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Spatiotemporal supply-demand characteristics and economic benefits of crop water footprint in the semi-arid region

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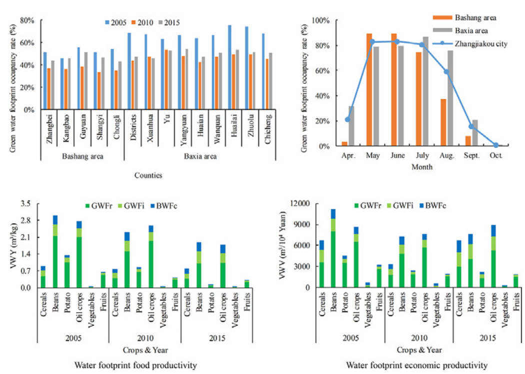
HIGHLIGHTS

- Water shortage has severely restricted the sustainable development of Zhangjiakou.
- The introduction of three new indicators will enrich research of crop water footprint.
- The green water plays a more important role in the growth of crops than blue water.
- Food productivity and economic productivity of crop water footprint are different.

GRAPHICAL ABSTRACT



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ABSTRACT

The notion of water footprint provides a novel perspective for understanding the relationship between physical water and virtual water, especially in agricultural production. In this study, with the help of CROPWAT 8.0 model, we estimate the water footprint requirement (WFr) of main crops growth for 2005, 2010 and 2015 in Zhangjiakou City, an extreme water shortage region in northern China, and three new indicators are introduced, i.e., green water footprint occupancy rate (GWFor), blue water footprint deficit (BWFd), and virtual water consumption per output value (VWV). The results indicate that the total WFr increased from 1.671 billion m^3 to 1.852 billion m^3 during the study period, of which the green water was always about twice as the blue water. Cereals, as the main staple food, had the largest WFr, while the WFr of potatoes increased the fastest, which was the result of large-scale promotion of potato cultivation in recent years. The spatial characteristics of the GWFor and BWFd are closely related to altitude, that is, the GWFor was less than 50% in higher-altitude Bashang area, while it was more than 50% in lower-altitude Baxia area, and the BWFd was generally smaller in Bashang area than in Baxia area. Due to differences in crop types and food prices, higher water footprint food productivity does not absolutely mean higher water footprint economic productivity. Therefore, it is vital to consider from two perspectives (food yields priority or economic benefits priority) to formulate a reasonable water footprint utilization policy. This study is expected to broaden the investigation of crop water footprint and make a contribution to sustainable agricultural water management.

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1. Introduction

Water shortage has already seriously threatened the health and robustness of the socio-ecological system (Mekonnen and Hoekstra, 2011). It will be further exacerbated as water demand increases in the foreseeable decades, due to rapid urbanization, global population expansion, and changes in dietary patterns (Liu et al., 2018; Zhao et al., 2016). Therefore, the global water security issue has become one of the most serious systemic risks facing humanity in the 21st century (Bakker, 2012; Vorosmarty et al., 2010). Since agricultural irrigation accounts for more than 70% of freshwater water use worldwide (Chen et al., 2018), and more than 90% of water footprint consumption comes from agricultural products (Hoekstra and Mekonnen, 2012), the water-saving in agricultural sectors thus attracts increasing global attention. In the meantime, however, food security is also facing a great challenge, especially in developing countries with large population size, which results in water security and food security were simultaneously listed as the 2030 Sustainable Development Goals by the United Nations (Rasul, 2016; Weitz et al., 2014). Therefore, how to balance and coordinate the contradiction between water resources security and food production has raised great concern from policymakers to scholars (Cazcarro et al., 2019; Liu et al., 2018; Ren et al., 2018; Ruess and Konar, 2019; Sun et al., 2019; Vanham, 2016).

To quantify the flow of invisible and intangible water embedded in products and services through international trade, the concept of virtual water was first proposed by Allen (1993). Then Hoekstra (2003) introduced water footprint to water use assessment by referring to the concept of ecological footprint, which offers an innovative and effective way for shedding light on the relationship between physical water and virtual water (Cao et al., 2014; Zeng et al., 2012), especially in the field of agriculture production for its major responsibility of freshwater use. Generally, the water footprint includes three parts: blue water footprint (BWF), green water footprint (GWF) and gray water footprint. The blue water footprint refers to water comes from the surface and groundwater, such as irrigation water. The green water footprint refers to the consumption of rainwater that does not become runoff. The gray water footprint refers to the water used to dilute the load of pollutants given natural background concentrations and existing ambient water quality standards (Mekonnen and Hoekstra, 2011; Zhuo et al., 2019; Zhuo et al., 2016b).

For calculating the water footprint, there are two main methods in previous research: water footprint network (WFN) and life cycle analysis (LCA). WFN is the original method used by Hoekstra and Hung (2002), which favors the management of water resources, while LCA approach focuses on specific products. Through the comparative analysis of Manzardo et al. (2016), no matter which method is chosen, the water footprint of products, regions, or nations has coherent results. In terms of research scales, Hoekstra and Hung (2002) calculated the water footprint of multiple crops without distinguishing blue, green and gray water for the first time at a global scale. Since then, a lot of studies on the global and national scale were conducted. For example, Chapagain et al. (2006) assessed the water footprint of worldwide cotton consumption and found that worldwide cotton products require 256 Gm^3 of water per year for 1997–2001, out of which about 42% is blue water, 39% is green water, and 19% is gray water. Sun et al. (2013) calculated the water footprint and inter-provincial virtual water flow of wheat, corn, and rice in China, and found that the national average virtual water content of wheat, maize and rice were 1071 m^3 per ton, 830 m^3 per ton and 1294 m^3 per ton, respectively. With the regional transfer of wheat, maize and rice, virtual water flows reached 30 Gm^3. However, due to regional differences in climate, technology and crop yield, the results of global or national average value of these studies are not suitable for making specific regional policies, which has been confirmed in several studies (Chapagain et al., 2006; Lovarelli et al., 2016). Therefore, the research on the regional and watershed has grown rapidly. Zeng et al. (2012) estimated the water footprint consumption in the Heihe River Basin, northwest China, and found that agricultural production was the largest water consumer, accounting for 96% of the water footprint, and further pointed out that optimizing the crop structure is the key to the sustainable use of water resources in arid areas. Chu et al. (2017) calculated the crop water footprint of Hebei Southern Plain, China, and found that the total blue water, green water and gray water footprint were 288.5 km^3, 141.3 km^3 and 175.0 km^3 for 13 years (2000–2012), respectively, among which winter wheat, summer maize and vegetables consumed the most groundwater, accounting for 74.2% of the total blue water. In terms of crop types, cereals, fruits, vegetables and cotton were the most studied crops (Lovarelli et al., 2016). In addition, blue water footprint and green water footprint were estimated in most studies, while fewer concerns on gray water footprint (Mekonnen and Hoekstra, 2011).

Although there is a wealth of research that has focused extensively on the water footprint of a variety of crops, three shortcomings are discovered. First, the blue water footprint received considerable attention and many indicators were introduced (Cao et al., 2017; Cao et al., 2018; Cao et al., 2014; Hoekstra and Zhuo, 2017; Zhuo et al., 2016a; Zhuo et al., 2016b), while few indicators were used to analyze the green water footprint, despite the fact that green water is the major contributor to global agricultural production (Chu et al., 2017; Wei et al., 2016). Second, most studies did not consider or mention whether crops are fully irrigated or not, which could lead to the calculated water footprint higher than the actual water footprint, especially in arid areas. A few studies have taken this into account by using actual irrigation water as the blue water footprint, however, further using it as the blue water footprint requirement (BWFr) to measure the extent of blue water scarcity is unreasonable. It is obvious that the actual irrigation water consumption cannot represent the water requirement of crop growth, due to water shortage and the imperfect infrastructures. Third, so far one of the most common indicators for measuring crop water footprint is the virtual water content per unit of yield (VWY) (Zeng et al., 2012), which is used to depict water productivity from the perspective of food production. However, besides food yields, economic benefits also play a very critical role in government and farmers' decisions about crop structure (Ren et al., 2018). Therefore, it is necessary to calculate virtual water content per unit of output value (VWV), which can reflect water productivity from the perspective of economic benefits.

Zhangjiakou City, a semi-arid region with less than 400 m^3 water per capita, which is lower than the internationally recognized extreme water shortage standard (500 m^3), is located in the upstream of Beijing in northern China. Water scarcity not only seriously restricts the local social and economic development but also poses a great threat to drinking water safety in the capital city of Beijing due to their close geographical relationship (Ma et al., 2020). The main research objectives of this study are as follows: (1) to estimate the water footprint requirement for the main crops with the help of CROPWAT 8.0, and identify its characteristics of spatial distribution and dynamic changing trends in Zhangjiakou City for 2005, 2010 and 2015. (2) To analyze the green water, blue water and water footprint economic benefits using the three new indicators, i.e., green water footprint occupancy rate (GWFor), blue water footprint deficit (BWFd), and virtual water consumption per output value (VWV). (3) To enrich crop water footprint indicators and provide an alternative way for agriculture water conservation in Zhangjiakou City from the perspective of water footprint.

2. Methods

CROPWAT 8.0, developed by the Land and Water Development Division of the UN Food and Agriculture Organization (FAO), was employed to calculate the water requirement of crop growth in every stage in this study (Fig. 1).

2.1. Water footprint

2.1.1. Green water footprint

The amount of crop evaporation was calculated by CROPWAT 8.0, and the amount of green water evaporation every 10 days is equal to the minimum between the effective precipitation and the crop evapotranspiration. Effective precipitations were calculated using USDA SCS (United States Department of Agriculture Soil Conservation Service) method in CROPWAT 8.0, which are different among counties. The total green water footprint (GWFt) is equal to the sum of the irrigation farmland green water footprint (GWFi) and the rain-fed farmland green water footprint (GWFr).

$$ET_g = \sum \min(ET_c, P_e) \quad (1)$$

$$GWF_i = 10A_i \times ET_g \quad (2)$$

$$GWF_r = 10A_r \times ET_g \quad (3)$$

$$GWFt = GWF_i + GWF_r \quad (4)$$

where ET_g (mm) is the 10-day total green water evaporation; ET_c (mm) and P_e (mm) are the 10-day crop water evaporation and effective precipitation, respectively; A_i (ha) and A_r (ha) are the crop planting area

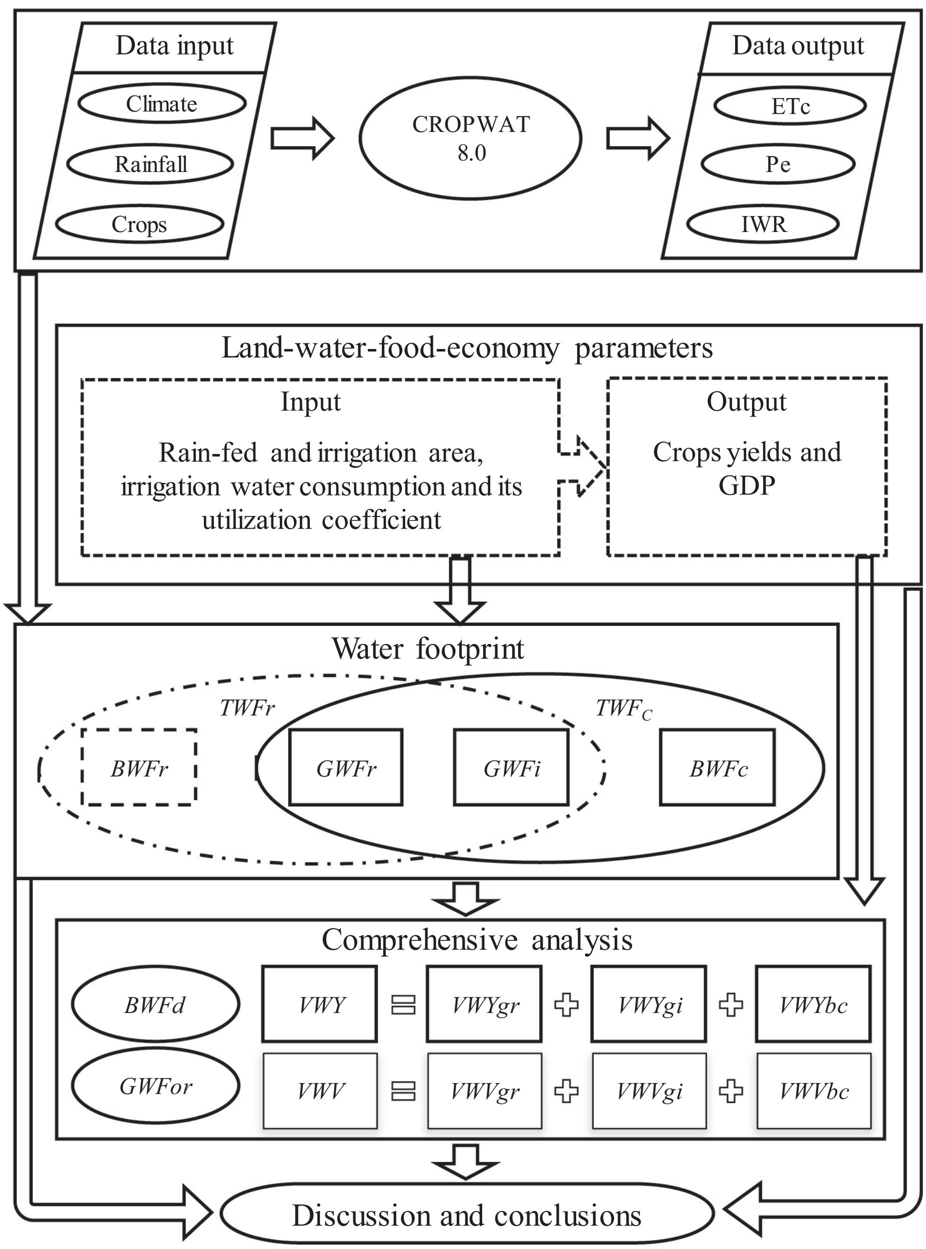

Fig. 1. Logic relationship of main variables and technical roadmap. Note: ETc: crop evapotranspiration; Pe: effective precipitation; IWR: irrigation water requirement; GDP: gross domestic product; TWFr: total water footprint requirement; TWFc: total water footprint consumption; BWFr: blue water footprint requirement; GWFr: rain-fed farmland green water footprint; GWFi: irrigation farmland green water footprint; BWFc: blue water footprint consumption; BWFd: blue water footprint deficit; GWFor: green water footprint occupancy rate; VWY: water footprint per unit of yield; VWYgr: rain-fed farmland green water footprint per unit of yield; VWYgi: irrigation farmland green water footprint per unit of yield; VWYbc: blue water footprint per unit of yield; VWV: water footprint per unit of GDP; VWVgr: rain-fed farmland green water footprint per unit of GDP; VWVgi: irrigation farmland green water footprint per unit of GDP; VWVbc: blue water footprint per unit of GDP.

of irrigation and rain-fed farmland, respectively; 10 is the coefficient from mm to m^3/ha.

2.1.2. Blue water footprint

Currently, there are two main methods for calculating the BWF of irrigation farmland. The first one is to multiply the amount of blue water evaporation requirement (calculated by CROPWAT 8.0) by the irrigated area. Since crops are often cannot fully irrigated, especially in arid areas, it is actually the blue water footprint requirement (BWFr). The second one is to use the actual irrigation water as the blue water footprint. But the irrigation water is not all consumed by crops, due to inevitable factors such as evaporation and infiltration causing water waste during the irrigation process. In other words, it is not the real blue water footprint consumption (BWFc) of crops. Based on this, the BWFr and BWFc will be calculated separately in this study.

$$ET_b = \sum \max(0, ET_c - P_e) \quad (5)$$

$$BWF_r = 10A_r \times ET_b \quad (6)$$

where ET_b (mm) is the total blue water evaporation;

$$BWF_c = W_i \times \eta \quad (7)$$

where W_i is the actual irrigation water, and η is the effective utilization coefficient of irrigation water.

2.1.3. Total water footprint

Correspondingly, the total water footprint includes the total water footprint requirement (TWFr) and the total water footprint consumption (TWFc).

$$TWF_r = BWF_r + GWF_i + GWF_r \quad (8)$$

$$TWF_c = BWF_c + GWF_i + GWF_r \quad (9)$$

2.2. Green water occupancy rate and blue water deficit

2.2.1. Green water occupancy rate

From the perspective of ecological hydrology, Sun et al. (2010) proposed the green water occupation index, which considered that the total green water is equal to the total precipitation minus the total blue water in the whole region. However, the green water that can be used by crops is only the precipitation that falls on the planting area. Therefore, this study propose a formula for calculating the green water footprint occupancy rate (GWFor) based on the planting area.

$$GWFor = \frac{\sum GWF}{10P\sum A} \times 100\% \quad (10)$$

where P (mm) is precipitation, $\sum$GWF and $\sum$A are the sum of the green water footprint and planting area of crops, respectively.

2.2.2. Blue water deficit

At present, studies on the blue water footprint only calculate the requirement or consumption of blue water, which cannot reflect the extent of blue water scarcity. Therefore, we put forward the blue water footprint deficit (BWF_d) with reference to the concept of ecological deficit.

$$BWF_d = \frac{(BWF_r - BWF_c)}{\eta} \quad (11)$$

when BWF_d is less than zero, it represents a state of blue water surplus. The larger the BWF_d, the bigger the blue water shortage.

2.3. Virtual water content

2.3.1. Virtual water content per unit of yield

The virtual water content per unit of yield is also called water footprint per unit of yield (VWY). It consists of three parts: the blue water footprint per unit of yield (VWYbc), the irrigation farmland green water footprint per unit of yield (VWYgi), and the rain-fed farmland green water footprint per unit of yield (VWYgr).

$$VWY_{bc} = \frac{BWF_c}{Y} \quad (12)$$

$$VWY_{gi} = \frac{GWF_i}{Y} \quad (13)$$

$$VWY_{gr} = \frac{GWF_r}{Y} \quad (14)$$

$$VWY = VWY_{bc} + VWY_{gi} + VWY_{gr} \quad (15)$$

where Y is the crop yield.

2.3.2. Virtual water consumption per output value

For comparing the characteristics of the virtual water consumption per output value at the same price, it is necessary to eliminate the impact of price changes on the gross domestic product (GDP) of crops.

(1) GDP standardization
Based on 2005, the total GDP of crops in 2010 and 2015 were revised. By calculation, when 2005 = 1, 2010 and 2015 were 1.56 and 2.04 respectively.

$$GDP_{2010} = GDP_{2005} \times 1.56 \quad (16)$$

$$GDP_{2015} = GDP_{2005} \times 2.04 \quad (17)$$

where GDP_{2005} is the actual GDP of crops in 2005.

(2) Virtual water consumption per unit of GDP
The virtual water consumption per unit of GDP (VWV), equals to the water footprint divided by GDP, and also consists of three parts, will reflect the economic benefits of the water footprint.

$$VWV_{bc} = \frac{BWF_c}{GDP} \quad (18)$$

$$VWV_{gi} = \frac{GWF_i}{GDP} \quad (19)$$

$$VWV_{gr} = \frac{GWF_r}{GDP} \quad (20)$$

$$VWV = VWV_{bc} + VWV_{gi} + VWV_{gr} \quad (21)$$

where VWVbc is the blue water footprint per unit of GDP, VWVgi is the irrigation farmland green water footprint per unit of GDP, and VWVgr is the rain-fed farmland green water footprint per unit of GDP.

3. Study area and data sources

3.1. Study area

Zhangjiakou City is located in Hebei Province, China (Fig. 2). There are two parts with different geographical features, i.e., northwestern Bashang area with an average elevation of 1368 m and southeastern Baxia area with an average elevation of 681 m.

The Bashang area is characterized by a lower temperature that is suitable for planting crops with a shorter growing time, such as vegetables; while the Baxia area is characterized by a higher temperature that is suitable for planting crops with a longer growing time, such as corn. In terms of water resources, the per capita water resources is about 350 m^3 in Zhangjiakou City, less than one-fifth of the national level, making it one of the most severe water scarcity cities in China. In addition, Zhangjiakou City plays a significant role in freshwater sources and ecological security for Beijing. In 2017, it was identified as the "water conservation function zone and ecological environment support zone of the capital" by the central government of China. Moreover, Zhangjiakou and Beijing will jointly hold the 2022 Winter Olympic Games, making the task of water-saving and improving water efficiency more important and urgent.

Agricultural irrigation has been accounted for more than 70% of freshwater use in Zhangjiakou City, which is 10% higher than the national level. However, the irrigation farmland area increased by 50,167 ha from 2005 to 2015, with an increase of 28%. This has led to an increase in the lack of water resources, which requires an urgent need to figure out the structure and changing trends of crop water use. The main crop types and representative crops are shown in Table 1. The planting area and the yield of these crops accounted for about 75% and 72%–80% in total, respectively.

3.2. Data sources

The meteorological parameters required for the CROPWAT 8.0 model include relative humidity, wind speed and sunshine hours were obtained from the *Zhangjiakou City Economic Yearbooks* (2006, 2011, 2016), which originally collected from 14 local weather stations. The maximum and minimum temperatures of every county were obtained from this weather website (http://www.tianqi.com/qiwen/city_zhangjiakou/). The parameters of crops, such as sowing and harvesting date, root depth, crop coefficient, growth period, and crop height, were modified in accordance with the actual situation of Zhangjiakou City based on the default values of CROPWAT 8.0 and the irrigation and drainage paper 56 "*Crop evapotranspiration – Guidelines for computing crop water requirements*" of FAO (Allan et al., 1998).

The data, e.g., the planting area of crops in irrigation farmland and in rain-fed farmland, yields, and the regional GDP, were all obtained from the *Zhangjiakou Ctiy Economic Yearbooks* (2006, 2011, 2016). The data of irrigation water and utilization efficiency were obtained from the *Water Resources Bulletin* (2006, 2011, 2016) and other relevant government reports.

4. Results

4.1. Distribution of water footprint requirement

As shown in Fig. 3b, in 2005–2015, the total water footprint requirement of crops in Zhangjiakou City increased from 1.671 billion m^3 to 1.852 billion m^3, with an average annual growth rate of 1.03%. The water footprint requirement of irrigation farmland increased by 0.232 billion m^3, of which the blue water footprint requirement (BWFr) increased from 0.526 billion m^3 to 0.661 billion m^3, and the green water footprint requirement (GWFi) increased from 0.290 billion m^3 to 0.387 billion m^3. The water footprint requirement of rain-fed farmland (GWFr) decreased from 0.854 billion m^3 to 0.803 billion m^3. As a result, the water footprint requirement of irrigation farmland increased from 49% to 57%, and the water footprint of rain-fed farmland decreased from 51% to 43%.

4.1.1. Spatial patterns of water footprint requirement

In general, the relationships between water footprint requirement and altitude were negatively correlated (Fig. 4). That is, the water

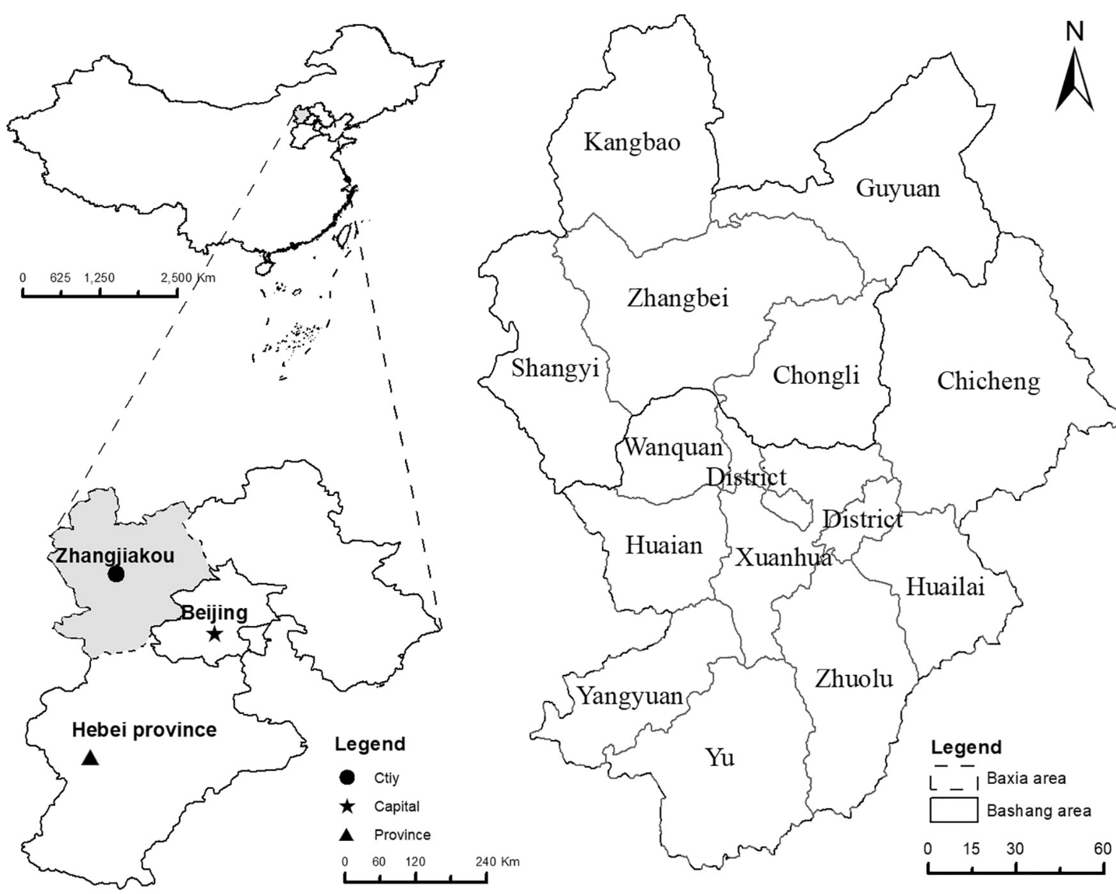

Fig. 2. Location of Zhangjiakou City and counties distribution.

Table 1
The planting area and yield of main crops in Zhangjiakou City.

Crop type	Representative crop	2005		2010		2015	
		Area (10^4 ha)	Yield (10^4 ton)	Area (10^4 ha)	Yield (10^4 ton)	Area (10^4 ha)	Yield (10^4 ton)
Cereals	Maize	15.4	69.0	17.4	80.8	17.6	83.2
	Millet	3.1	4.0	4.6	15.0	3.9	13.5
	Buckwheat	7.2	5.4	5.6	5.4	5.9	6.0
Beans	Soybean	5.5	3.7	3.5	3.0	2.7	3.4
Potatoes	Potato	7.3	14.7	7.7	24.2	10.1	205.2
Oil crops	Rapeseed	0.4	0.3	0.5	0.3	0.4	0.4
	Sesame	4.0	2.1	3.9	2.6	3.2	3.0
	Sunflower	1.2	1.5	1.2	1.0	1.5	2.6
Vegetables	Spinach	0.1	3.5	0.1	6.2	0.2	12.0
	Celery	0.8	64.5	0.7	54.9	0.8	71.8
	Chinese cabbage	2.0	148.3	2.3	183.8	1.8	158.4
	cabbage	1.5	75.5	1.4	85.0	1.7	124.5
	Tomato	0.3	12.5	0.4	19.9	0.5	36.0
Fruits	Apple	4.1	8.4	3.2	8.9	2.9	9.8
	Grape	1.6	16.1	2.8	29.2	3.4	49.8
In total		54.5	429.5	55.3	520.4	56.5	779.7

footprint requirement of higher altitude counties was lower than that of lower altitude counties, and the gap between them was expanding. During the study period, the average water footprint requirement per country in Bashang area increased from 0.101 billion m^3 to 0.105 billion m^3 (Fig. 3a), while it increased from 0.130 billion m^3 to 0.147 billion m^3 in Baxia area (Fig. 3c). Among them, the water footprint requirement decreased in Chongli County, Shangyi County, Wanquan County, and Chicheng County, and it increased in other counties. In 2015, the county with the highest water footprint requirement was Zhuolu County (0.205 billion m^3), with a contribution rate of 11%; the county with the lowest water footprint requirement was Chongli County (0.041 billion m^3), with a contribution rate of 2%.

In terms of the source of water footprint, the contribution rate of water footprint requirement from rain-fed farmland positively correlated with altitude. That is, in general, the higher the altitude, the larger the proportion of water footprint requirement from rain-fed farmland in this area; the proportion of water footprint requirement from irrigation farmland is exactly the opposite (Fig. 4). From 2005 to 2015, the proportion of WFr from rain-fed farmland decreased from 78% to 51% in Bashang area, while it remained at 40%–43% in Baxia area. In 2015, the three counties with the highest proportion of water footprint requirement from rain-fed farmland were Chicheng County (73%), Shangyi County (72%) and Wuyuan County (63%); the three counties with the highest proportion of water footprint requirement from irrigation farmland were Wanquan County (79%), municipal districts (77%) and Zhangbei County (71%).

4.1.2. Water footprint requirement of different crops

During the study period, the water footprint requirement of beans and vegetables in Zhangjiakou City decreased from 0.133 billion m^3 and 0.134 billion m^3 to 0.079 billion m^3 and 0.095 billion m^3, respectively. It was increasing in other crops with significant different growth rates. The water footprint requirement of potatoes had the largest increase of 47%, from 0.227 billion m^3 to 0.333 billion m^3, while the water footprint requirement of oil crops had the smallest increase of 8%, from 0.121 billion m^3 to 0.131 billion m^3.

Due to the large difference of the planted areas, the contribution rates of water footprint requirements were very different in crops, especially between the Bashang area and Baxia area (Figs. 5 and 6). In Bashang area, the contribution rate of potatoes increased from 25% to 44%, while vegetables and beans decreased from 18% and 11% to 9% and 5%, respectively, and fruits was the smallest, only accounting for 1%–3%. In Baxia area, the contribution rate of cereals was always the largest, accounting for 62%–66%, while vegetables was the smallest, accounting for 3%–4%.

Regarding the blue water footprint (BWFr), in Bashang area, the contribution rate of vegetables dramatically decreased from 70% to 10%, and potatoes and cereals increased from 5% and 12% to 25% and 40%, respectively. In Baxia area, the contribution rates of cereals had been the largest, accounting for 68%–73% .

Regarding the total green water footprint (GWFt), in Bashang area, the contribution rate of cereals decreased from 34% to 29%, and potatoes increased from 28% to 42%. In Baxia area, the contribution rate of cereals had also been the largest as BWFt, accounting for 58%–63%, followed by fruits, accounting for around 20%.

According to the above analysis, the contribution rates of cereals' BWFr and vegetables' BWFr were higher than those of GWFt, which means that these two types of crops needed more irrigation water than rainwater. The contribution rates of BWFr were less than the contribution rate of GWFt in other crops, which means that these crops were more dependent on rainwater to growth.

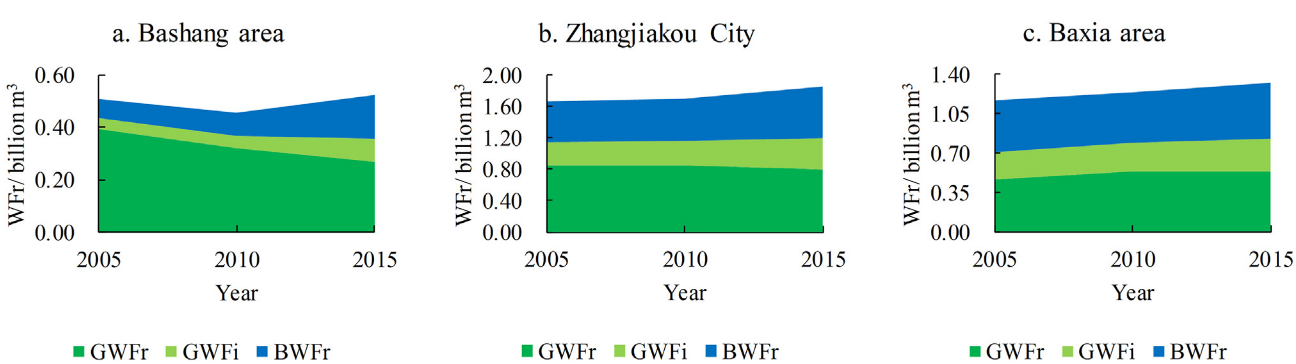

Fig. 3. Total water footprint requirement of crops in 2005–2015.

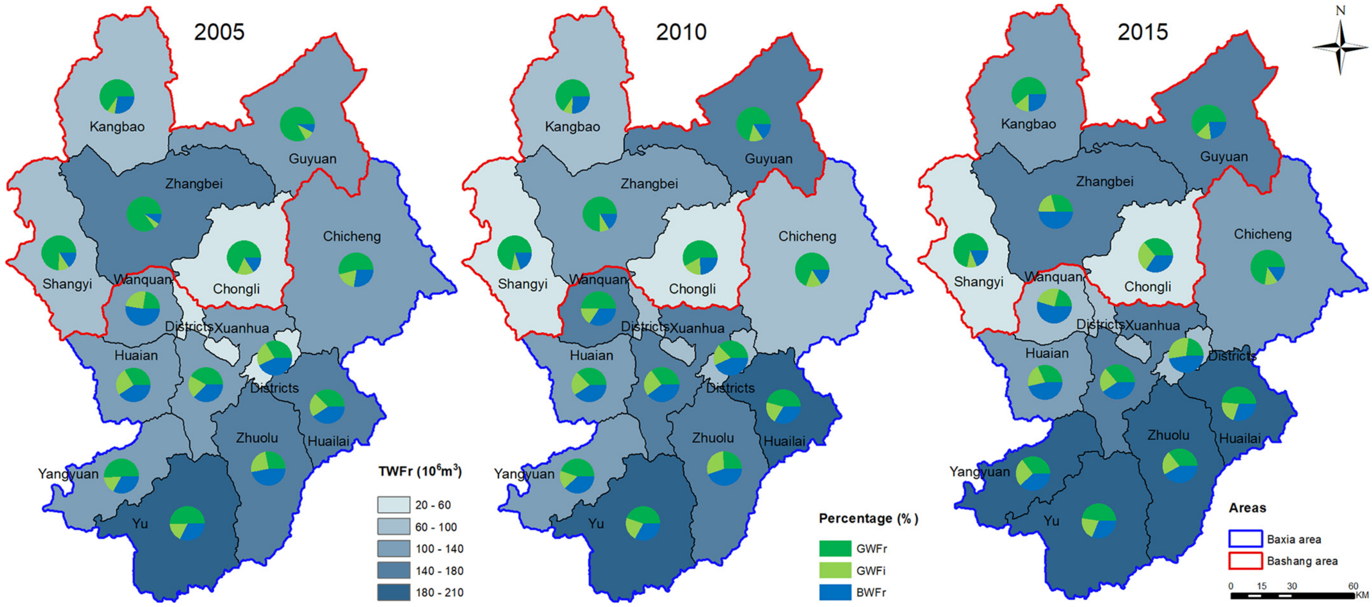

Fig. 4. Spatial distribution of water footprint requirement (WFr) of crops in 2005–2015.

4.2. Supply-demand relationships of the water footprint

4.2.1. Green water footprint occupancy

In 2005–2015, the green water footprint occupancy rates were 48%–60% in Zhangjiakou City (Fig. 7). Among them, it was 43%–49% in the counties of the Bashang area, with an average of 44%, while it was 51%–59% in the counties of the Baxia area, with an average of 54%. Therefore, in general, the green water footprint occupancy in Bashang area was lower than that in Baxia area. In terms of months, as shown in Fig. 8, it was zero from January to March and from November to December, since the growth periods of main crops were between April and October. The green water footprint occupancy rate was the highest from May to August, with a multi-year average of 58%–83%; and it was 20% in April, 15% in September, and less than 1% in October. In addition, from May to June, the green water footprint occupancy rate in Bashang area was higher than that in Baxia area due to differences in climate and planting area, and vice versa in other months.

4.2.2. Blue water footprint deficit

The blue water footprint deficit of Zhangjiakou City decreased from 0.544 billion m^3 in 2005 to 0.480 billion m^3 in 2010 due to the improvement of irrigation water efficiency. However, the improvement of water use efficiency was not enough to offset the rapid increase of water demand due to irrigation farmland expanding after 2010, resulting the blue water footprint deficit increased to 0.612 billion m^3 in 2015 and the shortage of blue water became more severe.

In terms of counties (Fig. 9), the blue water footprint deficits of counties in Bashang area were generally lower than that of counties in Baxia area. A few counties of the Bashang area were even in the state of blue water surplus before 2015, while the counties of the Baxia area has always been in the state of blue water deficit. It was the largest in Yangyuan County (located in Baxia area), increasing from 0.088 billion m^3 to 0.116 billion m^3. It was the smallest in Shangyi County (located in Bashang area), decreasing from 0.075 billion m^3 to 0.043 billion m^3.

In terms of crops (Fig. 10), the blue water footprint decreased in cereals, beans, and fruits, while it increased in potatoes, oil crops, and vegetables. Among them, cereals was the largest, with an average annual blue water deficit of 0.363 billion m^3, while vegetables was the smallest, even in the state of blue water surplus in 2005 and 2010.

4.3. Water footprint productivity

4.3.1. Virtual water content per unit of yield

As shown in Fig. 11, the virtual water content (VWY) decreased from 0.331 m^3/kg in 2005 to 0.195 m^3/kg in 2015 in Zhangjiakou City, of which green water comes from rain-fed farmland (VWYgr) decreased from 0.199 m^3/kg to 0.103 m^3/kg, green water comes from irrigation farmland (VWYgi) decreased from 0.068 m^3/kg to 0.050 m^3/kg, and blue water (VWYbc) decreased from 0.065 m^3/kg to 0.043 m^3/kg. As a result, the proportion of green water decreased from 80% to 78%, and the proportion of blue water increased from 20% to 22%. In Bashang area, the virtual water content decreased from 0.205 m^3/kg to 0.091 m^3/kg, of which the proportion of VWYgr decreased from 77% to 64%, the proportion of VWYgi increased from 8% to 21%, and the proportion of VWYbc remained at around 15%. In Baxia area, the virtual water content decreased from 0.505 m^3/kg to 0.393 m^3/kg, of which the proportion of VWYgr decreased from 51% to 43%, the proportion of VWYgi decreased from 27% to 24%, and the proportion of VWYbc increased from 22% to 34%. The virtual water contents of Yangyuan County and Kangbao County were the largest (0.872 m^3/kg) and smallest (0.063 m^3/kg) in 2015, respectively.

In terms of crops, as shown in Fig. 12, the multi-year average of virtual water contents from high to low were beans (2.398 m^3/kg), oil (2.381 m^3/kg), cereals (0.825 m^3/kg), potatoes (0.777 m^3/kg), fruits (0.46 m^3/kg), and vegetables (0.037 m^3/kg). Regarding changing trends, the potatoes decreased from 1.364 m^3/kg to 0.123 m^3/kg, with the largest decrease of 91%, while the cereals decreased from 0.892 m^3/kg to 0.807 m^3/kg, with the smallest decrease of 10%. In terms of blue water content, the VWYbc decreased in vegetables and fruits, while it increased in other crops. The proportion of VWYbc in vegetables had been the largest, although it decreased from 58% to 38%; the proportion of VWYbc has always been the smallest in fruits, decreasing from 7% to 5%. In addition, the average VWYbc of each crop in Bashang area was lower than that in Baxia area. Apart from vegetables, the proportion of VWYbc was only 7% in Bashang area, while it was 26% in Baxia area.

4.3.2. Water footprint consumption per output value

The water footprint consumption per output value (VWV) of Zhangjiakou City dropped from 3380 $m^3/10^4$ Yuan in 2005 to 2183 $m^3/10^4$ Yuan in 2010 and then increased to 2344 $m^3/10^4$ Yuan in 2015, which

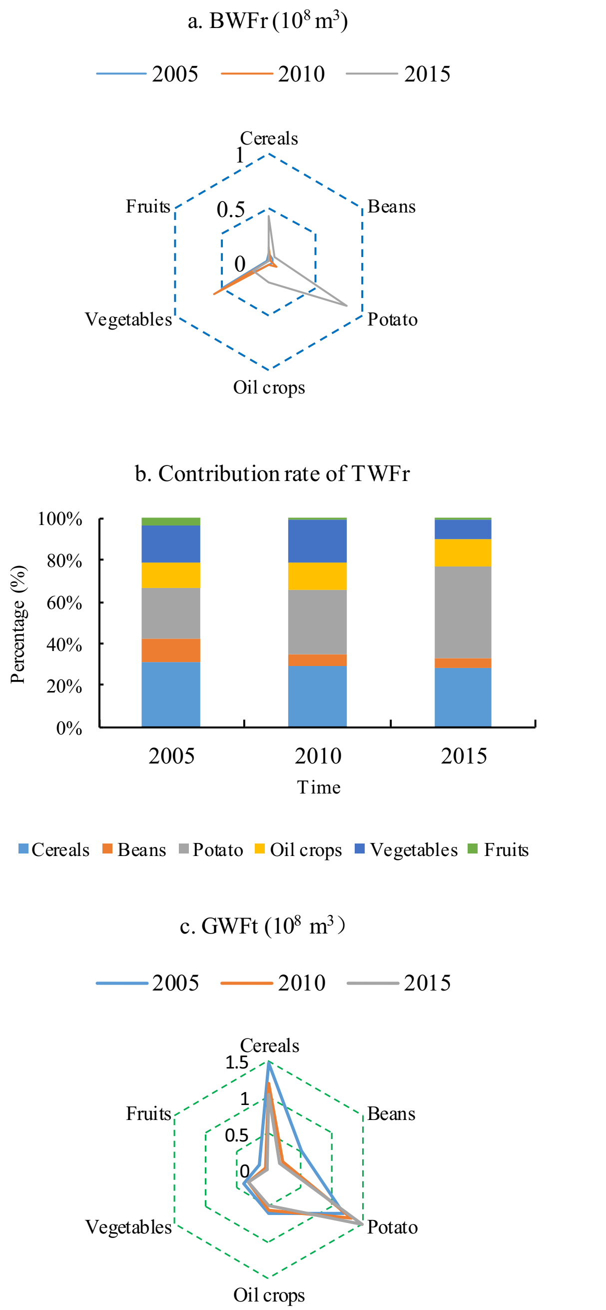

Fig. 5. Total water footprint requirement (TWFr) and contribution rate in Bashang area.

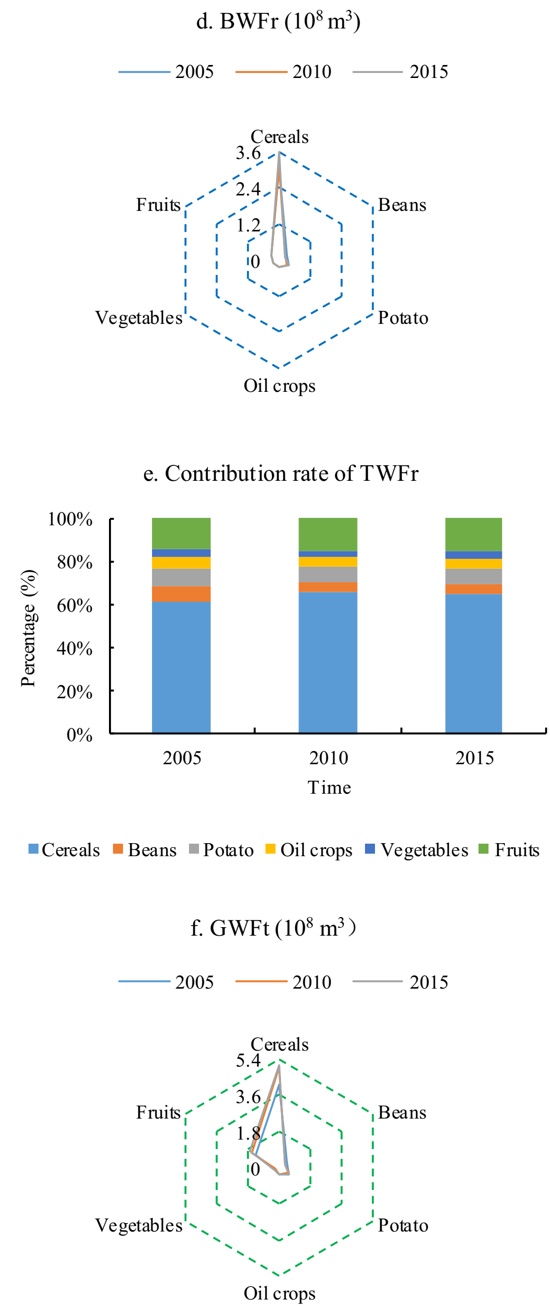

Fig. 6. Total water footprint requirement (TWFr) and contribution rate in Baxia area.

was different from the virtual water content per unit of yield (continuous decline). The contribution rate of green water decreased from 80% to 78%, and the contribution of blue water increased from 20% to 22%, which was the same as the virtual water content per unit of yield. The VWV decreased from 2811 $m^3/10^4$ Yuan to 1394 $m^3/10^4$ Yuan in Bashang area, with a decrease of 50%, while it decreased from 3811 $m^3/10^4$ Yuan to 3164 $m^3/10^4$ Yuan in Baxia area, with a decrease of only 17%. Chongli County had the largest decline of 65%, decreasing from 3062 $m^3/10^4$ Yuan to 2004 $m^3/10^4$ Yuan; Municipal districts had the smallest decline of 2%, decreasing from 2197 $m^3/10^4$ Yuan to 2155 $m^3/10^4$ Yuan. However, the VWV did not decline in every county. The VWV of Wanquan County and Yangyuan County increased from 4148 $m^3/10^4$ Yuan and 6350 $m^3/10^4$ Yuan to 4306 $m^3/10^4$ Yuan and 8382 $m^3/10^4$ Yuan, respectively.

In terms of spatial differences of contribution rate (Fig. 13), in Bashang area, the proportion of VWVgr decreased from 77% to 64%, the proportion of VWVgi increased from 8% to 21%, and the proportion of VWVbc remained stable at around 15%. In Baxia area, the proportion of VWVgr decreased from 51% to 49%, the proportion of VWVgi remained stable at around 27%, and the proportion of VWVbc increased from 22% to 24%. In general, the total green water content was relatively stable, but the proportion of GWFr and GWFi changed greatly, showing that the GWFr decreased and the GWFi increased.

As shown in Fig. 14, in 2005–2015, the VWV of cereals, beans and oil crops decreased first and then increased, while the VWV of potatoes, vegetables, and fruits decreased continuously. Multi-year average values of VWV from high to low were beans (8697 $m^3/10^4$ Yuan), oil crops (8391 $m^3/10^4$ Yuan), cereals (5590 $m^3/10^4$ Yuan), potatoes (3062 $m^3/10^4$ Yuan), fruits (2356 $m^3/10^4$ Yuan) and vegetables (540 $m^3/10^4$ Yuan). In addition, in 2005, only the VWV of potatoes in Bashang area was lower than that in Baxia area, while in addition to potatoes, there were beans, oil crops, and vegetables in 2015. In terms of

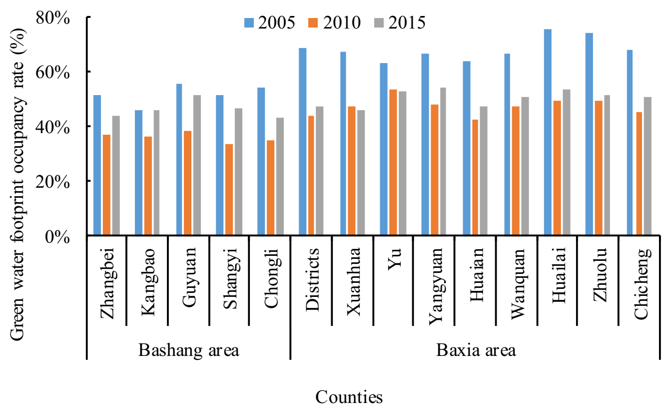

Fig. 7. Green water footprint occupancy rate in counties.

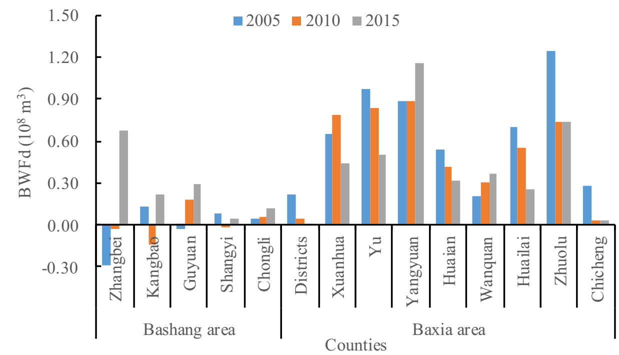

Fig. 9. Blue water footprint deficit in counties.

blue water and green water proportion, the proportion of blue water was the highest (53%) in vegetables, while it was the lowest (6%) in fruits.

5. Discussion

5.1. Water footprint requirement and blue water deficit

The CROPWAT 8.0 is developed for estimating the amount of water evaporation (water requirement) of crops at each growth stage under local climatic conditions, e.g., soil temperature and sunshine hours, and for guiding agricultural irrigation. However, due to water shortage and imperfect water supply infrastructures, crops cannot always be fully irrigated, especially in arid and semi-arid regions like Zhangjiakou. Therefore, in this study, in order to distinguish it from the actual consumption of water footprint, we propose the concept of water footprint requirement. Since the difference between them comes from whether the crops are fully irrigated, we further proposes the concept of blue water footprint deficit (BWFd).

In Zhangjiakou City, the planting area of main crops increased from 544,527 ha in 2005 to 565,010 ha in 2015, of which the irrigation area increased from 141,560 ha to 182,933 ha. There is no doubt that it would inevitably lead to an increase of water requirement for crops, which confirmed by this study that the WFr increased from 1.671 billion m^3 to 1.852 billion m^3. In addition, 20,890 ha of rain-fed farmland was converted to irrigation farmland over the study period, resulting in BWFd increased from 0.544 billion m^3 to 0.612 billion m^3. Therefore, controlling the expansion of farmland, or even returning farmland to forests, is the primary task of Zhangjiakou City to reduce the water demand of crops. Meanwhile, it is necessary to restrict the conversion of dry land into paddy fields and irrigated land. In terms of spatial differences, the irrigation area increased from 30,202 ha to 55,320 ha in Bashang area, while it increased from 111,359 ha to 127,612 ha in Baxia area. That is, the irrigation area in Baxia area was always much larger than that in Bashang area, so the BWF_d of counties in Baxia area were higher than that in Bashang area. That is, the Baxia area is the key area for agricultural water saving in Zhangjiakou City. It is vital to vigorously increase the irrigation water efficiency by increasing investment in irrigation facilities, improving management level, and changing irrigation methods. Meanwhile, it is also necessary to slow down the growth rate of irrigation farmland in Bashang area.

5.2. Improve green water occupancy rate by optimizing crop structure

In Zhangjiakou City, although the virtual water content per unit of yield (VWY) decreased from 0.331 m^3/kg in 2005 to 0.195 m^3/kg in 2015, the contribution rate of blue water and green water has always remained about 20% and 80%, respectively. This is because the irrigation area of Zhangjiakou City was only 26% -32% from 2005 to 2015, that is, most crops were still growing in rain-fed farmland, and only consumed green water. Therefore, the contribution rate of green water was always much higher than blue water for crops growth, and how to make full use of green water resources is of vital importance to the sustainable development of agriculture.

In Zhangjiakou City, green water occupancy rates were only 48%–60% and showed a significant spatial and temporal difference during the study period. Because the precipitation from May to September accounts for 80% of the annual total precipitation, and the temperature in these months is also the most suitable time for crop growth, so the green water occupancy rates in these months were higher than in other months. In addition, due to the higher altitude and the lower accumulated temperature, the green water occupancy rate was higher than 70% from May to July in Bashang area,

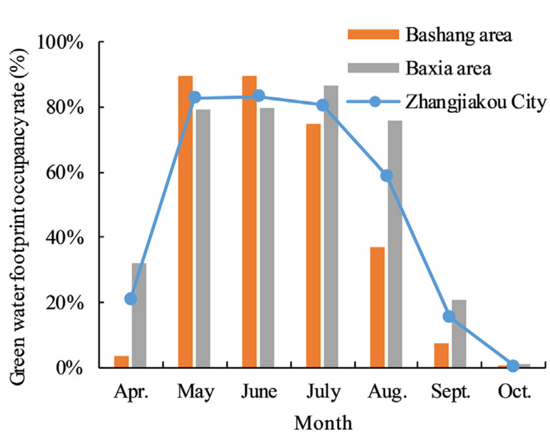

Fig. 8. Green water footprint occupancy rate in months.

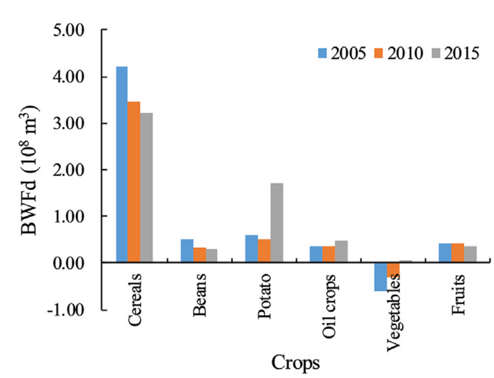

Fig. 10. Blue water footprint deficit in crops.

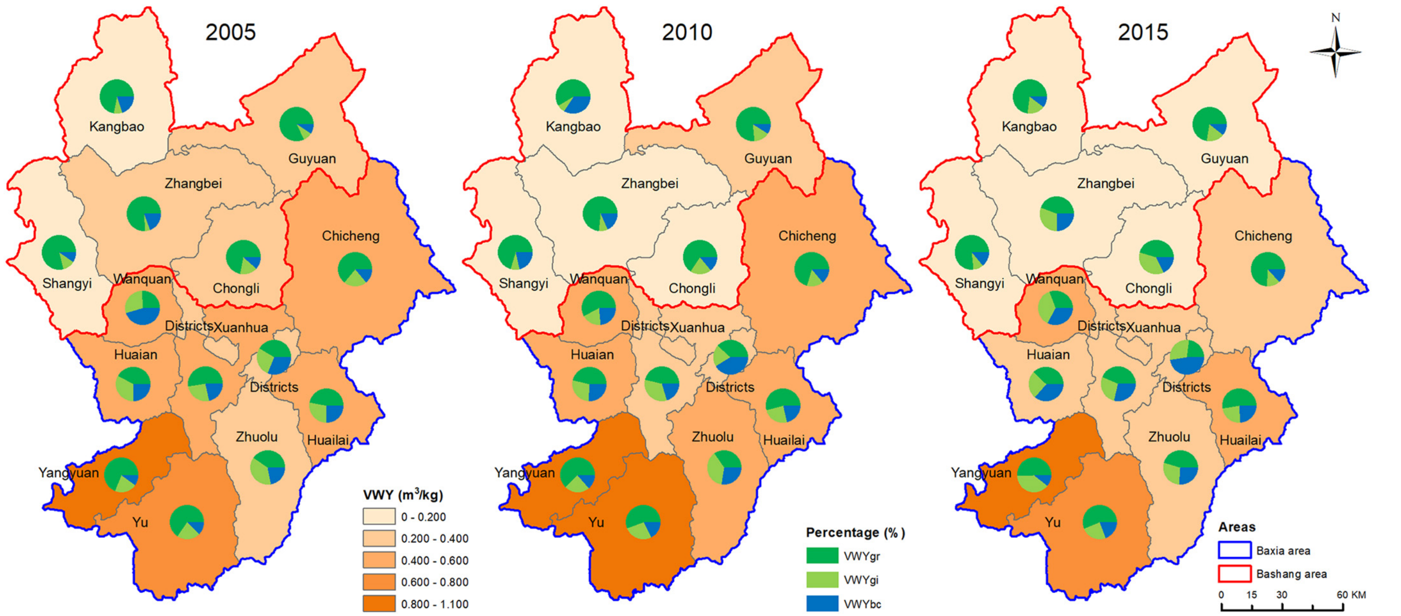

Fig. 11. Spatial distribution and structure of virtual water content per unit of yield (VWY).

while from May to August in Baxia area. Therefore, regardless of Bashang area or Baxia area, the possibility of improving the utilization rate of green water is limited in May to July. However, it could be improved by planting crops which are suitable to grow in August and September, especially in Bashang area, because the average temperatures in these two months are 20 and 15 degrees, respectively. The green water occupancy rate is introduced in this study provide a novel way of thinking for the research of the green water utilization.

5.3. Food productivity and economic benefits of water footprint

Virtual water content per unit of yield (VWY) and water footprint consumption per output value (VWV) can be considered as food productivity and economic productivity of water footprint, respectively. The VWY has been analyzed in almost all existing studies, but the VWV was largely neglected. There are three possible reasons. Firstly, the development of the water footprint concept derived from virtual water, and the virtual water was proposed to explore the flow characteristics of water embedded in products in international trade. Secondly, the analysis of the water footprint from the perspective of food would be easy to make comparisons between countries and regions. Thirdly, with the explosive growth of the global population, food security issues are receiving increasing attention, and the accessibility of freshwater is the biggest challenge for food production.

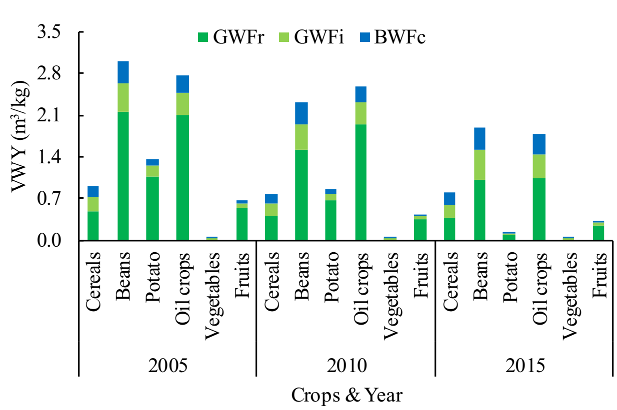

Fig. 12. Virtual water content per unit of yield (VWY) in different crops.

However, the economic benefits of crop water footprint should get more attention because higher food productivity does not necessarily mean higher economic benefits. Economic benefits are always changing due to unstable crop prices, the cost of labor and other factors. Based on the results, the relationship between VWY and VWV in Zhangjiakou City can be summarized into three types: (a) mutual match among crops, which means when the VWY is lower (higher), the VWV is also lower (higher), such as fruits and oils. (b) Mismatch among crops. In 2005, the VWY of potatoes was higher than that of cereals, but the VWV of potatoes was lower than that of cereals. Therefore, whether to plant potatoes or vegetables depends on the priority of food yields and economic benefits. (c) Mismatch among regions. In 2005, the VWY of vegetables in Bashang area (0.045 m^3/kg) was lower than in Baxia area (0.054 m^3/kg), while the VWV of vegetables in Bashang area (792 $m^3/10^4$ Yuan) was higher than in Baxia area (591 $m^3/10^4$ Yuan). That means, for vegetables, water footprint food productivity in Bashang area was higher than in Baxia area, but the water footprint economic productivity were reversed. Therefore, it is clear that significantly different policies could be made from different perspectives (VWY or VWV).

5.4. Limitations and future improvements

In the *Water Resources Bulletin*, irrigation farmland was only classified as three types of paddy fields, irrigated land and vegetable fields, and there is no other available data source that can be used to identify the irrigated area and the rain-fed area of each crop. Therefore, except vegetables, we estimated them by using the ratio of the total irrigated area to the total rain-fed area in every county, which means that the ratios of the irrigated area to the rain-fed area of all crops are same. Despite that it has relatively insignificant impacts on the results in this study due to calculation on the small scale of county level, it is recommended that the exact area of irrigated crops and rain-fed crops should be adopted for future research to make the results more accurate.

In addition, there were only total yield and GDP data for each crop can be used in Zhangjiakou City, without distinguishing irrigation farmland and rain-fed farmland, which limited us to compare economic benefits and food productivity of crop water footprint from irrigated crops

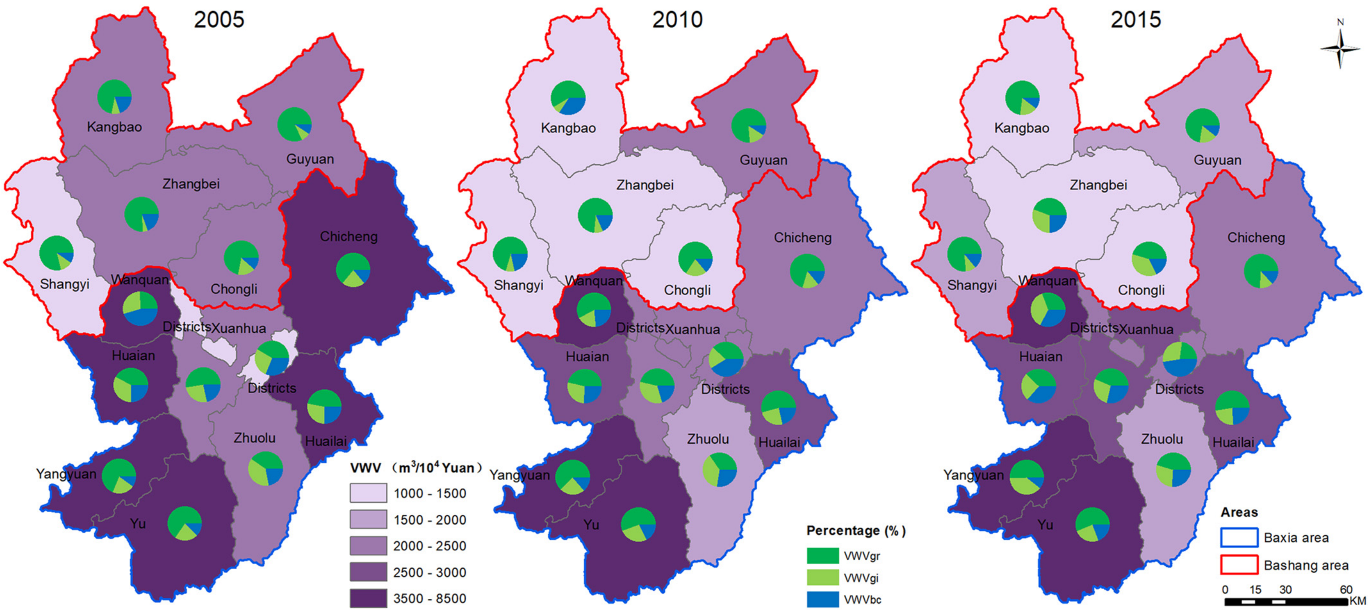

Fig. 13. Spatial distribution and structure of virtual water content per unit of GDP (VWV).

and rain-fed crops perspective. It is necessary to improve this in future research when data are available, which could be beneficial to crop structure optimization.

6. Conclusions

In this study, with the help of CROPWAT 8.0, the water footprint and its spatiotemporal characteristics and variations of the main crops were estimated in Zhangjiakou City for 2005, 2010, and 2015. Furthermore, an in-depth analysis of blue water, green water, and food productivity and economic benefits of water footprint were conducted by introducing three new indicators, i.e., green water footprint occupancy rate, blue water footprint deficit and virtual water consumption per output value. The main results are as follows:

(1) The results of this study agree with previous studies in terms of the importance of green water in crop production. The total water footprint requirement of Zhangjiakou City increased from 1.671 billion m^3 in 2005 to 1.852 billion m^3 in 2015, of which the ratio of green water to blue water was around two, which means green water plays a greater role than blue water. In addition, the total water footprint requirement in the counties of the mountainous Bashang area is lower than those of the Baxia area, and the gap between them was further expanding.

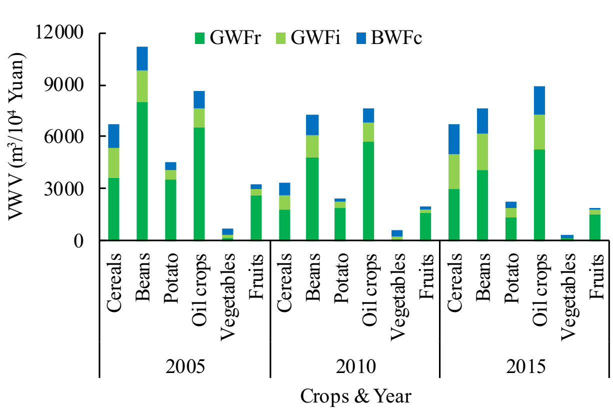

Fig. 14. Virtual water content per unit of GDP (VWV) in different crops.

(2) Cereals, as the main staple food, had the largest water footprint requirement in Zhangjiakou City, accounting for 52%–55%. Meanwhile, the water footprint requirement of potatoes increased the fastest, with an increase of 47%, which is a result of large-scale planting in recent years. The crop with the highest proportion of blue water was vegetables, but it declined from 55% to 40% gradually, while the crop with the highest proportion of green water was fruits, accounting for 83%–85%.

(3) By introducing the green water footprint occupancy rate, we found that there were significant differences between the higher-altitude Bashang area and the lower-altitude Baxia area in terms of green water use. The green water footprint occupancy rate in counties of the Bashang area was 43%–49%, with an average of 44%, while it was 51%–59% in counties of the Baxia area, with an average of 54%. The highest utilization rates of green water in a year were from May to August, which were 58%–83%. In terms of blue water footprint deficit, it dropped from 0.544 billion m^3 in 2005 to 0.480 billion m^3 in 2010 and then increased to 0.612 billion m^3 in 2015. In general, it was lower in Bashang area than in Baxia area.

(4) From 2005 to 2015, the virtual water content per unit of yield dropped from 0.331 m^3/kg to 0.195 m^3/kg continuously, while the virtual water consumption per output value dropped from 3380 $m^3/10^4$ Yuan to 2183 $m^3/10^4$ Yuan and then rose to 2344 $m^3/10^4$ Yuan. In other words, the changing trends of water footprint food productivity and water footprint economic benefits were not always the same. The relationships between them in Zhangjiakou City can be classified into three types: mutual match among crops, mismatch among crops, and mismatch among counties. It is important to consider them simultaneously when formulating policies from the perspective of water footprint.

CRediT authorship contribution statement

Weijing Ma: Conceptualization, Methodology, Software, Data curation, Writing - original draft. **Christian Opp:** Supervision, Writing - review & editing. **Dewei Yang:** Data curation, Writing - review & editing, Project administration, Funding acquisition.

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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