest China is very rich in land, energy and mineral resources. The arable land accounts for 35% of the national total, and the coal resources account for 70% (Ministry of Land and Resources, 2018). According to the latest statistics, Northwest China produced 12% of total national grain and 50.4% of the national electricity in 2017 (China's Bureau of Statistics, 2018), proving that it plays an essential role in China's crop and energy security. Thus, it is necessary to identify the water security problems in northwest regions and propose corresponding countermeasures to maintain the harmonious development of WEF production. In 2011, the Bonn Conference first proposed the concept of "water-energy-food nexus (WEFN)" (Hoff, 2011). Since then, the researchers gradually realized that the three subsystems are relatively independent and closely related (Sanders and Webber, 2012). In recent years, the academic community mainly focused on the internal relationship of WEF and developed some analytical tools to evaluate the stability and potential risks of WEF systems (Biba, 2016; Varis and Keskinen, 2018). However, they often emphasize the efficient utilization of "water-energy" (Zhu et al., 2015), "water-food" (Zhuo et al., 2019), and "food-energy" studies (Popp et al., 2014), which causes the WEFN research is still in its infancy. With the progress of water science, the virtual water (VW), as the water resources embedded in products, provides a new insight to cope with the current situation of water shortage and water pressure caused by the unreasonable industrial structure and food and energy trade from its unique perspective (Allan, 1997; Allan and Olmsted, 2003; Gao et al., 2019a,b). For example, based on the perspective of VW, Salmoral and Yan (2018) first mapped the physical linkages of WEF in the UK Tamar basin by using the virtual water theory. White et al. (2018) quantitatively evaluated the VW of WEFN in East Asia, and their findings showed that China was a net VW output area. At the same time, as a further extension of the VW concept, the water footprint theory (WF) is used to quantify water consumption required for products and services, in addition, the impact of human activities on water resources (Chapagain et al., 2006; Hoekstra and Chapagain, 2007). It also provides an important basis for evaluating regional water carrying capacity and formulating water resources strategy (Li and Chen, 2014; Wang et al., 2014). Walker et al. (2018) further evaluated water and energy inputs in the food processing industry throughout its life cycle. Lee et al. (2018) quantified the water and energy demand of rice in Japan from the perspective of WF. It is concluded that the concept of VW and WF could depict the connection of WEFN in time and space, broadening the discussion on the water, energy and food coordinated management among countries (Khan and Hanjra, 2009).

However, due to the industrial segmentation and different concerns, the previous studies always focused on WF assessment in a single system (agriculture system or energy system), and they paid less attention to comprehensive consideration of the WF for both food and energy and the VW flow patterns with food and energy trade. To seek effective solutions to provide decision-making advices for the common security of WEF, this study analyzes the water consumption for energy and food production from the perspective of WF and mapped the VW transfer accompanied by water-intensive crops and energy trade of northwest from 2000 to 2015. The study contents are following: 1) To calculate the WF of grain and energy production and quantify the effect of VW output on the water pressure of Northwest China; 2) To analyze the main reasons of the VW output of Northwest China and its associated consequences; 3) To propose the corresponding countermeasures to alleviate the current water stress and provide rational solutions for sustainable water management and water-adjusted industrial structure optimization in Northwest China.

2. Materials and methods

2.1. Study area

In this study, Northwest China is selected as the target area, which mainly includes Shaanxi Province (SN), Gansu Province (GS), Ningxia Autonomous Region (NX), Qinghai Province (QH), Xinjiang Autonomous Region (XJ) and the west part of Inner Mongolia (WIM, including Baotou City, Ordos City, Bayan Nur City, Wuhai City and Alxa League City), as shown in Fig. 1. The northwest area is a typical zone with fertile cultivated land and rich mineral resources, where the land area accounts for 35% of the national total, the coal reserves are as much as 1013.48 billion tons (Ministry of Land and Resources, 2018). Oil reserves are 510 million tons, accounting for nearly 23% of China's total onshore reserves (Zhou et al., 2017). Natural gas reserves are 4354 × 10^8 m^3, accounting for 58% of the onshore gas reserves in China (Chen et al., 2010).

Nonetheless, the Northwest region is a typical arid and semi-arid area, with less precipitation and a drier climate. Therefore, the local water resources are very deficient, only accounting for 8% of China, in which as much as 88.5% of the water is used by agricultural sectors (Shi et al., 2015; Chen et al., 2016). Nowadays, water shortage in the northwest has become the most important factor restricting the local economic development and social progress.

2.2. Data collection

Used data are recognized for two parts:

(1) The data for WF assessment of crops. Data on crop yield, planting area, and effective irrigated area in Northwest China were obtained from the China Statistical Yearbook from 2001 to 2016 (China's Bureau of Statistics, 2001–2016). Precipitation data in major meteorological stations were collected from the China Meteorological Science Data Sharing Service Network (http://www.cma.gov.cn/2011qxfw/2011qsjgx/). The data of agricultural water consumption and irrigation quota were obtained from the Water Resources Bulletin at the provincial level and the Yearbook of China Water Resources (China Ministry of Water Resources, 2001–2016; China's Bureau of Statistics, 2001–2016).

(2) The data for WF assessment of energy production. Coal, oil, natural gas, and electric power production and transportation data from China Energy Statistics Yearbook (China's Bureau of Statistics, 2001–2016). The WF per unit of coal, oil, natural gas and electricity is an important parameter for calculating the WF of energy products. In this study, we used the water intake quota as the unit water footprint. Water quotas for different energy production processes were determined according to the water access standards for the energy exploitation industry in Water Intake Quota (GB/T 18916-2012) and our investigations.

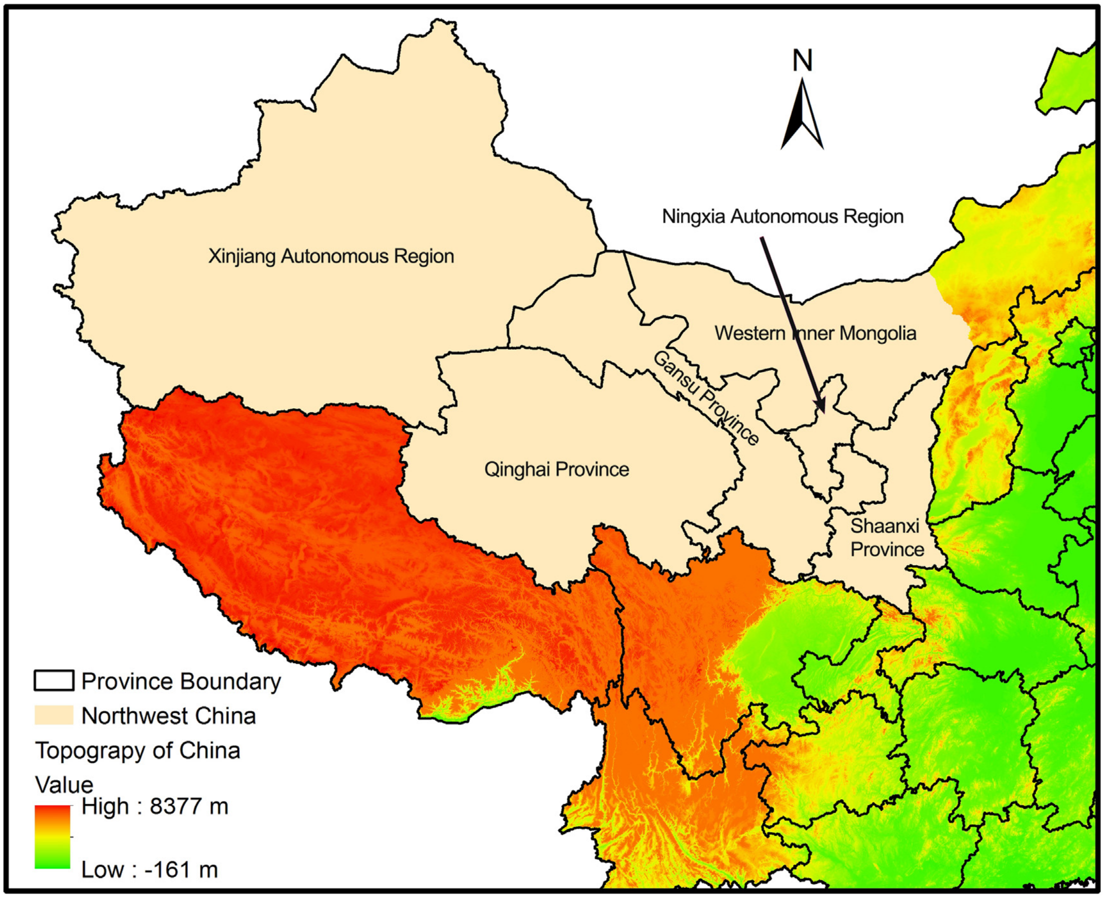

Fig. 1. Research area.

2.3. Determination of the types of agriculture and energy products

Theoretically, we should consider all the types of agriculture and energy products for WF assessment and VW flow mapping. However, there are numerous kinds of products in practice, making it impossible to include all the products. Therefore, to accurately measure the WF of the water-intensive products in Northwest China, this study identified the main water-intensive crops and energy based on the water consumption. Firstly, we collected the water usage data of different kinds of products from the provincial water resources bulletin and our investigation. Secondly, we sorted all the kinds of products according to the water consumption in ascending order. At last, we set a threshold (80%), and the products with water consumption higher than the threshold are recognized as the research objects and seeing the results in Table 1.

Table 1
Water intensive products in Northwest China.

Water-intensive agricultural products	Water-intensive energy products
Wheat, corn, beans, potatoes, oil plants, cotton, apple	Coal, petroleum, natural gas, electricity

2.4. Methods

2.4.1. Water footprint assessment

2.4.1.1. Water footprint for agricultural products. Crop WF is the water quantity used in the crop production process, including blue water footprint (BWF), green water footprint (GWF) and gray water footprint. In this study, only BWF and GWF were considered (Hoekstra et al., 2011). The crop WF is calculated by the formula (1) (Sun et al., 2013):

$$WF_i^{food} = WF_i^{green} + WF_i^{blue} \tag{1}$$

where, WF_i^{food} is the crop WF in the *i* province (m^3). WF_i^{green} and WF_i^{blue} is the GWF and BWF during the crop production in the *i* province (m^3). WF_i^{green} refers to the effective precipitation consumed during the crop growth (when the amount of effective precipitation is larger than the water demanding of the crop in the corresponding period, the effective precipitation shall be replaced by the water requirement of the crop for calculation).

$$WF_i^{green} = \frac{10^5 P_i^e S_i^G}{\lambda_i^G} \tag{2}$$

where, λ_i^G is the multiple cropping index in the *i* province and S_i^G is the crop sown area in the *i* province (10^4 hm^2). P_i^e is the effective precipitation in the *i* province. In this study, the method recommended by the soil conservation service of the United States Department of Agriculture (Döll and Siebert, 2002) was used to calculate the effective precipitation during crop growing periods in each provincial administrative region, as shown in formulas (3) and (4).

$$P_e = \frac{\mathrm{P}(4.17-0.02\mathrm{P})}{4.17} \text{ when } \mathrm{P}<83 \tag{3}$$

$$P_e = 41.7 + 0.1P \text{ when } \mathrm{P} \geq 83 \tag{4}$$

where, P and P_e are precipitation and effective precipitation of ten days, mm.

WF_i^{blue} is calculated by the formula (5).

$$WF_i^{blue} = IR_i^G S_{i,IR}^G \tag{5}$$

where, IR_i^G refers to the irrigation water use per unit area of crop(mm) and $S_{i,\,IR}^G$ is crop irrigated area (effective irrigated area) in the i province (10^4 hm^2).

2.4.1.2. Water footprint for energy products. As mentioned before, the study focuses on the WF assessment of coal mining and washing, petroleum and natural gas extraction processes and electricity generation in Northwest China using the life cycle assessment method (LCA). LCA is an effective means to assess the environmental impact of a given product or process over its entire life cycle (from the cradle to the grave) and is widely used to quantify the WF of industrial products (Yang et al., 2015). Under the framework of LCA, the energy types and life cycle stages covered by the study were determined and the WF was calculated

(1) Water footprint for coal mining and washing

The life cycle of coal includes the process of coal mining, washing, transportation and use (N. Wang et al., 2019; W. Wang et al., 2019). Its main water consumption link in the mining and washing link. The transportation and use process consume little water, can be ignored. Therefore, this study includes the BWF of coal mining and washing process, and the calculation formula is shown in Eq. (6).

$$WF_i^{coal} = wf_i^m \cdot P_i^{coal} + \alpha_i \cdot wf_i^w \cdot P_i^{coal} \tag{6}$$

where, WF_i^{coal} is the WF of coal mining and washing in province i (m^3). wf_i^m and wf_i^w represent the WF per unit of coal mining and coal washing respectively (m^3/kg). α_i is the percentage of coal washed and P_i^{coal} is the coal production (kg).

(2) Water footprint for electricity generation

The life cycle of electricity generation includes the process of coal production and power generation, in which coal production includes coal mining and coal washing, and electricity generation includes thermoelectric power generation, cooling and auxiliary systems (Meldrum et al., 2014). Therefore, the WF of electricity generation includes an indirect WF and a direct WF. The calculation formula is shown in Eq. (7).

$$WF_i^{ele} = WF_i^d + \mu \cdot WF_i^{ind} \tag{7}$$

where, WF_i^{ele} refers to the WF of electricity generation (m^3). WF_i^d is the direct WF of electricity generation (m^3). WF_i^{ind} is the WF of coal production (m^3). μ is a conversion factor. μ is generally in the range of 0.3–0.35 in China (Zhu et al., 2020). And WF_i^d calculated using Eq. (8).

$$WF_i^d = wf_i^{cc} \cdot E_i^{cc} + wf_i^{ac} \cdot E_i^{ac} + \left(wf^t + wf^a\right) \cdot \left(E_i^{cc} + E_i^{ac}\right) \tag{8}$$

where, wf_i^{cc} and wf_i^{ac} refer to the WF per unit of electricity during the cooling process in the cycle-cooling and air-cooling system, respectively (m^3/kW·h). E_i^{cc} and E_i^{ac} refer to the electricity production in the cycle-cooling and air-cooling power plant, respectively. wf^t and wf^a are the WF per unit of electricity in the thermoelectric power generation process and auxiliary system, respectively. WF_i^{ind} is calculated using Eq. (6)

(3) Water footprint for petroleum and natural gas

The water used for petroleum exploitation mainly includes water used for drilling and water used for petroleum extraction. The ratio of water used for drilling and petroleum extraction is about 1:5. The calculation formula of blue WF for petroleum exploitation is shown in Eq. (9).

$$WF_i^{oil} = wf_i^p \cdot P_i^{oil} \cdot \beta + wf_i^o \cdot P_i^{oil} \cdot (1-\beta) \tag{9}$$

where, WF_i^{oil} is the WF of petroleum exploitation (m^3). wf_i^p and wf_i^o are the WF per unit of the petroleum drilling process and extraction process in the i province respectively (m^3/kg). P_i^{oil} is the petroleum production in the province i (kg). β is the ratio of water used for drilling and petroleum extraction. In our country, usually β is 0.2 (Luis et al., 2017).

Natural gas WF is shown in Eq. (10).

$$WF_i^{gas} = wf_i^g \cdot P_i^{gas} \tag{10}$$

where, WF_i^{gas} is the WF of natural gas extraction in the province i (m^3). wf_i^g is the WF per unit of the petroleum drilling process of the gas extraction in the i province (m^3/kg) and P_i^{gas} is the natural gas production in the province i (kg).

2.4.2. Virtual water (VW) transfer

The VW transfer means the local water embedded in the agriculture and energy products being transferred to other regions with the interregional trade process, which can be quantified by the following methods:

2.4.2.1. VW transfer of agricultural products. In the calculation process of VW transfer of agricultural products, this paper assumes that there is no crop inventory in northwest provinces and that the production gives priority to local consumption, and the VW transfer is not affected by import and output.

The calculation formulas for the VW transfer amounts of crops in Northwest China are shown in Eq. (11).

$$VW_i^f = G_i' wf_i^{food} \tag{11}$$

where, VW_i^f is the VW transfer amount of crops in the i province (m^3). wf_i^{food} refers to the WF per unit of crop production (m^3/kg). G_i' refers to the crop transfer in the i province. The calculation formula of crop transport amount is as follows.

$$G_i' = G_i - P_i \frac{G_N}{P_N} \tag{12}$$

where, P_N and P_i are the national population and the population in the province i (10^4 people). G_N is the total crop demands of the country. G_i is the crop production in the i province.

2.4.2.2. VW transfer amount of energy. The calculation process for the VW transfer with energy products trade is shown in Eq. (13).

$$VW_i^e = wf_i^{coal} T_i^{coal} + wf_i^{oil} T_i^{oil} + wf_i^{gas} T_i^{gas} + wf_i^{ele} T_i^{ele} \tag{13}$$

where, VW_i^e is the VW transfer amount embedded in energy products trade in the i province (m^3). T_i^{coal}, T_i^{oil}, T_i^{gas} and T_i^{ele} are the total amount of coal, petroleum, natural gas and electricity transferred by trade from i province, respectively (kg). wf_i^{coal}, wf_i^{oil}, wf_i^{gas} and wf_i^{ele} are the WF per unit of the coal, petroleum, natural gas and electricity production, respectively (m^3/kg).

2.4.3. Water stress index (WSI) induced by VW flow

The WSI refers to the ratio of water withdrawal to water availability. This indicator directly reflects the degree of regional water shortage and reveals the relationship between local water use and available water resources, which is conducive to decision-making and improved management of the local limited water volume (Zhao et al., 2015; Gao et al., 2018). In this study, an actual water stress index (WSI, only considering the amount of physical water taken from the local region, while neglecting the net inflow of VW) and a hypothetical water stress index (WSI*, considering both the amount of physical water taken from the local region and the net inflow of VW) were constructed to analyze the impact of the VW trade on regional water resources, as shown in Eqs. (14) and (15).

$$WSI = \frac{WW}{Q} \tag{14}$$

$$WSI^{*} = \frac{WW + VW_{net}}{Q} \tag{15}$$

where *WW* refers to the total amount of water used (m^3), Q is the available water resources (m^3), and VW_{net} refers to the net import of VW. Using *WSI*, the degree of water shortage can be categorized into five levels: no stress ($WSI \leq 0.2$), moderate stress ($0.2 - 0.4$), severe stress ($0.4 - 1$), and extreme stress ($WSI > 1$).

According to Eqs. (14) and (15), the difference between WSI* and WSI, shown in Eq. (16), represents the contribution of net VW flows in terms of increasing or ameliorating water stress

$$WSI^{*} - WSI = \frac{VW_{net}}{Q} \tag{16}$$

3. Results and analysis

In the next chapter, we first summarize the production and transportation of agricultural products and energy in Northwest China from 2000 to 2015, and then discuss the spatial and temporal characteristics of WF and VW flow in Northwest China. The influence of VW flow on water resources in Northwest China is also evaluated.

3.1. The characteristics of agriculture and energy production and their inter-regional trade

Food productions in Northwest regions from 2000 to 2015 are shown in Fig. 2a. The water-intensive crop output in all provinces of Northwest China showed an increasing trend. These productions increased from 3670 × 10^4 tons in 2000 to 6796 × 10^4 tons in 2015 and accounted for 40% of food productions in China over the past 15 years. Among them, wheat and corn production are the main types of agriculture products, occupying 28% and 33% of the total production, respectively. In terms of the spatial distribution, Shaanxi Province has the

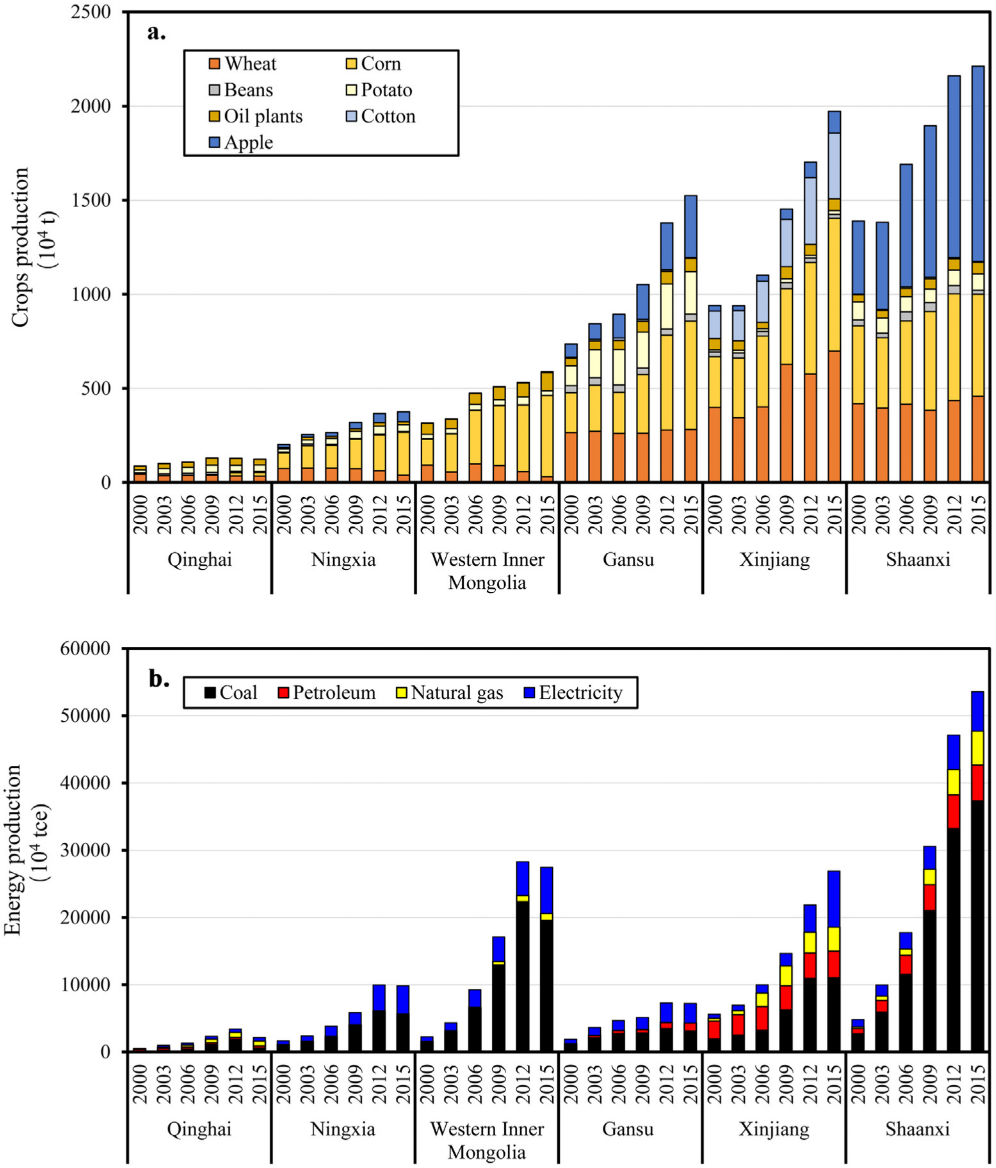

Fig. 2. (a) Agriculture and (b) energy production in Northwest China from 2000 to 2015.

highest agricultural production yield in Northwest China due to its high production of wheat, corn, and apple. In 2000, Shaanxi's agricultural production was 13.89 million tons, but it reached 22.12 million tons in 2015, with an increasing rate of 59%. Xinjiang Autonomous Region is rich in solar radiation, which provides a good condition for cotton growth. Accordingly, Xinjian becomes the main producing area of cotton of China, whose cotton production accounts for 94% of the production in the Northwest. Qinghai has the smallest agricultural production but has large animal production. According to statistics, the grain yield of Qinghai Province increased from 0.87 million tons (2000) to 1.24 million tons (2015), accounting for only 2.2% of the agricultural production in Northwest China.

Fig. 2b shows the energy productions in Northwest China from 2000 to 2015. Similar to food, energy productions in Northwest China also showed a significant increase. In 2000, energy productions amounted to 168.07 million tons of standard coal, whereas in 2015, this value increased to 1271.57 million tons of standard coal. Fig. 2b shows that coal and electricity were the main energy product in Northwest China, occupying 59% and 21% of the total energy production. The two major coal and electricity bases in northern Shaanxi and Ningdong have resulted in high local energy production in Shaanxi province, rising from 48.20 million tons standard coal (2000) to 535.85 million tons standard coal (2015). At the same time, along with the western economic strategy, especially during the 12th Five-Year Plan period (2011–2015), the state is committed to developing Inner Mongolia and Xinjian into important strategic resource support bases. Energy production in western Inner Mongolia and Xinjian has grown rapidly, increasing 9.94 times and 13.7 times in 2015 compared with 2000, respectively.

In the 16 years, the production in the Northwest far exceeded the local demand for food and energy. With the increase of agricultural and energy production, the inter-regional trade of agricultural and energy production in Northwest China is also rising. According to statistical results, the agricultural products output ratio in Northwest China increased from 0.34 (2000) to 0.44 (2015) (Fig. 3), among which the Western Inner Mongolia (0.57) and Xinjiang (0.53) had the larger agricultural products output volume. Similar to agriculture products, the energy products output ratio also showed a significant increase. These outputs ratio increased from 0.29 in 2000 to 0.49 in 2015. Shaanxi (0.52) and western Inner Mongolia (0.46) have large energy output due to their rich coal and power resources.

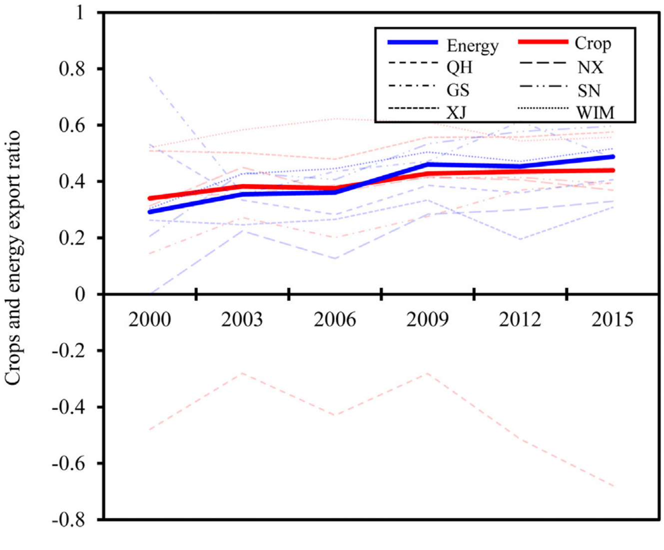

Fig. 3. Changes in crops and energy output ratio in Northwest China from 2000 to 2015. (Bold blue and red lines are the energy and crops output ratio in Northwest China. Light blue and red lines are the energy and crops output ratio in each province. Different Line types represent different provinces' output ratio. For specific data, see Table S1).

3.2. Water footprint for agriculture and energy production from 2000 to 2015

Growing agriculture and energy productions have led to an increase in WF. In 2000, 76.37 billion m^3 of WF related to agriculture was recorded in Northwest China, among which the contributions of Shaanxi province and Xinjiang province were 25.8% and 41.9%, respectively; in 2012, this value increased sharply to 80.56 billion m^3, and then slightly decreased to 73.96 billion m^3 in 2015 (Fig. 4a). Although the crop yield of Shaanxi province was increasing year by year, the improvement of agricultural water use technology and management level has declined the crop WF from 21.49 billion m^3 in 2000 to 16.54 billion m^3 in 2015. In comparison, Xinjian province's WF is higher than that in other provinces, and the crop WF increases continuously with the increase of yield, from 30.90 billion m^3 (2000) to 32.54 billion m^3 (2015).

As shown in Fig. 4b, the WF of energy in Northwest China was on the rise from 2000 to 2015, among which Shaanxi province, Western Inner Mongolia and Xinjian are the main energy production bases in China, and the WF associated energy is significantly higher. The WF related to energy in Shaanxi province increased from 176.11 million m^3 in 2000 to 351.11 million m^3 in 2015. WFs were mainly composed of electricity's WF. In 2000, the WF for electricity was 604.55 million m^3, and this value increased to 1487 million m^3 in 2015. The main reason is that electricity WF not only considers direct water use, WF in coal production is also taken into counted.

One particular phenomenon is that the rate of increase in WF is very different from that in yield. Yield and per unit WF are the main factors

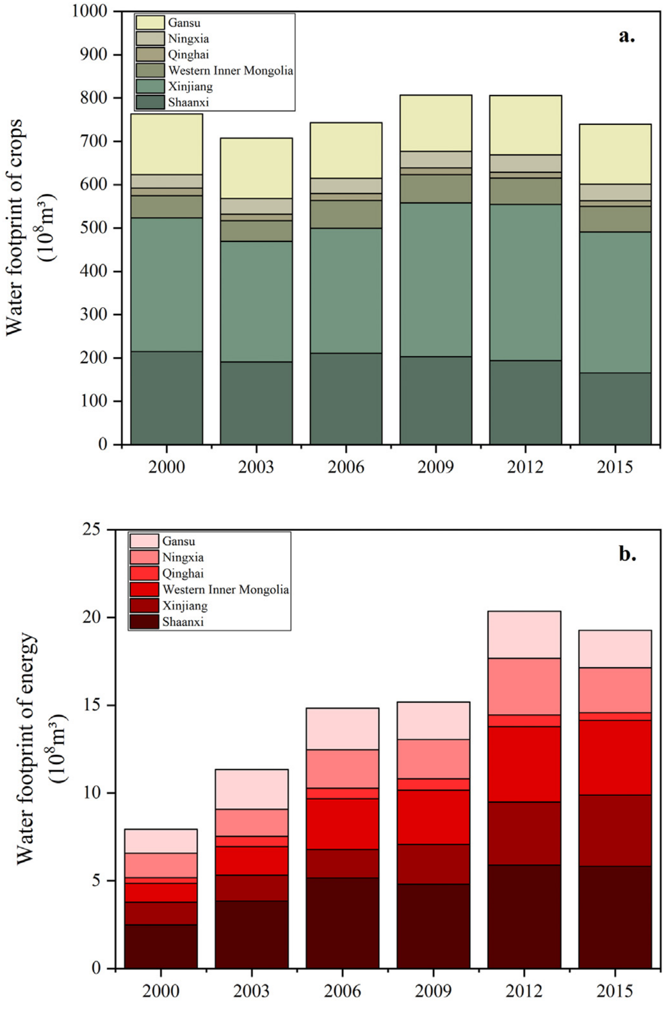

Fig. 4. Water footprint of (a) crops and (b) energy in Northwest China from 2000 to 2015.

driving the increase of WF. As shown in Fig. 5, between 2000 and 2015, the crops and energy output increased with a factor of 0.85 and 6.56. However, the increase in the WF has been flat and has declined since 2012. This indicates that scale advantage (yield) is the most significant driving factor of WF before 2012. From 2000 to 2015, especially after 2012, the declining unit WF became the biggest driver and had a positive effect on slowing the growth of the WF.

3.3. Current situation of VW flow with the inter-regional trade of agriculture and energy products

From 2000 to 2015, Northwest China was the VW output region of agriculture and energy products. Furthermore, the net VW output volume showed a rising trend in fluctuation, increasing from 28.72 billion m^3 (2000) to 32.85 billion m^3 (2015) with a growing rate of 14.4%. Among them, the VW output with crops accounted for more than 90% of the total VW output in Northwest. Fig. 6 shows the VW transfer structure of crops and energy in Northwest China. The crops VW outputs in Northwest China were predominantly wheat and cotton. Soybean was the mainly compose of VW inputs, which was totally supported by places outside Northwest China. The VW values for energy are smaller than those for crops, with the VW for energy increasing from 157.54 million m^3 (2000) to 562.27 million m^3 (2015), representing only 0.5% and 1.7% of crop's VW values over the same period, respectively. As shown in Fig. 6b, electricity's VW has always made up the bulk of total VW output. In 2000, the VW value for electricity was 69.14 million m^3, and this value increased to 342.61 million m^3 in 2015.

The regional differences of VW are relatively large due to differences in climatic conditions and population scale. Fig. 7 shows the crops VW outputs and inputs for the provinces in Northwest China in 2000 and 2015. From 2000 to 2015, crops VW outputs increased from 33.66 billion m^3 to 36.97 billion m^3, while VW inputs decreased from 5.10 billion m^3 to 4.48 billion m^3. Wheat was the largest VW output crop, followed by cotton and corn. Compared with the output of VW, the input volume of VW in Northwest China is very small, accounting for only 12% of the output volume of VW. Except for soybean, the VW inputs of other crops were from the internal VW flow in Northwest China. Soybeans have become the most needed crop in Northwest China. Although the virtual water input volume of soybean in Northwest China has decreased from 1.61 billion m^3 to 0.65 billion m^3, improving the soybean self-sufficiency rate is still an urgent problem in Northwest China. China is a net importer of soybeans. According to statistics, the average annual VW input volume of soybean in China reached 47.34 billion m^3 (Zhuo et al., 2016). Meeting the demand for soybean is also of great significance to improve China's food security.

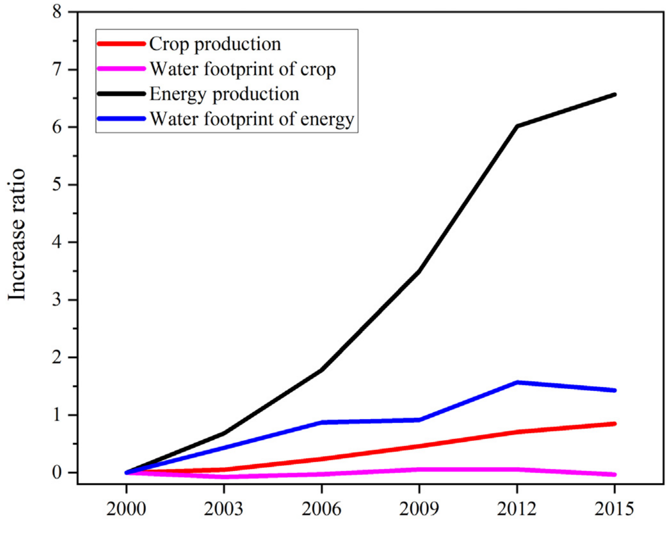

Fig. 5. The increase ratio in crops and energy production and WF in Northwest from 2000 to 2015.

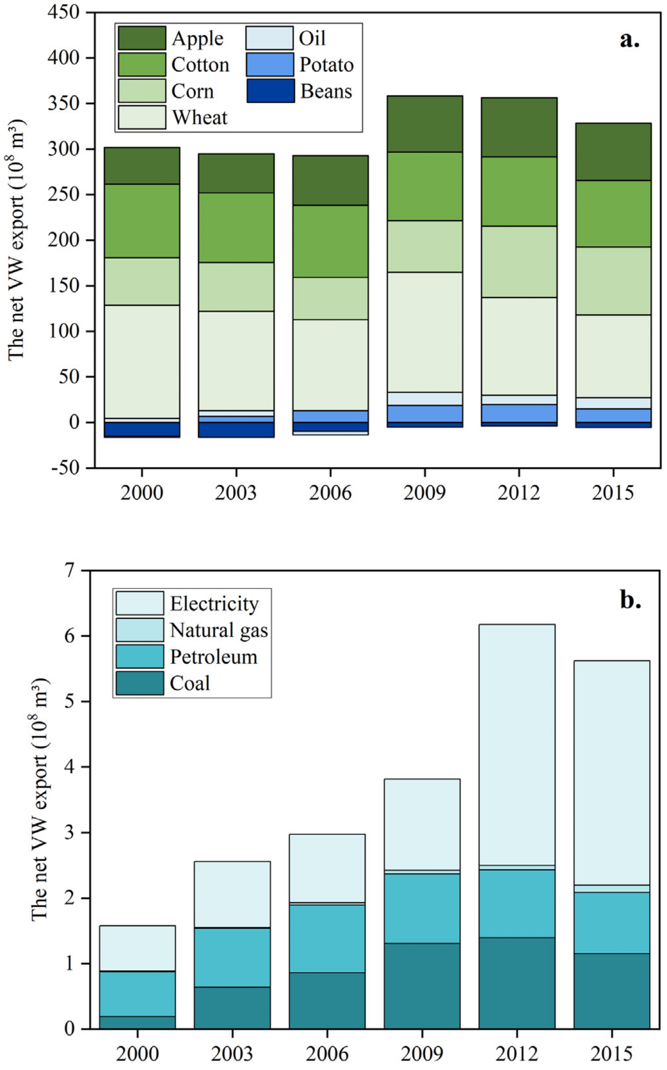

Fig. 6. The contribution of each (a) crop and (b) energy in the VW flows of Northwest China.

With the trade of energy products, the amount of VW flows in Northwest Provinces show different trends. In 2000, Gansu Province was the largest VW output area. Petroleum was the mainly compose of Gansu's VW outputs, accounting for 50% of its total VW outputs. In 2015, Shaanxi province became the largest VW output area. Unlike crop VW output, its energy VW output increased from 15.32 million m^3 (2000) to 189.68 million m^3 (2015). This also indicates that Shaanxi province is shifting from agricultural VW outputs to industrial VW outputs. The VW outputs of energy in Shaanxi province were predominantly coal and electricity. Western Inner Mongolia ranked second in VW output areas, accounting for 25.4% of the total output volume. Electricity is the largest VW output product in Western Inner Mongolia. What's more, the virtual water output volume of Ningxia Province changed from 0 to 87.37 million m^3. The establishment of Ningdong coal power base in 2003 is the main driving reason for its change. Therefore, electricity has also become the largest VW output product in Ningxia Province (Fig. 8).

At the same time, the VW outflow ratio (VOA) in Northwest increased year by year from 37.10% (2000) to 42.84% (2015) (Table 2), with the highest VOA in Xinjiang (57.98% on average) and Western Inner Mongolia (51.81% on average). It fully shows that the crops and energy products in Northwest China were mainly traded to other

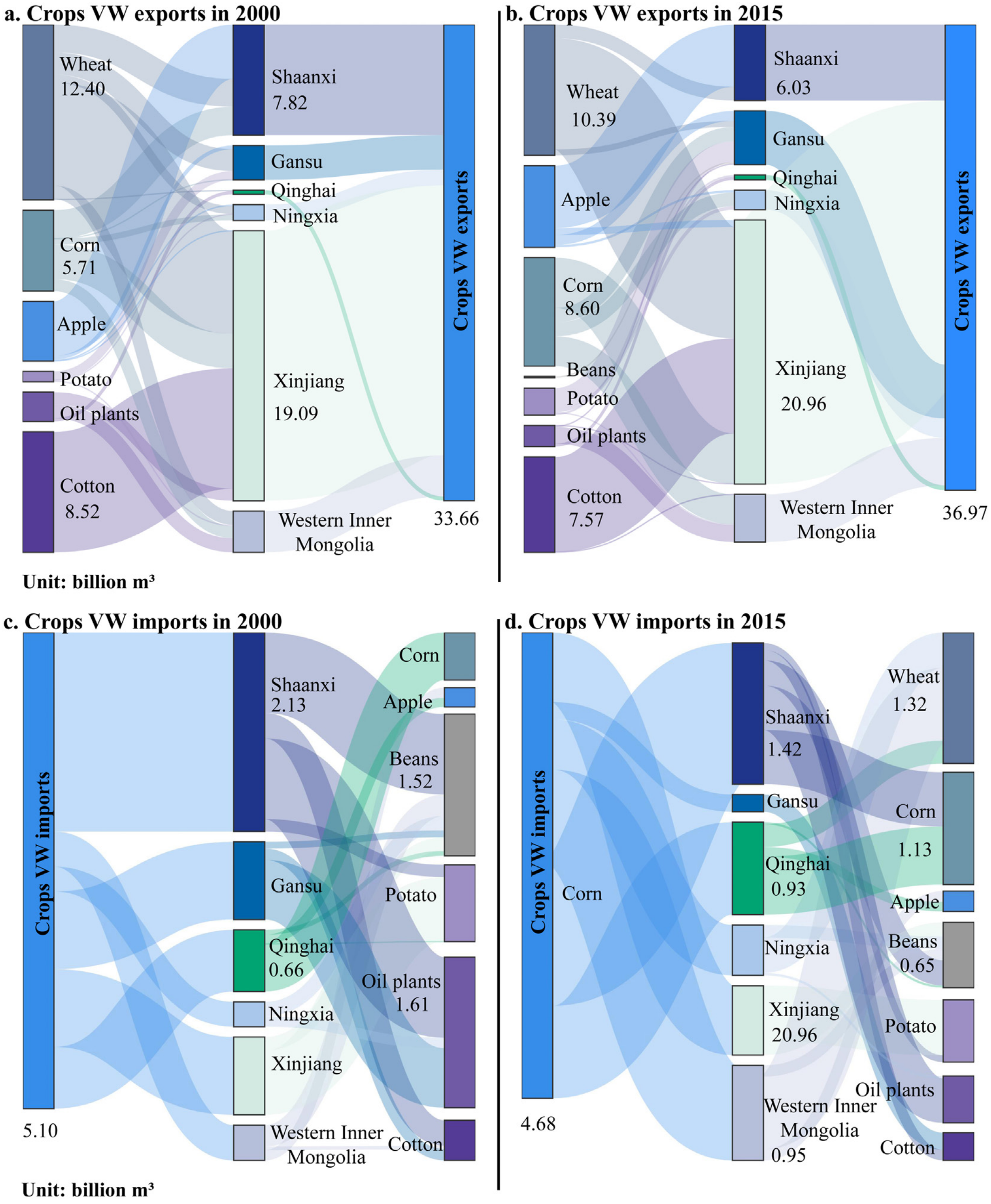

Fig. 7. The crops VW outputs and inputs among provinces for the year of 2000 (a) and 2015 (b) (Unit: billion m^3).

external regions, and the VW output embedded in crops and energy undoubtedly aggravated the pressure of water resources in Northwest.

3.4. The water stress induced by virtual water output from 2000 to 2015

The changes in local water resources caused by the transfers of regional VW can be described by the water stress index (WSI). With the increasing demand of Chinese society for crops and energy, the northwest region, as an important food and energy base, is gradually expanding the scope of production. The inter-regional trade of crops and energy products leads to the constant increase of regional VW output, which seriously threatens the water security of Northwest China and aggravates the difficulty of sustainable development of water resources. As Fig. 9 shows, according to the WSI (see Section 2.4.3), many regions in Northwest China are facing a severe shortage of water resources, particularly Shaanxi, Gansu and the Western Inner Mongolia.

Qinghai is a VW-receiving area ($WSI^* > WSI$). Therefore, the VW inflow plays a positive role in alleviating the local water scarcity. While, the other provinces of Northwest China's are VW output areas ($WSI^* < WSI$), which VW output exacerbates the local water scarcity situation, with the WSI threshold reaching the next level of severity. A further comparison of WSI and WSI* in these regions determined that the difference between WSI and WSI* in the Western Inner Mongolia was relatively significant. From 2000 to 2015, the water stress in the Western Inner Mongolia, without consideration of the VW transfer, was found to be severe (average $WSI^* = 0.49$). However, when the VW output was considered, water stress became extreme ($WSI > 1$). Shaanxi province is one of the regions with the most severe water shortage in Northwest, whose water consumption has exceeded the locally available water resources. From 2000 to 2015, although the WSI and WSI* of Shaanxi province decreased slightly from 2.13 and 1.57 to 1.68 and 1.21, respectively, it still faced severe water scarcity.

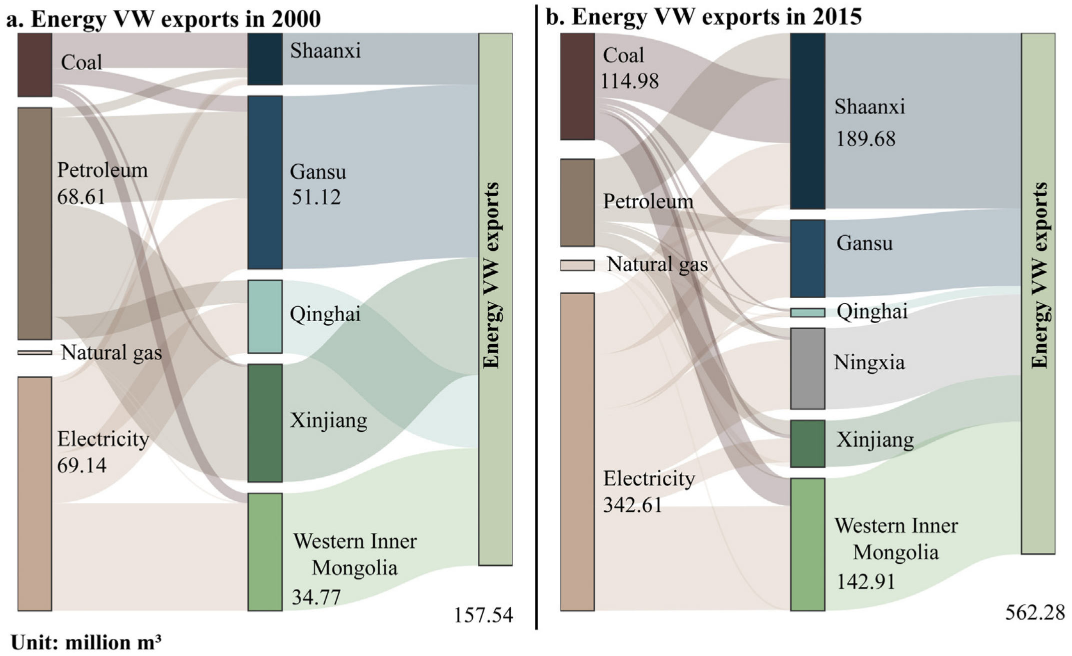

Fig. 8. The energy VW outputs among provinces for the year of 2000 (a) and 2015 (b) (Unit: million m^3).

In general, the VW output intensifies the water scarcity in Northwest China, and restricts the sustainable use of water. With the continuous promotion of the 13th five-year plan, northwest will face larger water pressure and great risk for WEF security. In the future, the low water resources condition in Northwest China will no longer support the local agriculture and energy production, and the sustainable inter-regional trade of crops and energy products will be endangered. Therefore, it is particularly necessary to adopt some corresponding measures and policies to cope with the current situations.

4. Discussion

4.1. The driving forces behind the VW flow pattern

Based on the above analysis, the Northwest is always a net VW output area, whose VW output associated with food and energy trade increases sharply in the past 15 years, thus seriously aggravating the local water resource pressure. Actually, there are mainly two reasons behind this. Firstly, Northwest China is endowed with vast arable land and abundant fossil energy resources, making it an important center of agriculture and energy production in China. According to the statistics, the per capita arable land in Northwest China is 2.7 mu, 74% higher than the national average (Ministry of Land and Resources, 2017). The fossil energy reserves are very rich. The coal reserves amount accounts for 67% of China's total (National Energy Administration, 2016). The oil reserves amount is 510 million tons, accounting for 23% of the national and the natural gas resources are 435.4 billion m^3, accounting for 58% of the national (Ning et al., 2009). In general, Northwest China is an important agriculture production base and energy production center due to its huge natural resource endowment, which is the fundamental driving force of inter-regional trade of the agriculture and energy products and the associated virtual water flow. Secondly, the other driving force should be attributed to the gap between the south and east developed regions and northwest regions. Li et al. (2020) pointed out that the production structure, population and economic development level were the biggest drivers of virtual water flow. This also corresponds to our conclusion. Because of the implementation of reform and opening in the 1980s, eastern and southern coastal areas paid much more attention to developing technology-intensive and capital-intensive industries and gradually ignored the low added-value and high-pollution industries (e.g., agriculture production and energy production). Gradually, the local food and energy production can't meet their demand, and they began to buy more and more grain and energy products from the northwest regions. Under this background, the Chinese government decided to construct the “North-to-South Grain Transfer Project” and “West-to-East Power Transmission Project” since 1990s. Nowadays, the eastern and southern coastal developed provinces have been the consumption center of agriculture and energy product, and more and more VW embedded in the inter-regional trade was also transferred from the underdeveloped and water-deficient regions to developed and water-rich regions, which is not a sustainable developing trend. In the long run, the VW outflow with the crops and energy trade will bring serious consequences. Firstly, the excessive exploitation and consumption of the scarce water resources in Northwest China will endanger the health of the local ecological and environmental system, which will inevitably affect the sustainable ecosystem development of Northwest China. Secondly, more and more VW outflow will further widen the economic gap between the undeveloped northwest areas and the developed southeast coastal areas.

Table 2
The ratio of VW outflow to water footprint in Northwest China from 2000 to 2015.

	2000	2003	2006	2009	2012	2015
Shaanxi	26.25%	25.22%	28.32%	30.87%	31.31%	28.05%
Xinjiang	58.95%	56.84%	52.48%	59.75%	58.23%	61.66%
Western Inner Mongolia	49.97%	52.30%	57.07%	56.65%	48.24%	46.61%
Qinghai	−19.76%	−13.75%	−17.75%	−8.54%	−18.67%	−39.55%
Ningxia	26.06%	40.73%	31.25%	34.42%	34.86%	27.92%
Gansu	11.65%	24.03%	16.49%	21.23%	29.05%	29.73%
Northwest China	37.10%	38.92%	37.08%	43.19%	42.98%	42.84%

As shown in Fig. 10, by comparing the economic value obtained by the virtual water flow in Northwest China and the eastern coastal region, it can be found that the economic compensation obtained by the VW output of crops and energy in Northwest China (purple) is far lower than the industrial value created by the virtual water in the region (dotted line). In contrast, the eastern coastal region has saved a lot of water resources and created a high economic value because of virtual water input, which is about 23 times of the final economic compensation in

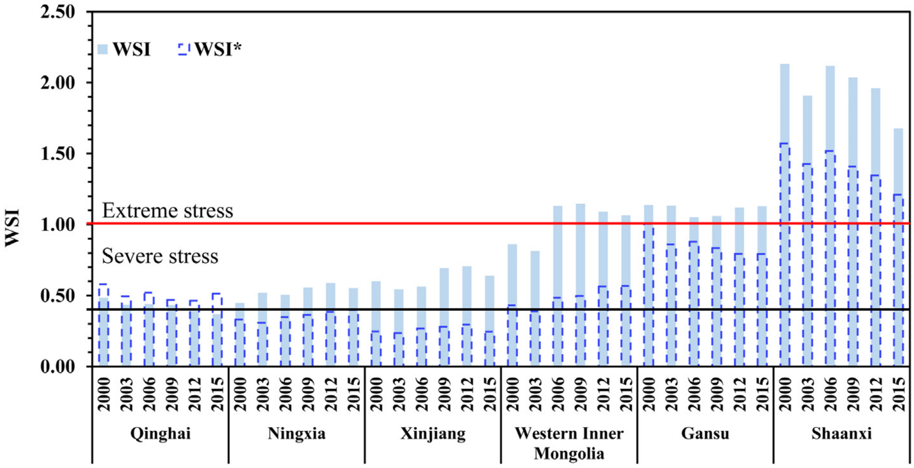

Fig. 9. Comparison of water stress index (WSI) and hypothetical water stress index (WSI*) in Northwest China from 2000 to 2015.

the northwest. Obviously, the economic development of Northwest China mainly relies on the agriculture and energy industries; however, the southern and eastern coastal regions are vigorously developing various new industries with higher added-values and economic benefits. Under such a trend, more and more agriculture and energy products are transferred to the developed regions, which will impede the optimal adjustment of the local industrial structure and accelerate the depletion of the natural resources and degradation of the ecosystem in the virtual water exporter areas.

4.2. Future countermeasures for the sustainable development

The above findings show that the VW outflow in the northwest further aggravated the current situation of water shortage in the water-scarce regions and seriously hindered the sustainable development of the local economy and society. To coordinate ensure the regional WEF security, it is urgent to establish a scientific planning and managing system and propose a series of efficient countermeasures to maintain the sustainable and balanced development in Northwest China. The efficient management and security assurance of the WEFN in Northwest not only require the progress of technical means but also need a comprehensive development strategic in the future including industrial structure adjustment and policy making involving stakeholders. To this end, this paper brings forward the following advice and countermeasures:

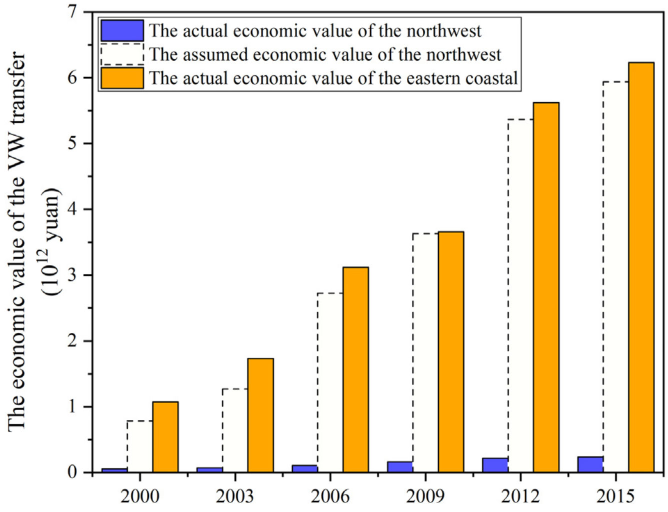

Fig. 10. The influence of virtual water transfer on regional economy from 2000 to 2015.

(1) Tap the water-saving potential and improve the water using efficiency for agriculture and energy production

Agriculture and energy industries are important basic industries for economic development. In face of the extreme water scarcity, it is necessary to increase the water using efficiency and reform the traditional water management policies to ensure regional water, energy and agriculture security. For water-saving in agriculture, the popularization of high-efficiency water-saving irrigation technologies, like micro-irrigation, sprinkling irrigation and pipe irrigation, can greatly improve the utilization rate of water (N. Wang et al., 2019; W. Wang et al., 2019). Meanwhile, it is also significant to carry out water-saving and drought-resistant cultivation measures, such as deep tillage of soil, selection of drought-resistant crops, application of organic fertilizers and film mulching in areas with water shortage. In addition, paying attention to water demand management can also effectively reduce agricultural water use (Jiang et al., 2017). For example, preventing canal leakage can greatly reduce agricultural water demand, which is of great significance to agricultural water-saving in irrigated areas. For water-saving in energy production, high technical standards and strict requirements should be adopted, like air cooling of thermal power units, water recycling in coal mines, zero discharge of waste water, etc. Moreover, the old equipment of power generation should be replaced with new processes and new technical equipment. Furthermore, clean energy consumes less water, which means the aggressive development of clean energy including solar and wind power is also significant for improving energy and water security.

(2) To rationally optimize the regional industrial structure based on water carrying capacity

At present, adjusting the current industrial structure according to the water carrying capacity is an effective way to solve water scarcity and maintain social and economic development. For the water-scarce areas in China, the matching conditions between the existing industrial structure and the local water carrying capacity should be deeply analyzed and optimized to establish an industrial structure compatible with local resource conditions, regional advantages and economic development. For example, Xinjiang Autonomous Region, as an important cotton production base of China, should pay much attention to improving the water carrying capacity for cotton production to meet the national cotton demand in the future, and should reduce the planting area of water-intensive crops (e.g., corn, wheat and rice) and control the water consumption of energy production through improving the proportion of renewable energy production and decrease the fossil energy. Therefore, optimizing the regional industrial structure and improving water resources adaptation are the key paths to ensure economic growth, ecological health and sustainable social development.

(3) Ensure the water security through the coupled management of physical and virtual water

In the water-scarce northwest regions, more and more physical water is being used for agriculture and energy production and then flowed to the developed regions as virtual water flow. To ensure the sustainable development of the social economy and ecosystem in northwest region, it is suggested to establish a coupled management framework for both physical and virtual water (Gao et al., 2019a,b). Apart from the physical water measures, e.g., constructing a new water supply project, increasing the non-conventional water, and planning water diversion projects, it is also imperative to strengthen the management of VW. For example, through the implementation of VW strategy, the water-scarce northwest regions purchase water-intensive products from the water-rich area to reduce the utilization of local water resources. The water resources saved can be used to support local economic construction and ecological restoration. Besides, the virtual water compensation mechanism framework is suggested to be established. Within the framework, the VW importing areas should pay the virtual water fee or virtual water compensation fee to the VW output areas, and the VW output areas could use these funds to compensate the farmers, to construct the water-saving projects and to promote the ecological restoration.

5. Conclusion

This study assessed WFs and VW flows for crops and energy in Northwest China from 2000 to 2015. On this basis, we also assessed the WSI induced by crop and energy transfer over the past 15 years. Our main conclusions are as follows:

(1) Northwest China was always a VW output area but the roles of each province vary greatly. For example, Xinjiang province is the largest VW output province of cotton, and Inner Mongolia is the largest VW output region of electricity. Therefore, an approach regarding industry and water resource management that adapts to local conditions is required.
(2) Except for Qinghai, the other provinces in Northwest China face a severe shortage of water resources, especially in Shaanxi province and the Western Inner Mongolia. With the continuous promotion of the 13th five-year plan, Northwest China will face larger water pressure and great risk for WEF security.
(3) The difference of resource endowment and the gap between the south and east developed regions and northwest regions are the driving force behind the VW flow pattern in northwest region. Our finding shows that the current situation of VW output in Northwest China aggravates the local water security problem and the imbalance of regional economic development. To ensure the future WEF security, we proposed three countermeasures and suggestions based on the above findings, including water-saving technology promotion, industrial and agricultural structure optimization, and the coordinated management of physical and virtual water.

CRediT authorship contribution statement

Xinxueqi Han: Methodology, Validation, Formal analysis, Writing – original draft. **Yong Zhao:** Methodology, Validation, Formal analysis, Writing – original draft. **Xuerui Gao:** Conceptualization, Writing – review & editing, Supervision. **Shan Jiang:** Writing – review & editing. **Lixing Lin:** Data curation. **Tingli An:** Visualization, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.144276.

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