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Assessing water scarcity in agricultural production system based on the generalized water resources and water footprint framework

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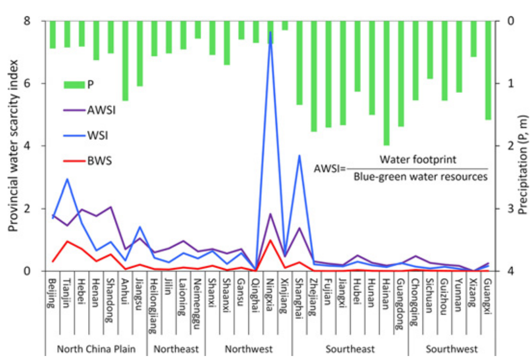
HIGHLIGHTS

- AWSI based on blue-green water and water footprint (WF) framework is established.
- Blue water dominates in water resources while blue WF accounts for 12.7% of the total.
- Water scarcity was aggravated from 1999 to 2014 in agricultural production of China.
- The AWSI is suitable for water scarcity evaluations, particularly in arid area.

GRAPHICAL ABSTRACT



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ABSTRACT

An indicator, agricultural water stress index (AWSI), was established based blue-green water resources and water footprint framework for regional water scarcity in agricultural production industry evaluation. AWSI is defined as the ratio of the total agricultural water footprint (AWF) to water resources availability (AWR) in a single year. Then, the temporal and spatial patterns of AWSI in China during 1999–2014 were analyzed based on the provincial AWR and AWF quantification. The results show that the annual AWR in China has been maintained at approximately 2540 Gm^3, of which blue water accounted for >70%. The national annual AWF was approximately 1040 Gm^3 during the study period and comprised 65.6% green, 12.7% blue and 21.7% grey WFs The space difference in both the AWF for per unit arable land (AWFI) and its composition was significant. National AWSI was calculated as 0.413 and showed an increasing trend in the observed period. This index increased from 0.320 (mid-water stress level) in 2000 to 0.490 (high water stress level) in the present due to the expansion of the agricultural production scale. The Northern provinces, autonomous regions and municipalities (PAMs) have been facing high water stress, particularly the Huang-Huai-Hai Plain, which was at a very high water stress level (AWSI > 0.800). Humid South China faces increasingly severe water scarcity, and most of the PAMs in the region have converted from low water stress level (AWSI = 0.100–0.200) to mid water stress level (AWSI = 0.200–0.400). The AWSI is more appropriate for reflecting the regional water scarcity than the existing water stress index (WSI) or the blue water scarcity (BWS) indicator, particularly for the arid agricultural production regions due to the revealed environmental impacts of agricultural production. China should guarantee the sustainable use of agricultural water resources by reducing its crop water footprint.

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1. Introduction

The issue of growing water scarcity has been increasingly perceived as a global systemic risk (Vörösmarty et al., 2010; Bakker, 2012). The efficient and sustainable utilization of water resources is the basis for maintaining social and economic development and the demand for environmental management. The agriculture industry use the largest amount of water, i.e., agricultural production has accounted for >80% of global (blue) water withdraws. Further, 90% of the human consumptive water footprint comes from agricultural products (Hoekstra and Mekonnen, 2012). Therefore, improving agricultural water efficiency and alleviating the water stress induced by agricultural production is an important measure for improving the sustainable utilization of regional water resources. Agricultural production processes involve the complex hydrological cycle and may cause adverse impacts on the environment. Therefore, the evaluation of the relationship between agricultural production and water resources has been of wide concern (Wang et al., 2014; Cao et al., 2015a; Majone et al., 2016).

The relationship between agricultural production and water resources evaluation has been conducted using the methods of water use efficiency, water scarcity and water footprint (WF) (Table 1). The water use efficiency assessment is that of the direct issues affecting the formulation of water resources management strategies. The effective use rate of water resources or the production capacity reveals the water use efficiency and measured using the indicators irrigation efficiency (IE) and water productivity (WP). The IE is a sophisticated and useful measure of irrigation performance that can be expressed by various indicators, such as the classical irrigation efficiency and net or effective irrigation efficiency (Israelsen, 1932; Bos, 1980; Bruce, 2012). The irrigation water withdrawal, water application efficiency, evapotranspiration, water consumed, return flow and net depletion (Yilmaz et al., 2009; Sepaskhah and Ghahraman, 2004; Bruce, 2012) are closely related to irrigation efficiency assessments. The agricultural WP, which was originally defined by Molden (1997), is used to measure the relationship between the crop yield and amount of water involved in the crop production process and is expressed as crop production per unit volume of water resources (Zwart and Bastiaanssen, 2004; Playán and Mateos, 2006; Wokker et al., 2014; Cao et al., 2015a, 2015b). The numerator is expressed in terms of crop yield (kg/ha), and several options are available for defining the volume of water per unit area (m^3/ha) in the denominator (Cao et al., 2015a, 2015b). The IE and WP are direct relevant to achieve efficient water use and have been extensively studied in water resources management (Playán and Mateos, 2006; Wokker et al., 2014). Water scarcity assessment should be used instead of water use efficiency to meet production needs. The Falkenmark Index, water stress index (WSI), International Water Management Institute (IWMI) indicator and blue water scarcity (BWS) are the indices commonly used in water scarcity evaluation. Initially, Falkenmark et al. (1989) allocated the water scarcity level using per capita water resources, and set 1700 m^3 as the water shortage threshold. The WSI and BWS parameters are used to measure the proportion of water use to resources availability. The amount of available water resources in a region is limited, and the water resource stress increases with water use and consumption (Lamastra et al., 2017). Water scarcity was usually divided into several levels, such as no water stress, low water stress, mid-water stress, high water stress and very high water stress (Raskin et al., 1997; Zeng

Table 1
Documented assessment approaches for water scarcity in agricultural production system.

Approach	Definition	Indicator	Calculation method	Object	Literatures emerged/studied
Water use efficiency	Effective use of water resources or production capacity	Irrigation efficiency (IE)	ET_b/IWW ET_b: field irrigation water evapotranspiration IWW: irrigation water withdrawal	Irrigation (blue) water	Israelsen, 1932; Bos, 1980; Sepaskhah and Ghahraman, 2004; Yilmaz et al., 2009; Bruce, 2012
		Water productivity (WP)	Y/WI Y: crop yield; WI: water input item	Irrigation (blue) and rain (green) water resources	Molden, 1997; Zwart and Bastiaanssen, 2004; Playán and Mateos, 2006; Wokker et al., 2014; Cao et al., 2015a, 2015b
Water scarcity	Ability of water resources to meet production needs	Falkenmark index	WA/PO WA: water resources availability; PO: population	Conventional (blue) water resources	Falkenmark et al., 1989; Ohlsson and Appelgren, 1998; Savenije, 2000
		Water stress index (WSI)	WD/WRA WD: water demand WRA: water resources availability		Raskin et al., 1997; Alcamo et al., 2000; Vörösmarty et al., 2000; Oki and Kanae, 2006
		IWMI indicator	PWS/UWS UWS: utilizable water supply PWS: primary water supply		Seckler et al., 1998; Zeng et al., 2013
		Blue water scarcity	BWF/BWA BWF: blue water footprint; BWA: blue water availability		Hoekstra et al., 2012; Pfister and Bayer, 2014; Sun et al., 2016; Liu et al., 2017
Water footprint	Appropriation of fresh water in volumes of water consumed and polluted	Blue water footprint (WF_{blue})	IWR × A IWR: irrigation water requirement; A: crop acreage	Irrigation (blue) water	Hoekstra et al., 2011; Sun et al., 2013; Cao et al., 2014; Zhuo et al., 2016; Veettil and Mishra, 2016
		Green water footprint (WF_{green})	ET_g × A ET_g: rain water evapotranspiration	Rain (green) water resources	Hoekstra and Chapagain, 2007; Hoff et al., 2010; Chukalla et al., 2015
		Grey water footprint (WF_{grey})	DWR × A DWR: dilution water requirement	Water environment (quality)	Pellicer-Martínez and Martínez-Paz, 2016; Wu et al., 2016; Vergé et al., 2017; Miglietta et al., 2017

et al., 2013) according to the assessed WSI values. IWMI water scarcity was defined as the rate of utilizable water supply in the primary water supply (Seckler et al., 1998).

In most present studies, green water resources and the potential impacts of agricultural production on the environment are rarely considered for the evaluation of water use efficiency and water scarcity (Schyns et al., 2015; Wang et al., 2015). The methods of assessing the WF have made considerable progress in this field. The WF of a crop product is defined as the volume of freshwater consumed during the crop production process and can be divided into blue, green and grey WFs. The blue WF refers to the consumption of blue water resources throughout the supply chain of a product; the green WF refers to the consumption of rainwater insofar as it does not become runoff; and the grey WF refers to the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011; Cao et al., 2014). The water footprint of a crop product is usually measured in two ways: the total WF in a specific region (in m^3) and the WF of a unit mass of product (in m^3/kg). The green and blue WFs of unit production reflect the regional water productivity and grey WF measures of the impact of agricultural production on the environment (Hoekstra, 2003; Hoekstra et al., 2011) The agricultural WF is a measure of crop appropriation of fresh water in volumes of water consumed and/or polluted, and quantitative research on WF and its composition for crops in different regions has been extensively conducted by academics (Lovarelli et al., 2016).

Scholars have tried to establish water resource stress indices based on regional WF and total water resources availability recently (Pfister et al., 2011; Hoekstra et al., 2012; Pfister and Bayer, 2014; Liu et al., 2017). However, most of these papers only observed blue water resources or do not take green water as part of agricultural water resources availability. The evaluation of water consumption has not considered the green and grey WFs. Therefore, biased results may be gained in determining the sustainable use water resources in regional agricultural production industry because information was not comprehensive. The aim of current study is to establish an index for regional water scarcity evaluation within the framework of generalized (blue and green) water resources and WF theory. Based on the generalized water resources and water footprint of agricultural production system calculation in China, the temporal and spatial distribution of agricultural production water scarcity will be assessed. Additionally, we expect to provide a new perspective for research on regional water resources and environment management.

2. Methods and data

2.1. Agricultural water stress index (AWSI)

Regional agricultural water scarcity is measured by the agricultural water stress index (AWSI) in this report. The recognized method for calculating conventional water stress index (WSI) is the ratio of water withdraws (water use) to the amount of water resources available (Raskin et al., 1997):

$$\mathrm{WSI} = \frac{\mathrm{WW}}{\mathrm{WR}} \tag{1}$$

where, WW and WR are regional (blue) water withdraw and water resources available respectively, in m^3. The agricultural water stress index (AWSI) in a region is defined as the ratio of the total crop water footprint to agricultural water resources availability during a given period. Referring to this method, AWSI for agricultural production system that is based on the blue-green water resources and water footprint framework is calculated as:

$$\mathrm{AWSI} = \frac{\mathrm{AWF}}{\mathrm{AWR}} \tag{2}$$

where, AWF is the regional agricultural water footprint, which is the sum of water footprints for all types of crop product in m^3 and AWR is the water resources provided for crop production (including all primary crop products) in a region. The AWR includes blue or so called conventional water resources availability ($\mathrm{AWR_{blue}}$) and the green or so called rain water resources availability ($\mathrm{AWR_{green}}$) as in:

$$\mathrm{AWR} = \mathrm{AWR_{blue}} + \mathrm{AWR_{green}} \tag{3}$$

where AWR is the regional agricultural water resources availability. $\mathrm{AWR_{blue}}$ is calculated as:

$$\mathrm{AWR_{blue}} = \mathrm{WR} \times \frac{\mathrm{AWU}}{\mathrm{WU}} \tag{4}$$

where, WR is regional total (blue) water resources availability in m^3; and AWU and WU are the regional agricultural and total water use (withdrawn) respectively in m^3. $\mathrm{AWR_{green}}$ refers the yearly effective precipitation in arable land:

$$\mathrm{AWR_{green}} = 10 \times \mathrm{A} \times \mathrm{P_e} \tag{5}$$

where, A is the area of regional arable land in hm^2 and P_e is yearly effective precipitation in mm, which was estimated as the method recommended in the FAO CROPWAT model as follows (FAO, 2010):

$$\mathrm{P_e} = \begin{cases} \mathrm{P} \times \left(\dfrac{4.17 - 0.02 \times \mathrm{P}}{4.17}\right), & \mathrm{P}<83 \\ 41.7 + 0.1 \times \mathrm{P}, & \mathrm{P} \geq 83 \end{cases} \tag{6}$$

Following the definitions used in the Chinese National Yearly Statistics for agricultural crops including cereals (i.e., rice, wheat and maize), beans (soybean and other leguminous crops), tubers (potato, sweet potato and other types of tubers), cotton, oil-bearing crops, sugar crops, fiber crops, fruits, tobacco and tea. The AWF was calculated by:

$$\mathrm{AWF} = \sum_{i=1}^{n} (\mathrm{CWF}_i \times \mathrm{G_i}) \tag{7}$$

where, i is the number of crop category, CWF_i is the WF of per unit product of crop i, in m^3/kg and G_i is the total production of crop i in kg. For each kind of crop, the CWF is the sum of the blue, green and grey WFs

$$\mathrm{CWF} = \mathrm{CWF_{blue}} + \mathrm{CWF_{green}} + \mathrm{CWF_{grey}} \tag{8}$$

Hoekstra et al. (2011) set the standard computational methods of blue, green and grey WFs in crop production system. According to the standard computational methods, $\mathrm{CWF_{blue}}$and $\mathrm{CWF_{green}}$ was calculated using CROPWAT 8.0 model (Cao et al., 2014). The $\mathrm{CWF_{grey}}$ was estimated as follow:

$$\mathrm{CWF_{grey}} = (\alpha \times \mathrm{AR})/(c_{max} - c_{min}) \tag{9}$$

where α is the leaching-runoff fraction; AR is the rate of chemical application to the field per hectare, kg/ha; c_{max} is the maximum acceptable concentration (10 mg/L for T-N); c_{max} is the concentration in natural water, assumed to be 0 mg/L.

The AWF can be computed by using Eq. (7), and then, regional AWF intensity (AWFI) can be calculated as follows:

$$\mathrm{AWFI} = \frac{\mathrm{AWF}}{\mathrm{A}} \tag{10}$$

where AWFI in Eq. (10) is regional agricultural water footprint per unit of arable land in mm; A is the arable land in ha.

The regional green water resources availability and its consumption in a crop growth period are considered in the current study. The qualification of AWSI reveals the relationship between the overall impact of crop growth on the generalized water resources and regional generalized water resources availability. This indictor mirrors whether agricultural water resources can meet the demands of the crop production industry for water resources and the environment. Regional AWSI is combined affected by precipitation, agricultural production scale, agronomic measure, crop types and irrigation development. A high AWSI value indicates that regional agricultural production is unsustainable and the region faces enormous water volume and environmental stress. The calculation principle of AWSI is similar to the WSI in Eq. (1) defined by Raskin et al. (1997), regional agricultural water scarcity level is also stipulated into five gradations: no water stress (<0.1), low water stress (0.1–0.2), mid-water stress (0.2–0.4), high water stress (0.4–0.8) and very high water stress (>0.8).

2.2. Data resource

The observing period of current study is 1999–2014. Water resources availability (WR), total water use (WU), agricultural water use (AWU) and irritation efficiency (IE) for the period 1999–2014 in 31 provinces, autonomous regions and municipalities (PAMs) of China are obtained from the China Water Resources Bulletins 1999–2014 (MWR, 1999–2014). Provincial arable land (A) and sown area (A_s), chemical application to the field and production for all types of crop (G) in the observed years were collected from the China Statistical Yearbook 2000–2015 (NBSC, 2000–2015) The growth period data and of selected grain crops from 180 agricultural observation stations (Cao et al., 2015b) are supplied by the Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences. Finally, the meteorological data for CROPWAT 8.0 model, including maximum temperature, minimum temperature, relative humidity, wind speed, sunshine hours and precipitation, of 835 weather stations in 31 PAMs of China were downloaded from the Climatic Data Center, China Meteorological Administration (http://data.cma.cn/) (See Fig. 1). Annual precipitation averaged together for each PAM prior to calculation of AWR_{green}.

3. Results

3.1. AWR

The national annual total AWR during 1999–2014 was calculated as approximately 2540 Gm^3, of which the blue water (AWR_{blue}) and green water (AWR_{green}) resources were 1842 and 698 Gm^3 respectively. The AWR and its composition in China during the study period are shown in Fig. 2.

As illustrated in Fig. 2, neither the AWR_{blue} nor AWR_{green} showed noticeable changes over time. The AWR_{blue} varied between 1562 (in 2013) and 2084 (in 2011) in Gm^3, and the AWR_{green} changed from 641 to 737 Gm^3 in 2007 and 2003. The coefficient of variation (CV) of the AWR_{blue} and AWR_{green} were 0.098 and 0.044, respectively, which reveals that interannual variation in the AWR_{blue} was greater than in the AWR_{green}. The AWR_{blue} was determined as the total amount of regional WR and water supply structure correlating to the computing method in Eq. (6). Because of the increase in IE (the ratio of the irrigation water consumed by the crops of an irrigated farm to the water diverted from natural water source into the farm project canals), which went from 0.418 in 1999 to 0.530 in 2014, the share of the AWU in WR withdraws decreased from 69.2% in 1999 to approximately 62.0% in the most recent five years, which is the primary reason why the AWR_{blue} decreased gradually after 1999. Large amounts of the AWR_{blue} during 2010 and 2013 are attributed to plentiful rain. The WR of these two years exceeded 3.00 Tm^3, about 8.0% higher than the annual average value (2.78 Tm^3). The AWR_{green} is jointly determined by the amounts of arable land and precipitation. From 1999 to 2014, the area of farmland in China remained stable at approximately 127 M ha. Although the precipitation varied among the years, it did not affect the P_e significantly. Because the P_e does not increase with precipitation linearly (Eq. 8), the excess precipitation leaves the farmland as runoff; therefore, it is maintained at a stable value, yielding the variation in the annual AWR_{green}. Fig. 2 also shows that the AWR_{blue} was the major component of agricultural available water resources, and accounted for 72.4% of the AWR during 1999–

Fig. 1. Location of 835 weather stations in 31 PAMs of China.

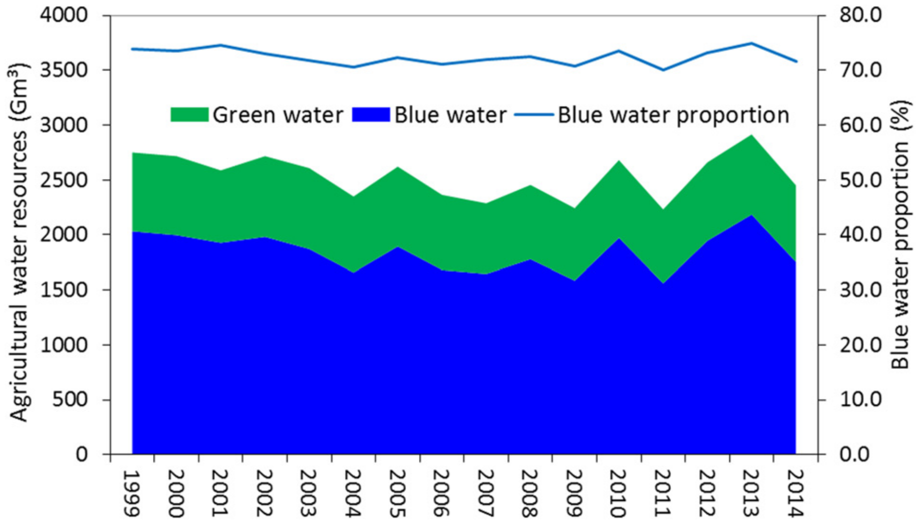

Fig. 2. Agricultural water resources availability of China during 1999–2014.

2014. Moreover, this ratio was never below 70.0% during any of the years. The AWR per unit arable land (AWRP) of China was approximately 2000 mm. The average amount of the AWRP and its composition in the 31 PAMs in the observing period are mapped in Fig. 3.

By large space differences, the AWRP was high in the PAMs located in Southwest and Southeast China but low Northeast, Northwest and North China Plain PAMs (Fig. 3). The AWRP was below 1000 mm in 13 PAMs, all of which were in North China except Shanghai. The AWRP of Ningxia was only 305 mm, which ranked the lowest in the country. The PAMs with similar AWRP values showed significant aggregation. Distributions of the PAMs with high AWRP values are centered on Southeast China, and the PAMs with low AWRP values were distributed in North and Northeast China. Specifically, the AWRPs of Tianjin, Shanxi, Hebei, Beijing and Shandong on the North China Plain were <800 mm, while they were approximately 900 mm in the Northeast PAMs. In the Yangtze River Basin, including in Jiangsu, Chongqing, Anhui, Guizhou and Hubei, the values were approximately 1500 mm, which is lower than the national average. The AWRP of 12 PAMs exceeded 3500 mm, i.e., in Hunan, Guangdong, Guangxi, Jiangxi, Yunnan Hainan and Fujian and reached up to 8000 mm in Qinghai and Xizang. Fig. 3 shows that blue water dominated in the AWR of the PAMs with high AWRPs, while the regions that held low AWRPs had a higher green water proportion, except the three Northeastern provinces and Gansu and Xinjiang in the Northwest. The proportion of blue water north of the Yangtze River and North China Plain was only approximately 30.0%, and above 50.0% in the northeast PAMs. This proportion closes to

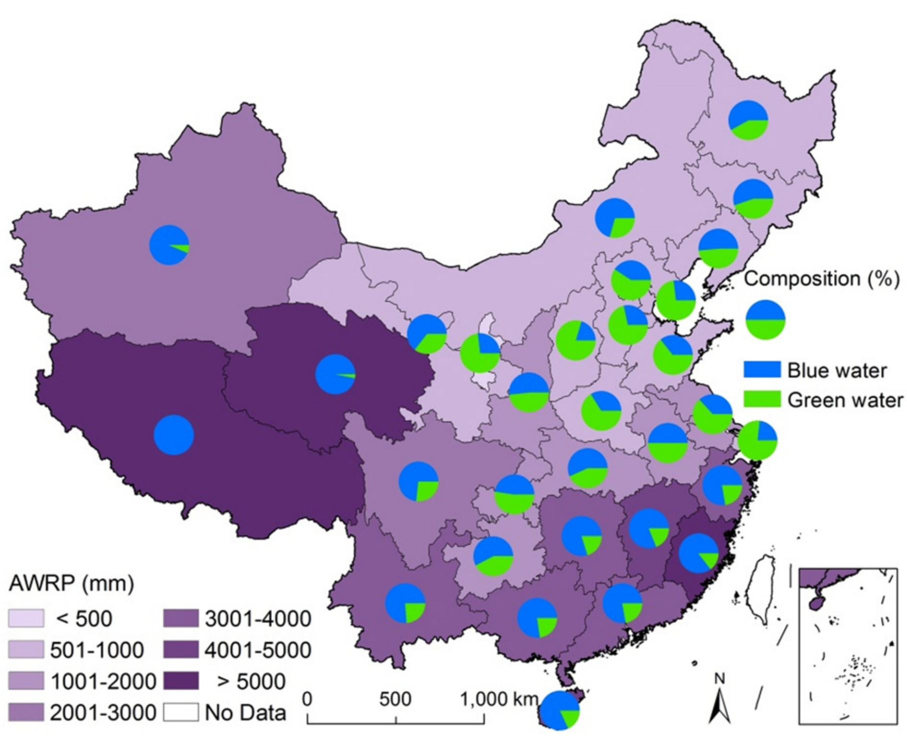

Fig. 3. Spatial distribution of agricultural water resources availability per unit arable land (AWRP) and its composition in 1999–2014.

80.0% in south of the Yangtze River and exceeded 90.0% in Xinjiang, Qinghai and Xizang. The spatial distribution of the AWRPs and their compositions reflect the differences in water resources, precipitation, farmland area and water supply structures in China. The Tibetan Plateau is the cradle and water source of the Yangtze and Yellow Rivers, China's two largest rivers. The combination of abundant blue water resources and few arable lands result in the high amounts of available water and the high blue water proportion in Xizang and Qinghai. Precipitation south of the Yangtze River was above 1500 mm, and most of the region's shape determines that the surface and groundwater are in the form of runoff. The abundance of blue water resources also causes high available water resources per unit area and the proportion of blue water. The agricultural production relies on irrigation due to the rare rainfall in Xinjiang and their agricultural water consumption accounted for >90.0% of total water use, which explains why Xinjiang's AWR_{blue} accounted >90% of the AWR.

3.2. AWF

China's AWF was calculated as 1042 Gm^3 in 1999 to 2014, of which the AWF_{blue}, AWF_{green} and AWF_{gray} were approximately 131, 684 and 227 Gm^3, respectively. The national AWF and its composition for each studied year are shown in Fig. 4.

Fig. 4(a) shows that the national AWF remained at 850 Gm^3 during 1999–2002, and then was followed by an increasing trend over time that reached up to 1285 Gm^3 in 2014. The blue, green and grey WFs were increased from 120, 565 and 185 Gm^3 to 160, 840 and 285 Gm^3, respectively. Because of the growing population, the total demand for China's agricultural products showed a significant increase during the study period. Although the promotion of crop yield per unit area (e.g., grain yield increased from 4.6 kg/ha in 1999 to 5.8 kg/ha in 2014) reduced the WF per unit product, the expansion of the agricultural production scale caused a significant change in the water footprint as shown in Fig. 4. The increase in the blue WF was caused by the expansion of the irrigation area. China's effective irrigation area expanded from 53 Mha in 1999 to nearly 65 Mha in 2014, and the irrigation proportion of arable land increased from 40.9% to 53.0%. The field total irrigation water evapotranspiration (blue WF) has yet been controlled, although the improvement of IE inhibited the irrigation water diversion per unit cropland. The increase in the AWF_{green} primarily resulted in the growth of crop acreage and changes in the planting structure. The crop acreage has increased by 10.0% in the last 16 years, which led to increased rainfall availability for crops. The sum of the acreage proportions of crops with a dominant green WF, i.e. oil-beaning crops, cotton, fruits and tea, increased from approximately 15.0% to 20.6%. The AWF_{grey} was caused by the loss of fertilizer according to the calculation method. The amount of fertilizer used in per unit of cultivated area in China increased from 320 to 440 kg/ha, while the effective utilization rate has not yet significantly improved (Fan et al., 2012). This is the primary reason for the increase in the AWF_{grey}. The national annual average proportion of blue, green and grey WFs in 1999–2014 was estimated to be approximately 12.7%, 65.6% and 21.7%, respectively. Rainfall was the definitive water resource for China's agricultural production. Fig. 4(b) reveals that the water footprint composition did not show a significant change trend over the years. The scale of agricultural production primarily determined the amount of provincial AWFs, so the differences in the AWFs among PAMs were quite large. The regional AWFs ranged from 2.1 Gm^3 in Qinghai to 113.7 Gm^3 in Shandong. The spatial distribution pattern of the AWFI and its composition in China from 1999 to 2014 is shown in Fig. 5.

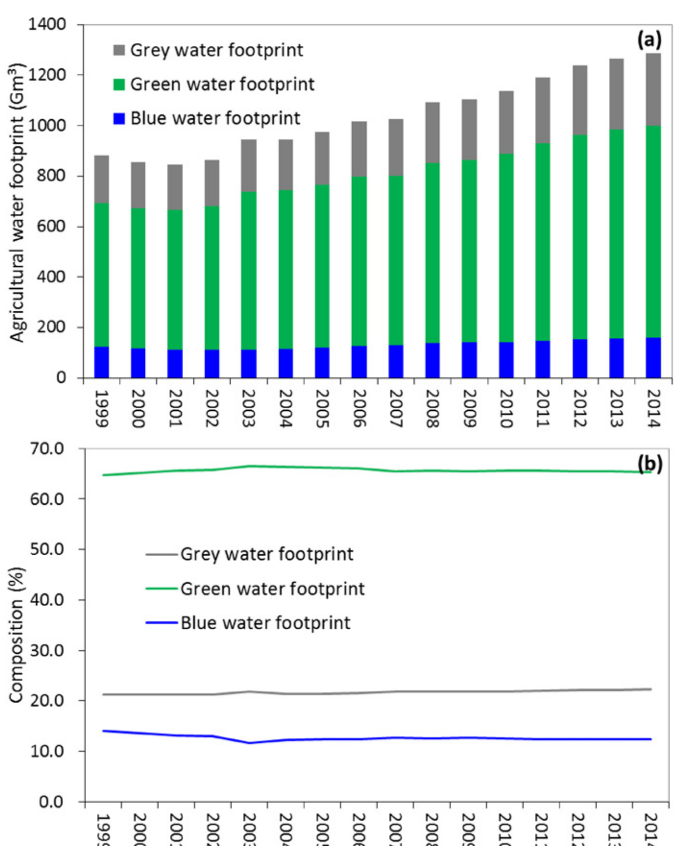

Fig. 4. Yearly agricultural water footprint (AWF) (a) and its composition (b) of China during 1999–2014.

China's annual AWFI of was approximately 822.7 mm during the study period. Fig. 5 shows that the AWFI presented a significant spatial aggregation. The PAMs on North China Plain held a high AWFI and were followed by the southeastern regions. The AWFI in the southwestern and northwestern PAMs (except Xinjiang) was low. The lowest AWFI was found in Qinghai and was only 310.5 mm. The intensity of Guizhou, Gansu, Neimenggu and Xizang was approximately 400 mm, which was considered a low level in the country. The AWFI in another 11 PAMs, including Shanxi, Heilongjiang, Yunnan, Ningxia, Shaanxi, Chongqing, Jilin, Sichuan, Tianjin, Liaoning and Jiangxi, was not greater than the national value. The AWFI in eight of the remaining 15 PAMs was above the national value, ranged from 900 to 1100 mm, and exceeded 1200 mm in Fujian, Jiangsu, Henan and Shandong. The Shandong was also the province with the highest AWF intensity in China. Both the AWF and AWFI in Jiangsu, Henan and Shandong were in the forefront of all the PAMs, and these PAMs played an important role in agricultural production and water utilization in the country. Given the water footprint composition, the green WF played a dominant role in the AWF, and its proportion was higher than the blue (except Xinjiang) and the grey WF in all of the 31 PAMs. The Compositional structure of the AWF varied among the regions. The AWF_{blue} proportion ranged from 3.6% in Fujian to 42.3% in Xinjiang and showed an opposite spatial distribution pattern to the AWF_{green}. It can be seen that the AWF_{blue} proportion in the Northwest and North was significantly higher than in the Southeast and Southwest PAMs. The blue water ratios of Shandong, Qinghai, Hebei, Gansu, Tianjin, Ningxia and Xinjiang were >15.0% but <5.0% in Fujian, Guangdong and Guangxi. The green water proportion in Southern China was generally higher than that in the Northern PAMs. The AWF_{green} proportion in Chongqing, Zhejiang, Tibet, Guizhou, Yunnan, Hainan, Guangdong, Guangxi and Fujian was above 70.0%. There is no obvious spatial variability in the grey proportion, which ranged from 17.1% in Xizang to 26.8% in Hunan. The ratio of the blue and green WFs is closely related to precipitation, while the proportion of the grey WF depends on the amount of fertilizer applied and lost.

3.3. AWSI

The annual AWSI was calculated as 0.413 during 1999–2014 and the yearly national values during the period are shown in Fig. 6. The AWSI in

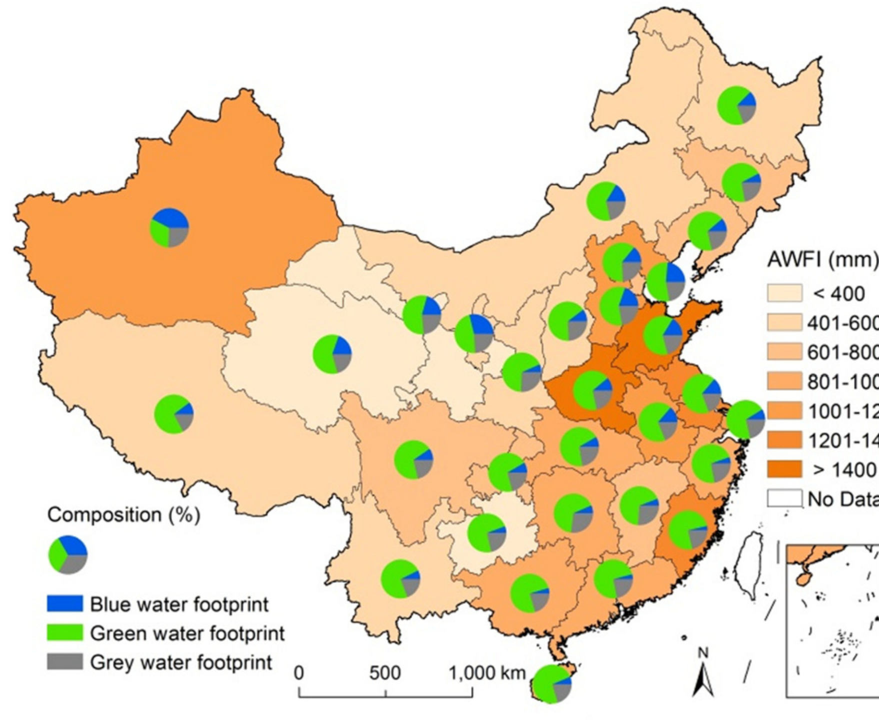

Fig. 5. Spatial pattern of agricultural water footprint intensity (AWFI) and its composition in 1999–2014.

each year was >0.200, which indicates that China's agricultural production industry has been facing water stress in the most recent 16 years. The AWSI showed a trend (significant trends cannot be made on this time scale) of increasing, from approximately 0.320 in 2000 to 0.490 in 2014, during the study period. China was in the mid-water stress levels before 2006 and then fell into the high water stress level. China's water scarcity in agriculture resulted from both crop water requirements and non-point source pollution, with the latter being attributing approximately 22%. Provincial AWSI values in the nine selected years and the observed period are mapped in Fig. 7 to demonstrate spatial pattern and temporal variation of the indicator in China.

Fig. 7 shows that the variation of AWSI over time varied among the PAMs, while it has an overall tendency of increasing water stress in the different regions of China. The AWSI in Ningxia and almost all of the North China Plain PAMs was above 0.800 in each subplot, and these regions have been facing very high water stress in agricultural production systems. The North China is urgent to ease water stress through taking effective action, such as restructure agricultural industry and reduce the proportion of the grain crops with high water requirement. In contrast, the indicator in Xizang and Qinghai was <0.100 during all the years, and both of the areas were at a no water stress level. The remaining PAMs in the north of China ranged between a high water stress (AWSI > 0.400) and a very high water stress (AWSI > 0.800) level as shown in each subplot of Fig. 7. The WASI in most of the PAMs in South China was between 0.100 and 0.200, and only faced low water stress levels in the beginning. However, the value exceeded 0.200 in all of the PAMs by 2014, and even >0.400 in Guizhou, Chongqing and Hubei, which results in the areas being above the mid-water stress levels. The high water stress areas extended from the arid North to the humid South in China.

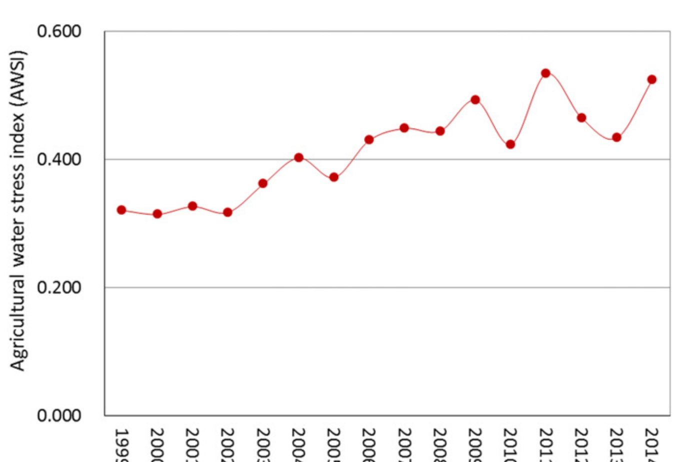

Fig. 6. National agricultural water stress index (AWSI) of China during 1999–2014.

The average AWSI for each province during 1999–2014 (Fig. 7) reveals the spatial distribution pattern of agricultural water scarcity in China. Shandong's AWSI reached 2.056, ranked the highest of all the PAMs. Followings were Hebei, Ningxia and Beijing, where the AWSI was calculated as 1.978, 1.833 and 1.791 respectively. The water resources demand per consumptive use and pollution appropriation for the agricultural production industry in these four PAMs was much greater than the generalized agricultural water resources availability. Other values above 0.800 were found in Jiangsu, Shanghai, Tianjin and Henan, all of which should be classified as very high water stress level regions. Severe water scarcity limits the expansion of the agricultural production scale and promotion of grain production, and may threat regional and national food security. Simultaneously, pressing water resources issues in agriculture may affect other industries due to its leading position in regional water utilization. Agricultural water consumption is normally far greater than that in other industries and domestic use. Crop production processes occupied most of the blue water diversion and might also contaminate the industrial or domestic water source when the AWSI exceeds 1.000. That is, the agriculture water scarcity is related to the sustainable utilization of water resources by the whole society, particularly in the highly water-stressed areas. Therefore, it is urgent to promote water and fertilizer use efficiency, control the non-point source pollution or consider polluted water treatment and reuse in PAMs above.

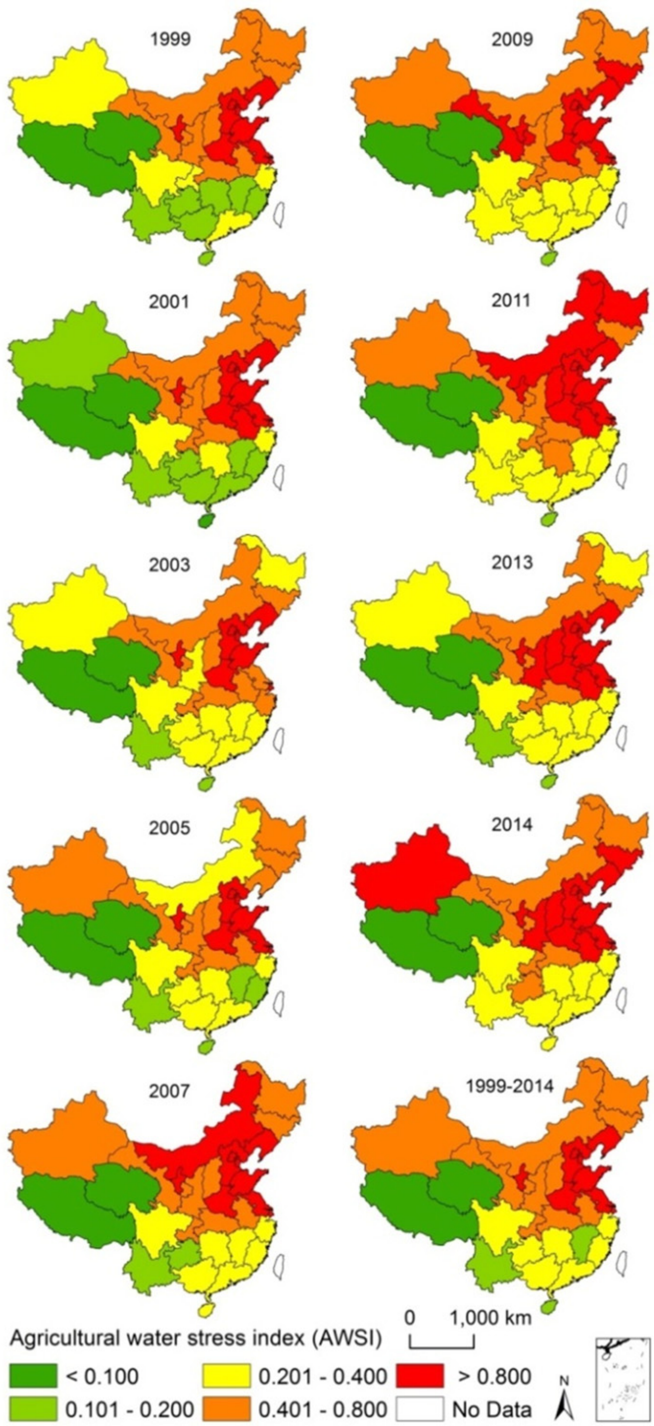

Fig. 7. Spatial and temporal pattern of agricultural water stress index (AWSI) of China.

The AWSI in the other 11 PAMs was higher than the national value (0.413), including in Xinjiang, Chongqing, Hubei, Shaanxi, Heilongjiang, Inner Mongolia, Anhui, Gansu, Shanxi, Jilin and Liaoning. Only five PAMs held an AWSI value below 0.200 and were at the low or no water stress level. The lowest AWSI was found in Xizang (0.004) and water use is the most sustainable in this municipality due to the small scale of the population and agriculture and the abundant water resources.

4. Discussion

The accounting of the ability of water resources to meet the production industry demand can be used to assess the extent of regional water scarcity. The agricultural water stress index (AWSI) in the current study, which is based on the blue-green water resources and water footprint framework, differs from previous water scarcity evaluation indicators such as the WSI and BWS listed in Table 1. The WSI was quantified as the proportion of blue water withdraws to the total blue water resources (Zeng et al., 2013). The BWS is defined as the ratio of the total blue water footprint to the blue water availability during a given period (Hoekstra et al., 2012; Liu et al., 2017). Moreover, the previous studies have overlooked green water because of the difference properties between green and blue water. We believe that the regional green water resources availability and consumption are equally important to blue water in agricultural production systems. Green water resources are essential to ease the pressure on regional water resources. Green water is the source of water in rain-fed farmland, which is an important water resource that supports agricultural production in the arid areas. Additionally, green water also plays a significant role in irrigated farmland (Cao et al., 2015b). Improving the utilization of green water can reduce the dependency on blue water and ease the water stress. On the other hand, the use of water resources in agricultural production was considered from the perspective of the WF. The difference between the WF and conventional water intake is that the former considers both precipitation use and the also transmission of the environmental impacts of agricultural production into water resources. To compare the performances of the different indicators, the national (in 1999–2014) and provincial (average in 1999–2014) values of the three water scarcity evaluation indicators (AWSI, WSI and BWS) in the agricultural production system of China were calculated and are presented in Fig. 8.

Fig. 8(a) illustrates explicitly that, from multiple perspectives, the water scarcity caused by China's agricultural production increased over time. To maintain the sustainable utilization of water resources, water use efficiency should be improved based on blue water withdraw, blue water consumption and WF frameworks. There are big differences between any two of the three indicators in each of the observed years. The conventional (blue) water was the study object of the WSI and BWS, and the denominator in the calculation process of the two indicators was regional blue water availability (Table 1). The numerators selected for the WSI and BWS quantification were blue water withdrawal (total blue water supply) and blue water footprint (consumptive blue water use), respectively. The blue WF is less than the blue water withdrawal, particularly in agricultural systems since a significant portion of the irrigation water is leaked into the subsurface or other forms of water. China's IE is only approximately 0.500 (Cao et al., 2015b), that's the primary reason for the BWS being smaller than WSI. The national AWSI (0.413) during 1999–2014 was approximately 1.9 and 2.4 times of the WSI and BWS, respectively. According to the WSI and BWS, China was facing none or low water stress (Sun et al., 2016; Liu et al., 2017) in the studied years. However, the country was in mid-water stress and high water stress levels as indicated by the AWSI. The framework upon which the water scarcity evaluation index was established determined this outcome. Not only the consumption of blue water, but also the consumption of green water and dilution water demand (grey WF) were included in the water use item in the AWSI assessment. In China, blue water footprint accounts for <13% of the total footprint and the AWF is significantly larger than blue water withdraws. Even considering the loss of water in transportation, agricultural blue water use is merely a quarter of the sum of the green and grey WFs. Regarding the water resources availability item, the extra term in the of AWSI compared to the WSI is the green water resources. The utilization degree of green water resources is related to the utilization rate of arable land and the length of the crops covering period. In China, the utilization rate of arable land is very high due to the scarcity of arable land. The cultivated land is almost covered by crops throughout the year in South China and the North China Plain PAMs. There was a time when uncultivated land was only in certain Northeast and Northwest PAMs. The green water resources utilization rate had reached 80%, which led to an AWSI higher than the WSI. The

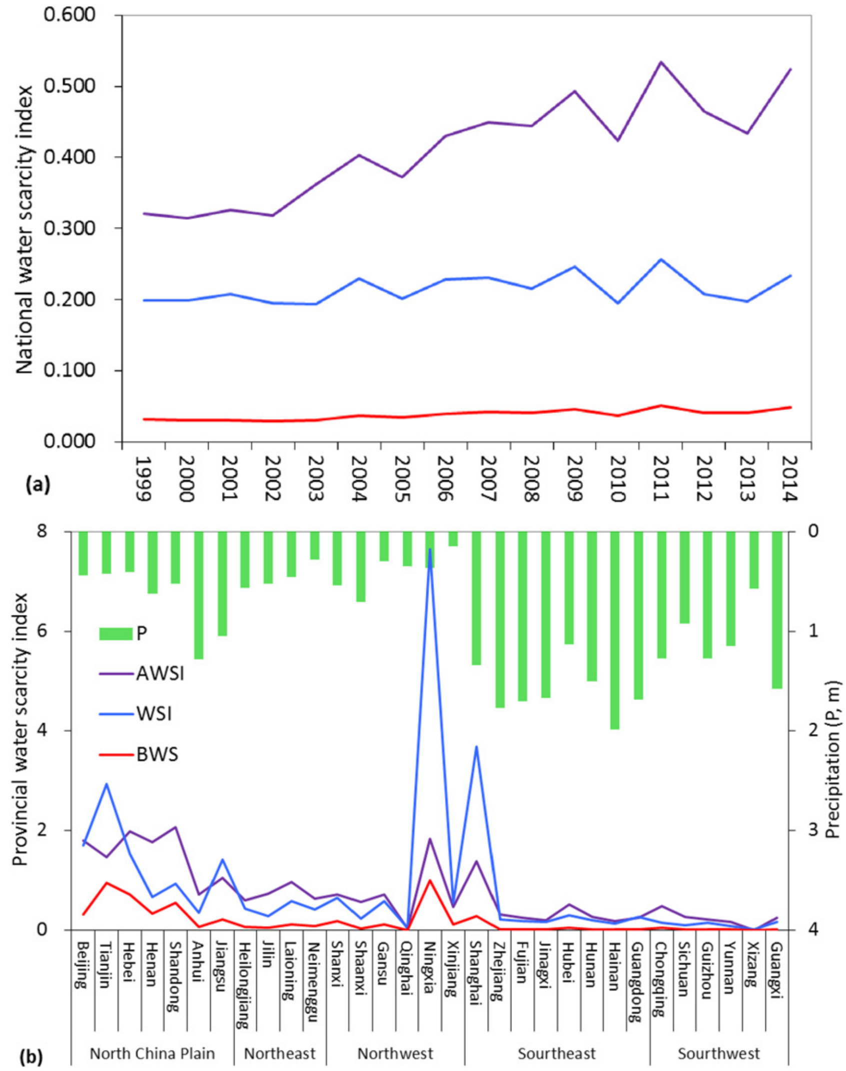

Fig. 8. National (a) and provincial (b) values of three water scarcity evaluation indices in China. (AWSI is agricultural water scarcity index, BWS blue water scarcity and WSI water stress index).

sustainable utilization of water resources in regional agricultural production processes could be comprehensively reflected by the relationship between water footprint and generalized water resources. Therefore, the WSI and BWS may underestimate the extent of China's water scarcity at the national scale.

Fig. 8(b) shows that there is a good agreement in the spatial patterns of the three water scarcity evaluation indicators. The BWS in the humid Southeast and Southwest PAMs (including Anhui, Fujian, Jiangxi, Zhejiang, Guangdong, Guangxi, Hainan, Sichuan, Guizhou, Yunnan and Xizang) was close to zero during 1999–2014. At the same time, the WSI and AWSI of these PAMs were very close, and both of the values were <0.100. The PAMs above were at a no water stress level as indicated by any of the three indices. These PAMs have abundant precipitation and water resources, so agricultural production activities have less impact on the water resources and water environment. Therefore, there is no significant difference in the indicators for the extent of water scarcity measurement in water-rich areas. Similar to the national situation, the BWS was lower than the WSI and AWSI in all of the PAMs, which was determined by the concept and calculation of the three indicators. The PAMs at high water stress levels were only Beijing, Tianjin, Hebei, Shandong, Henan and Ningxia as indicated by the BWS. Per the WSI and AWSI, the high-stress levels also included Shanxi, Heilongjiang, Liaoning, Jilin, Anhui, Hubei, Shaanxi, Gansu and Xinjiang. Therefore, the WSI and AWSI are more capable of reflecting the regional water scarcity compared to the BWS. However, the WSI and AWSI differ in the regional performances, not only by scientific connotations but also in the following aspects. First, the variation coefficients of the two indicators were 1.54 and 0.85 respectively. The spatial differences in the WSI were significantly greater than those in the AWSI. The AWSI reduced the degree of difference water shortages among the PAMs. Fig. 8(b) also shows that the AWSI was higher than the WSI in all of the PAMs, except for in the three resource types' water shortage regions, Tianjin, Shanghai and Ningxia. These regions have to transfer water in from outside to meet the demand of industrial, domestic or irrigation requirements. Green water resources and the AWR per unit arable land were considerable, and the AWFI values were low in these three provinces (Fig. 5). Therefore, the water scarcity may be overestimated by using the WSI of these areas. The PAMs where the AWSI was significantly higher than the WSI are the primary grain-producing areas in North China, including in Hebei, Neimenggu, Liaoning, Jilin, Heilongjiang, Shandong and Henan. The blue water resources of these areas are not as rich as those of the southern PAMs. Simultaneously, these held a large scale of agricultural production and quantity of the total water footprint. These factors explain why these PAMs were found to be facing more severe water stress when they were assessed based on the water footprint framework. Therefore, the AWSI is more suitable for water scarcity evaluations in arid agricultural and food production regions.

5. Conclusion

The blue water makes up the vast majority of available water resources for China's agricultural production, and it provides the possibility of a stable increase in future grain production. However, crops consumed more green water due to the crop water requirement rule, the limits in the extent of irrigation development and the level of blue water diversion and allocation technology. China's agricultural water footprint reached 1042 Gm^3, and the green water footprint accounted for an absolute majority of the total. The grey water footprint accounted for approximately 21.7% and was greater than the blue water footprint. The effect of agricultural production processes on the water environment cannot be ignored, because it may be directly related to water use sustainability. Thus, it is necessary to construct an indicator based on the blue-green water and water footprint framework to reveal the water scarcity in the regional agricultural production industry. The AWSI presented in this paper reflects the capability of regional generalized agricultural water resources to satisfy the agricultural water appropriation. The level of China's water scarcity has been aggravated, rising from mid-water stress levels at the beginning of this century to high water stress levels in the most recent five years. The situation of the water footprint and water resources relationship in the Southern PAMs is better than that in the Northern regions. However, the water scarcity in the South China was also aggravated from 1999 to 2014. Improving water use efficiency and reducing agricultural nonpoint source pollution are the urgent issues currently facing the country. Considering information that is more comprehensive is the advantage of the AWSI compared to the WSI and BWS, although there is no significant difference between water scarcity assessments in the wet areas. However, the AWSI can reveal the situation of agricultural water shortages in the arid agricultural areas more clearly. Strategies for agricultural development and water use formulation in the North grain producing areas should be made base on the areas' AWSI performance. Moreover, it should be noted that the intensification of water resources in certain areas is caused by producing agricultural products for other regions due to the mismatch of agricultural production and population. This phenomenon has not been quantified or analyzed in this paper, but needs to be studied in the future.

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