Science of the Total Environment 739 (2020) 140032

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Towards quantification of the national water footprint in rice production of China: A first assessment from the perspectives of single-double rice

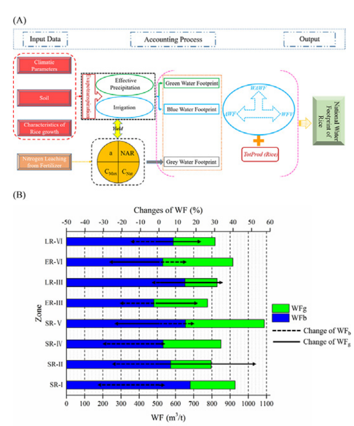
Jiazhong Zheng [a,b,e], Weiguang Wang [a,b,*], Guoshuai Liu [a,b], Yimin Ding [a,b], Xinchun Cao [a,c,d], Dan Chen [c,d], B.A. Engel [e]

[a] *State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China*
[b] *College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China*
[c] *Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China of Ministry of Education, Hohai University, Nanjing, Jiangsu 210098, China*
[d] *College of Agricultural Sciences and Engineering, Hohai University, Nanjing 210098, China*
[e] *Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47906, USA*

HIGHLIGHTS

- The concept of 'national water footprint' (NWF) was applied in rice production for the first time in China.
- The WF of single-rice and double rice (early-rice and late-rice) in eight agro-ecological zones was distinguished.
- The single-rice accounted for the greatest portion of NWF, followed by early-rice and late-rice.
- Compared with WF_b and WF_{gr}, the WF_g plays a dominant role in the growth of rice NWF.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 March 2020
Received in revised form 27 May 2020
Accepted 4 June 2020
Available online 06 June 2020

Editor: Ouyang Wei

Keywords:
Rice production
China
National water footprint
Single-double rice
Water resources management
Food security

ABSTRACT

Rice is one of the most important crops in China, contributing to approximately 28% of total cereal yield. Despite substantial production, given that rice is a high water-consuming crop, the water shortage due to the irreversible decline in available water resources on a global scale induced by undergoing climate change will pose grave challenges to rice reproductive growth and related water resources utilization. As a consequence, investigating the responses of rice productivity and water consumption to more pronounced climate changes is of great significance for water resources sustainable utilization in terms of reducing irrigation water requirements and ensuring food security. Present water footprint (WF) methods do not calculate the weighted average of each WF component at the national level when evaluating the effects of prospective climate change upon rice production. The national water footprint (NWF), i.e. taking the share of each province in the total production of crops as weighting factors, has been regarded as an effective approach to determine where each WF component is originally located. In this study, the temporal change characteristics of NWF for single-rice (SR), early-rice (ER) and late-rice (LR) in different agro-ecological zones across China during 2001–2010 were assessed for the first time. The results exhibited that NWF of rice was an estimated 304,848 million cubic meters (MCM) per year. The SR accounted for the greatest portion of NWF, followed by ER and LR. The NWF rank was SR-V > SR-I > ER-VI > SR-IV > LR-III > LR-VI > SR-II > ER-III. The blue water footprint (WF_b) presents decreasing trends in most

* Corresponding author at: State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China.
E-mail address: wangweiguang006@126.com (W. Wang).

https://doi.org/10.1016/j.scitotenv.2020.140032

agro-ecological zones (SR-I, SR-II, SR-IV, ER-III and LR-VI), while green water footprint (WF_g) exhibits increasing trends within these regions. This study provides a beneficial approach for decision-making processes aiming at better agricultural water resources management strategies to alleviate water resources scarcity and reduce food risk in the context of surging demand, which will support agricultural water resources management of China towards a more balanced direction at the national level.

1. Introduction

The 2.7% of the earth's water that is freshwater is one of the most essential elements for all forms of life that is closely related to the subsistence and development of human beings (Li et al., 2019). The consumption of global water resources increased approximately sevenfold alongside the population of the world that has grown from 1600 million to over 6000 million during the 20th century (Gleick, 2000). Despite mitigation measurements that have been conducted, global water resources will become more pressing to meet the expected demand for 50% more food by 2030, and thus cause broad public concerns (White et al., 2018; Yang et al., 2016). Among the looming challenges, the most sensitive one is usually considered to be crop production (Cao et al., 2017; Huntiugton, 2006; Sun et al., 2016). Statistically, crop production constitutes 70% of the global water extractions, although advanced technologies have been promoted to improve water utilization efficiency (Bocchiola, 2015; Grafton et al., 2018). With the exception of the increasing demand, the availability of water resources greatly affects crop production, which has severe implications for food security and human welfare, especially in developing countries including China (Tuninetti et al., 2015). Against this background, recently, substantial efforts have been paid to investigate the influences of water stress on agricultural production, particularly the morphology, physiology and biochemistry of crops (e.g., Bolat et al., 2015; Jiménez et al., 2013; Kalefetoglu and Ekmekçi, 2005; Kulak et al., 2019; Ma et al., 2010; Rhodes and Nadolska-Orczyk, 2001; Sangwan et al., 2001; Yaşar, 2003). Globally, the adverse effects of water stress on crop growth and production, including limiting plant growth (Cetinkaya et al., 2017), impairing plant metabolism (Laribi et al., 2009), reducing photosynthesis (Gupta and Gupta, 2005) and restraining cell growth (Blokhina et al., 2003), and the benefits such as more active secondary metabolite production (Yadav et al., 2012) and positive tendency in synthesis of enzymes (Radwan et al., 2017), have been documented in literature reviews (Kulak et al., 2019).

In fact, apart from the crop growth, water resources utilization related to crop production is also affected by irreversible decline in available water resources on a global scale induced by ongoing climate change (Wang et al., 2016; Wang et al., 2017). Attempts to investigate the effects which climate variability exerts on water resources use in agriculture, such as crop water consumption and irrigation water requirement and efficiency, have been widely conducted, especially in recent decades (e.g., Cong et al., 2008; Ding et al., 2017; Döll, 2002; Fischer et al., 2007; Luo et al., 2015; Wang et al., 2014a; Yang et al., 2013). Providing a quantifiable indicator, the key factor that will measure the volume of consumptive water use as a consequence of various growing drivers in space and time, is the ultimate goal of characterizing the potential impacts of the amount of water embedded in crops for the entire agricultural production supply chain (Challinor et al., 2014; Zheng et al., 2018b). Hence, reliable estimation of the total amount of water required to produce specific crops is of increasing importance in agricultural water accounting (Hoekstra, 2013). As a quantifiable indicator to evaluate the interaction effects of ecophysiological processes on water consumption and water quality by crop production, water footprint (WF) is more feasible and reliable than other approaches (Zhang et al., 2014; Zhang et al., 2018; Zheng et al., 2019).

The notion of WF is proposed by Chapagain and Hoekstra (2002). Normally, WF is divided into three water components: green water footprint WF_g, blue water footprint WF_b and gray water footprint WF_{gr} (Mekonnen and Hoekstra, 2010). The water footprint of a product expressed in water volume per unit of product (usually m^3/t) is the sum of the water footprints of the process steps taken to produce the product. The WF_b refers to the volume of surface and groundwater consumed as a result of the production of a good; the WF_g refers to the rain water consumed (Nouri et al., 2019). The WF_{gr} of a product refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards (Chapagain and Hoekstra, 2011). Therefore, in contrast to the conventional approach of agricultural water resources evaluation for providing results in water volumetric terms only (Lovarelli et al., 2016), WF also focuses on the amount of polluted consumptive freshwater arising in the growth period of crops (Li et al., 2018). For this purpose, researching the linkage between food and water resources sustainability (Zhang et al., 2018) with the help of WF, which is expected to mitigate the pressure induced by heterogeneity of available water resources, is imperative to shape future agricultural sustainable development (Luan et al., 2018).

Rice is one of the most important staple foods in the world, which feeds more than half of global population and 60% of the Chinese people (FAO, 2014; Xiong et al., 2013). With population growth, the rice yield of the world increased from 285 million tons in 1961 to 741 million tons in 2016 (FAO, 2018). This is especially true for China, which has 145 million tons of yield and 30.16 million hectares of cultivated area, contributing 28% of the world rice yield and 19% of the global rice area (USDA, 2017). Apart from the substantial production, rice is submerged with a thin layer of water during the long growth season (Peng et al., 2009) and thus consumes 50% of the global irrigation water (Yunus et al., 2013). This high water-consuming activity inflicts adverse effects on rice production, which is expected to pose severe risk to water and food security in China and the rest of the world (Rodríguez et al., 2019). Therefore, investigating the responses of rice productivity and water consumption to more pronounced climate change in different agro-ecological zones will be a significant path to synergistically manage agricultural water resources and deserves further study (Zhang et al., 2014). Extensive studies have conducted to evaluate the climatic effects on crop production and related water resources utilization, which characterize the amount of water needed to produce specific crops by means of WF in terms of quantifying the interactions of the water-food nexus (e.g., Ababaei and Etedali, 2014; Chapagain and Hoekstra, 2011; Mali et al., 2017; Silalertruksa et al., 2017; Yan et al., 2015; Yoo et al., 2013, 2015). Present WF methods do not calculate the weighted average of each WF component on the national level, either conceptually or mathematically, when investigating the responses of crop WF to natural factors and anthropogenic activities as well as the changes in composition. Use of the share of each province in the total production of crops as weighting factors through employing the national water footprint (NWF) approach, has been implemented in the WF assessment of crops (e.g., Ababaei and Etedali, 2014, 2017; Sun et al., 2013; Yoo et al., 2013). In these studies, little investigation was devoted to the variation and composition of NWF for rice with diverse spatial patterns, especially in China. More importantly, to date, a comprehensive assessment of NWF for single-rice and double rice (early-rice and late-rice) across China is still missing. Hence, in-depth study on the eco-physiological and hydrological response of rice with the knowledge of NWF is a novel approach to improve the sustainability of water resources utilization and productivity, which is imperative, thus motivating our present research. This study distinguishes for the first time in a rice NWF assessment single-rice (SR), early-rice (ER) and late-rice (LR). The pioneering work is beneficial for tackling the challenge of alleviating pressures derived from rising food demand and limited water resources, then revealing the rationality of water resource utilization and providing valuable information for reducing the rice WF in China and the rest of the world.

2. Materials and methods

2.1. Study area

Primary cropping systems of rice in China contain single-rice and double rice (double rice refers to the rotation between early-rice and late-rice). The cropping systems includes eight zones (Single-rice I, II, IV and V; Early-rice III and VI; Late-rice III and VI). The study area is mainland China, which excludes the Taiwan Province, Hong Kong and Macao (Fig. 1).

2.2. Data collection

The phenology and climate data of rice were obtained from China agro-meteorological experimental stations and the China meteorological data sharing service system, respectively. The data include 127 stations for single-rice and 80 stations for double rice during the period of 2001–2010. The nitrogen application rates, yield and production area were obtained from the National Bureau of Statistics of China (see Tables 1 and 2).

2.3. Water footprint accounting

The WF_b, WF_g and WF_{gr} were calculated following the calculation framework provided by Hoekstra et al. (2011):

Table 1
Average nitrogen application rates of single-rice and double rice during the period of 2001–2010.

Provinces	Nitrogen application rates (kg/ha)	Provinces	Nitrogen application rates (kg/ha)
	Single-rice		Double rice
Anhui	127.6	Fujian	208.2
Guizhou	96.5	Guangdong	207.6
Henan	165.4	Guangxi	106.6
Helongjiang	55.8	Hainan	147.3
Hubei	194.7	Hunan	134.3
Jilin	134.0	Jiangxi	86.4
Jiangsu	240.8	Zhejiang	202.8
Liaoning	170.7		
Shandong	168.7		
Shanghai	221.7		
Sichuan	131.5		
Yunan	138.0		
Chongqing	144.6		

$$WF_{green} = \frac{CWU_{green}}{Y} = 10 \times \frac{ET_{green}}{Y} \tag{1}$$

$$WF_{blue} = \frac{CWU_{blue}}{Y} = 10 \times \frac{ET_{blue}}{Y} \tag{2}$$

$$WF_{Gray} = \frac{\alpha \times NAR}{C_{Max} - C_{Nat}} \times \frac{1}{Y} \tag{3}$$

$$ET_{green} = \min\ (ET_c, P_e) \tag{4}$$

$$ET_{blue} = \max\ (0, ET_c - P_e) \tag{5}$$

where Y is the yield (t, i.e. ton), WF_{green} is the WF_g (m^3/t), WF_{blue} is the WF_b (m^3/t); CWU_{green} and CWU_{blue} are green and blue water consumption (m^3/ha); the factor 10 is meant to convert water depths (in mm) into water volumes per land surface (in m^3/ha); NAR is the nitrogen

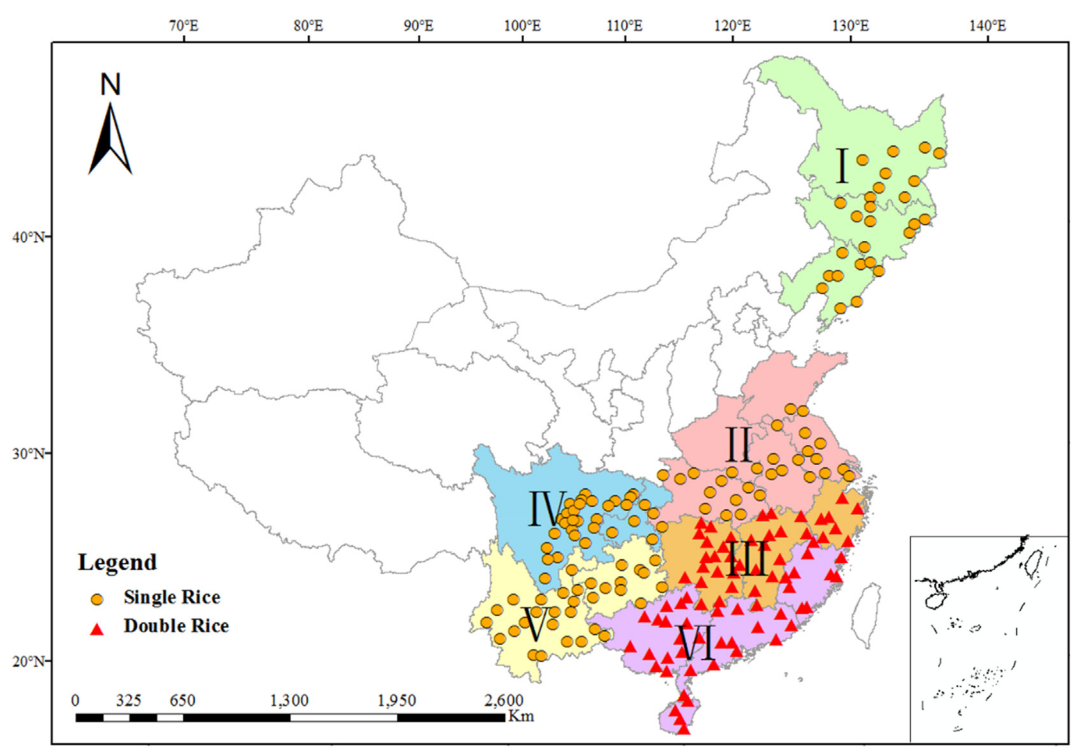


Fig. 1. Classifications of single-rice (with circle mark) and double rice (with triangle mark) agro-ecological zones across China.

Table 2
Average yield and production of single-rice, early-rice and late-rice during the period of 2001–2010.

Provinces	Yield/(kg/ha)			Provinces	Production/(10,000 t)		
	Single-rice	Early-rice	Late-rice		Single-rice	Early-rice	Late-rice
Anhui	6368.2			Anhui	1000.0		
Guizhou	6291.7			Guizhou	444.1		
Henan	6746.6			Henan	370.4		
Helongjiang	6534.1			Helongjiang	1274.6		
Hubei	8584.1			Hubei	1048.5		
Jilin	7113.7			Jilin	461.0		
Jiangsu	8037.3			Jiangsu	1708.2		
Liaoning	7213.3			Liaoning	431.2		
Shandong	7732.9			Shandong	102.8		
Shanghai	8062.9			Shanghai	91.3		
Sichuan	7167.2			Sichuan	1469.2		
Yunan	5870.8			Yunan	570.3		
Chongqing	6869.4			Chongqing	488.3		
Fujian		5481.9	5313.7	Fujian		143.7	141.4
Guangdong		5384.1	5326.9	Guangdong		539.2	570.3
Guangxi		5324.6	4868.2	Guangxi		563.9	515.4
Hainan		4773.1	3852.0	Hainan		67.5	71.2
Hunan		5590.3	6179.0	Hunan		731.1	889.3
Jiangxi		5220.5	5368.0	Jiangxi		668.9	745.9
Zhejiang		5556.4	6196.9	Zhejiang		84.8	123.6

application rates (kg/ha), ET_{green} and ET_{blue} represent green and blue water evapotranspiration and the total effective precipitation; ET_c is crop evapotranspiration during the crop growing period (mm); P_e is the effective precipitation over the crop growing period (mm). Considering the maximum allowable concentration (C_{Max}, in mg/L) of nitrate on surface and in groundwater, adopting the standard allowable concentration of 10 mg/L recommended by the USEPA (Chapagain et al., 2006). Moreover, since there is no data or model simulations on this spatial scale, the natural nitrogen concentration (C_{Nat} in mg/L) is conservatively assumed as zero. According to the assumptions of Chapagain et al. (2006) and Hoekstra et al. (2011), α is rate of leached nitrogen, used in this study is 10%.

ET_c is the total amount of evaporation and transpiration during the rice growing period. The ET_c is calculated by the single crop coefficient method (Allen et al., 1998):

$$ET_c = k_c \times ET_0 \tag{6}$$

where k_c is the crop coefficient (dimensionless); ET_o is the reference crop evapotranspiration (mm/d). The FAO Penman-Monteith (P-M) method is used to calculate ET_0 (Allen et al., 1998).

P_e is the portion of the total precipitation, as rainfall and snowmelt, that is available to the crop and does not run off, which is very difficult to determine without detailed site-specific information. Therefore, a simple method developed by the U.S. Department of Agriculture (Döll and Siebert, 2002) and improved by Li et al. (2018) was used as follows:

$$P_e = \begin{cases} P(4.17-0.2P)/4.17, & P<8.3 \\ 4.17+0.1P, & P\geq 8.3 \end{cases} \tag{7}$$

where P is the total precipitation (mm) at a daily time step.

2.4. Estimation of national water footprint components

The estimation of national WF components is to take the share of each component in the total rice production of all studied provinces as a weighting factor and take the average value of all provinces (Eqs. (8)–(9)). Finally, the volume of each WF component at the national level was calculated as a weighted average of the proportion of each WF component in the total national production (Eqs. (10)–(11)).

$$ptWFV_{i,w(b;g;gr),r(s;e;l)} = Prod_{i,w(b;g;gr),r(s;e;l)} \times WF_{i,w(b;g;gr),r(s;e;l)} \tag{8}$$

$$AWF_{w(b;g;gr),r(s;e;l)} = \frac{\sum_i WFV_{i,w(b;g;gr),r(s;e;l)}}{Prod_{i,w(b;g;gr),r(s;e;l)}} \tag{9}$$

$$WAWF_{w(b;g;gr)} = \beta \times AWF_{w(b;g;gr),s} + \gamma \times AWF_{w(b;g;gr),e} + \delta \times AWF_{w(b;g;gr),l} \tag{10}$$

$$NWF_{w(b;g;gr)} = TotProd \times WAWF_{w(b;g;gr)} \tag{11}$$

where WFV: the total volume of each WF component (MCM, i.e. million cubic meters); Prod: production in each province for rice (Mton, i.e. million tons); AWF: the national weighted average of each WF component (m^3/t) for rice; WAWF: the national weighted average of each WF component (m^3/t) for all production systems; TotProd: total national production (Mton); and NWF: the total volume of each WF component in the total national volume of each WF component (MCM).

b: blue; g: green; gr: gray; s: single-rice; e: early-rice; l: late-rice.

i: province index; w: WF component; r: rice variety; β, γ, δ: the proportion of total irrigated production in China ($\beta = 0.63$, $\gamma = 0.18$ and $\delta = 0.20$ for single-rice, early-rice and late-rice, respectively) (MWR, 2002-2011).

A schematic diagram of the adopted methodology is shown in Fig. 2.

3. Results

3.1. Variation of ET_c, P_e and IWR

The ET_c and P_e are the most important parameters for calculating the WF. Fig. 3 shows the variation of ET_c, P_e and irrigation water requirement (IWR) of rice during 2001–2010 in six agro-ecological zones across China. The variation of P_e for eight zones during the period of 2001–2010 ranges from 90 mm to 260 mm. The maximum value is in SR-V (254.97 mm), and the SR-IV (225.85 mm) took second place, followed by ER-VI (204.64 mm), SR-II (173.11 mm), SR-I (170.31 mm), ER-III (159.52 mm), LR-VI (119.85 mm) and LR-III (95.37 mm). The five zones presented an upward trend (SR-I, SR-II, LR-III, ER-VI and LR-VI), and the linear increase rates were 1.86 mm/annum, 3.53 mm/annum, 0.04 mm/annum, 0.08 mm/annum and 0.19 mm/annum, respectively. SR-IV, SR-V and ER-III exhibited a downward trend with linear decline rates 0.44 mm/annum, 2.76 mm/annum and 1.01 mm/annum, respectively.

The change of ET_c for eight zones during the period of 2001–2010 ranges from 420 mm to 650 mm. The maximum value is in SR-V

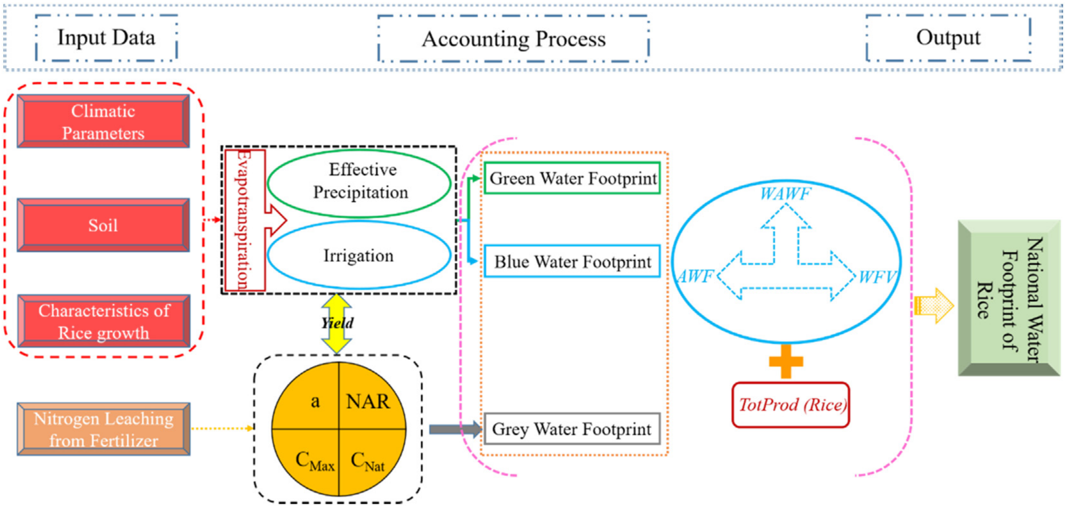


Fig. 2. The schematic diagram of the methodology adopted for this study.

(645.9 mm), and the SR-I (638.1 mm) was second highest, followed by SR-II (618.6 mm), SR-IV (598.1 mm), ER-VI (483.4 mm), LR-II (450.3 mm), LR-VI (431.6 mm) and ER-III (421.9 mm). Moreover, four zones exhibited an upward trend (SR-V, ER-III, LR-III and LR-VI), and the linear increase rates were 3.13 mm/annum, 1.55 mm/annum, 3.62 mm/annum and 3.41 mm/annum, respectively. While the SR-I, SR-II, SR-IV and ER-VI showed a downward trend with linear decrease rates 3.43 mm/annum, 2.62 mm/annum, 1.47 mm/annum and 3.03 mm/annum, respectively. The changes of IWR were consistent with the ET_c; however, comparing with P_e and ET_c, the variation rate of IWR was higher.

3.2. Spatiotemporal changes and interannual proportions of WF for rice

WF reflects a region's water utilization and agricultural production states. Fig. 4 suggests that the WF_b tended to decrease in most zones, while the WF_g presented an upward trend, with the variations of WF_b for eight zones ranging from −31.9% to 17.3%, with a variability between −25.1% and 52.6% in WF_g, that was strongly non-uniform in space. Moreover, for eight zones, under the combined influences of ET_c and P_e, the interannual variations of WF showed obvious fluctuation.

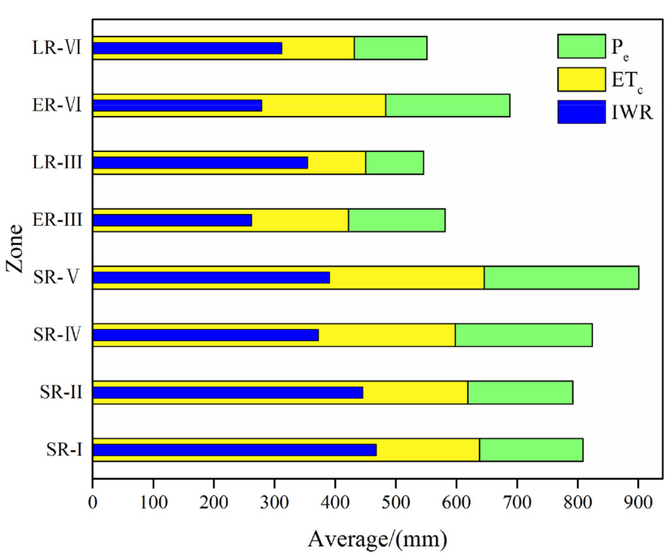


Fig. 3. Trends in ET_c, P_e and IWR for agro-ecological zones across China during the period of 2001–2010.

The value of WF rank as SR-V > SR-I > ER-VI > SR-IV > LR-III > LR-VI > SR-II > ER-III.

The explicit distinction between WF_b and WF_g will enable a better understanding of the impacts of climate change and human activity on agricultural water resources. Figs. 5 and 6 present the shares of WF_b and WF_g of rice in the agro-ecological zones across China for the period of 2001–2010. For single-rice, the proportion of WF_b is typically greater than WF_g. The share of WF_b ranges from 21% to 82%. However, in zone SR-V, a new phenomenon appeared that green water is higher than that of blue water (see Fig. 5). While for early-rice, the proportion of WF_g is typically greater than WF_b. The share of WF_g ranges from 10% to 61%. However, in Zhejiang province of zone ER-III and Hainan province of zone ER-VI, an opposite phenomenon appeared that blue water is higher than that of green water (see Fig. 6A). Identical to single-rice, the proportion of WF_b for late-rice is substantially greater than WF_g. The share of WF_b ranges from 29% to 85%. However, in Hainan province of zone LR-VI, a different situation occurred with blue water equal to that of green water (see Fig. 6B).

3.3. National water footprint of rice growth

Fig. 7 presents the trends in WFV for single-rice (Fig. 7A–C), early-rice (Fig. 7D–F) and late-rice (Fig. 7G–I) of agro-ecological zones across China during the period of 2001–2010. Jiangsu province has the most WFV of WF_b for single-rice (9613 MCM), and Heilongjiang province

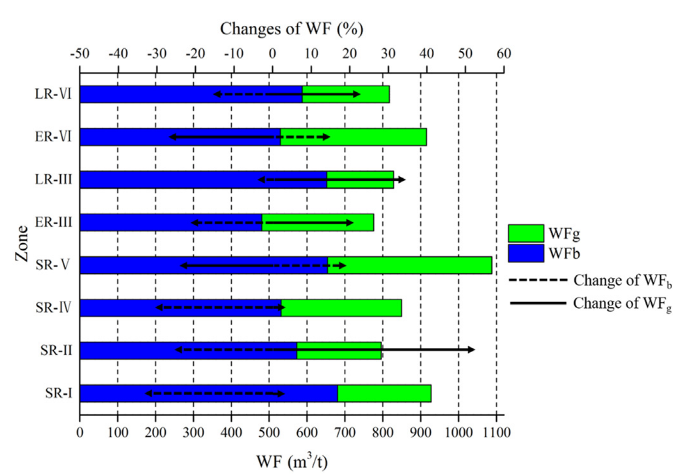


Fig. 4. Average value and percentage change of WF for agro-ecological zones across China during the period of 2001–2010 (arrow represents the direction of change).

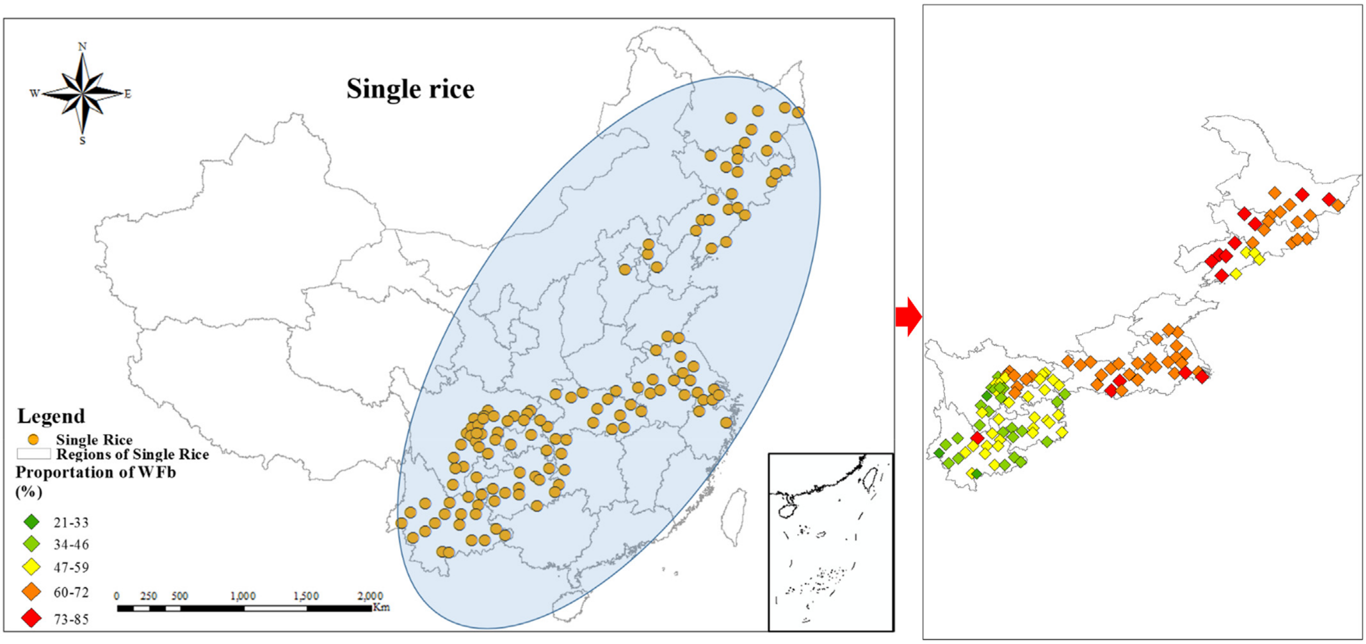


Fig. 5. Spatial pattern of water footprint for single-rice and its composition in 2001–2010.

(8780 MCM) took second place, followed by Sichuan (7599 MCM), Anhui (6843 MCM), Hubei (5457 MCM), Yunnan (3941 MCM), Liaoning (3072 MCM), Jilin (2915 MCM), Chongqing (2742 MCM), Guizhou (2549 MCM), Henan (2335 MCM), Shandong (545 MCM) and Shanghai (521 MCM). The WFV of WF_g rank as Sichuan > Jiangsu > Heilongjiang > Anhui > Yunnan > Hubei > Guizhou > Chongqing > Jilin > Liaoning > Henan > Shandong > Shanghai. Meanwhile, the WFV of WF_{gr} rank as Jiangsu > Sichuan > Hubei > Anhui > Yunnan > Heilongjiang > Chongqing > Liaoning > Henan > Jilin > Guizhou > Shanghai > Shandong.

Hunan province has the most WFV of WF_b for early-rice (3483 MCM), and Jiangxi province (3176 MCM) took second place, followed by Guangdong (2682 MCM), Guangxi (2648 MCM), Fujian (761 MCM), Hainan (576 MCM) and Zhejiang (423 MCM). The WFV of WF_g rank as Guangxi > Jiangxi > Guangdong > Hunan > Fujian > Zhejiang > Hainan. Meanwhile, the WFV of WF_{gr} rank as Guangdong > Hunan > Guangxi > Jiangxi > Fujian > Zhejiang > Hainan.

The Hunan province has the most WFV of WF_b for late-rice (5027 MCM), and Jiangxi province (4822 MCM) took second place, followed by Guangxi (3394 MCM), Guangdong (3277 MCM), Fujian (1036 MCM), Zhejiang (751 MCM) and Hainan (392 MCM). The WFV of WF_g rank as Jiangxi > Hunan > Guangdong > Guangxi > Hainan > Fujian > Zhejiang. Meanwhile, the WFV of WF_{gr} rank as Guangdong > Hunan > Jiangxi > Guangxi > Fujian > Zhejiang > Hainan.

The AWF and WAWF for each WF component of single-rice, early-rice and late-rice during the period of 2001–2010 are summarized in Table 3. For single-rice, the AWF of WF_b ranged from 550.0 to 679.3 m^3/t, the WF_g from 434.6 to 564.4 m^3/t, and the WF_{gr} from 476.8 to 695.6 m^3/t. For early-rice, the AWF of WF_b ranged from 742.6 to 1066.6 m^3/t, the WF_g from 275.8 to 376.1 m^3/t, and the WF_{gr} from 149.1 to 270.1 m^3/t. For late-rice, the AWF of WF_b ranged from 513.4 to 717.6 m^3/t, the WF_g from 250.3 to 275.7 m^3/t, and the WF_{gr} from 236.6 to 267.0 m^3/t. While for WAWF, the WF_b varied between 529.7 and 631.6 m^3/t, the WF_g varied between 561.9 and 771.5 m^3/t, and the WF_{gr} varied between 410.3 and 545.2 m^3/t.

Fig. 8 exhibits the temporal change in NWF and TNWF of the WF components of rice production. The TNWF of rice over the period 2001–2010 was 304,848 MCM/year (33% blue NWF, 38% green NWF and 29% gray NWF). Moreover, the TNWF presented an upward trend, and the linear increase rates were 5769 MCM/annum.

4. Discussion

Increased water stress will make China a hot spot in terms of studies with respect to the NWF, and thus drive the attention of policy makers. The current results with respect to the WF of rice production were compared to available documented literature (Table 4). As seen from Table 4, WF in most research was not devoted to the classification of single-rice and double rice. In this study, to investigate the performances of the different rice cropping systems, the historical change and composition characteristics of NWF for SR, ER and LR were assessed in eight agro-ecological zones (Single-rice I, II, IV and V; Early-rice III and VI; Late-rice III and VI) across China for the first time. The quantitative approach of NWF conducted in the current paper is similar to the study by Ababaei and Etedali (2017), which is evaluated by calculating the weighted average of each WF component at the national level, providing an effective tool to explore the nexus between food and water through the quantitative description of water resources utilization related to crop growth. In this research the concept of NWF is applied at the national scale for the first time in China. Therefore, the scope of NWF in terms of specific crop and study area is extended.

The differences in rice NWF accounting generally involve methods, regions, study periods and components. With regard to the WF component, scholars, namely Bulsink et al. (2010), He et al. (2010), Mekonnen and Hoekstra (2011), Xu and Zhang (2016), Yoo et al. (2013) and Zhuo et al. (2016) evaluated rice concerning WF_b, WF_g and WF_{gr}, with approaches similar to the present study. Separating the three components from each other could provide a complete evaluation of the water utilization related to crop production in terms of different impacts by both natural and anthropogenic factors. The study conducted by He et al. (2010) did not provide detailed values about the composition of WF. Mekonnen and Hoekstra (2011) pointed out that the term "water footprint" includes both consumptive water use (the WF_b and WF_g) and the water required to assimilate pollution (the WF_{gr}). Because of the distinct properties of the previous three components, several studies such as Gheewala et al. (2014), Marano and Filippi (2015) and Wang et al. (2014b) overlooked WF_{gr} since considering WF_{gr} is not a physical quantity of water use, but associated with water pollution. Moreover, in terms of measurement of WF, most papers are exclusively focused on WF_b and WF_g estimates due to data unavailability on WF_{gr}. In fact,

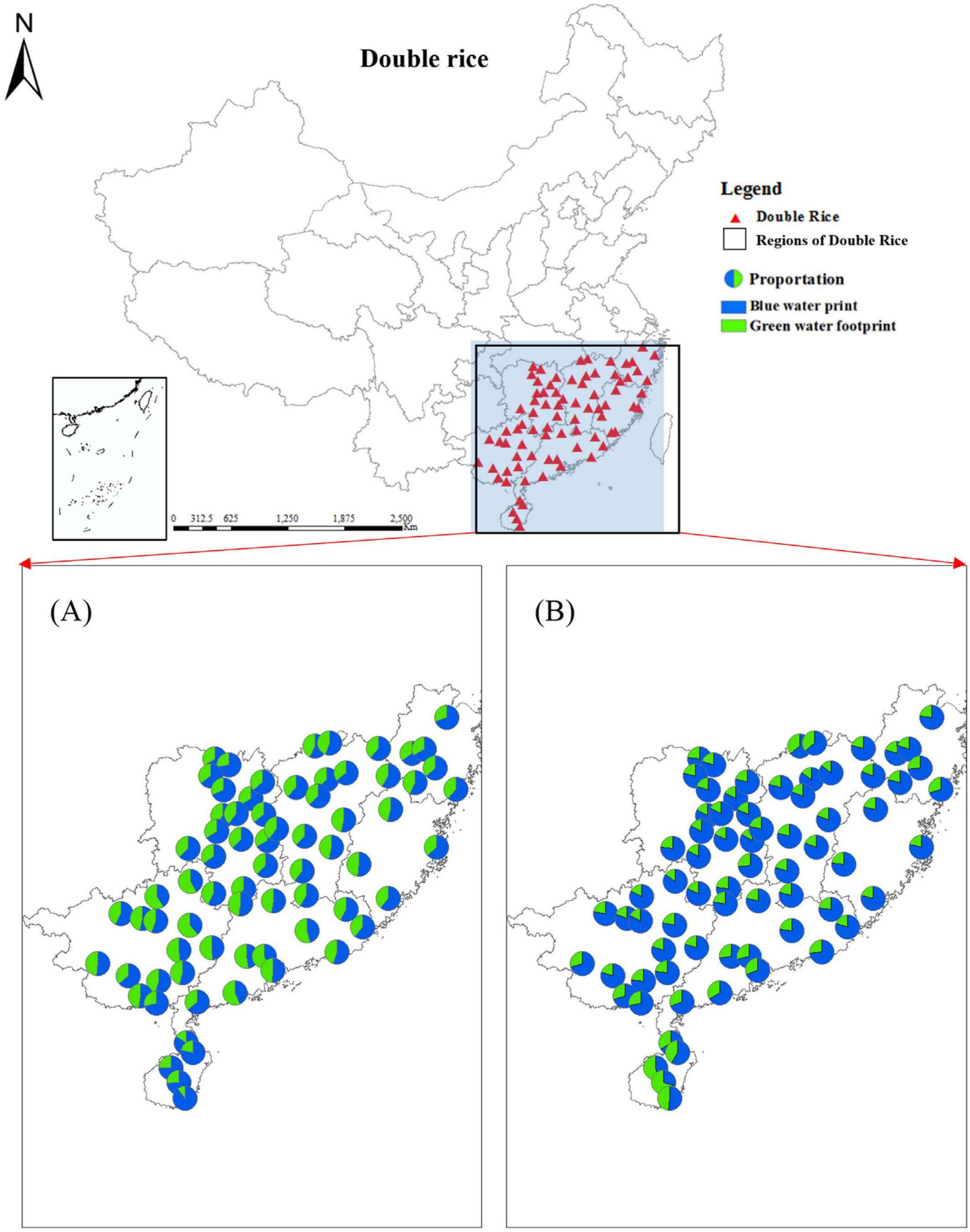


Fig. 6. The blue and green WF compositions for double rice (early-rice (A) and late-rice (B)) of agro-ecological zones across China during the period of 2001–2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

including WF_{gr} is relatively new in water use studies, but justified when considering the relevance of pollution as a driver of water scarcity. Meanwhile, the consumption of WF_{gr} is equally important to the sustainable utilization of water resources and environmental governance in agricultural systems. In accordance with related work (e.g., Bulsink et al., 2010; Mekonnen and Hoekstra, 2011; Xu and Zhang, 2016; Yoo et al., 2013; Zhuo et al., 2016), the WF_{gr} was considered in the present work.

For the period 2001–2010, the NWF of rice was estimated at 304,848 MCM per year which is around 82.6% of the total agricultural water resources withdrawal in China (369,149 MCM in 2010) (MWR, 2002-2011). Of this amount, the shares of WF_b, WF_g and WF_{gr} were 33%, 38% and 29%, respectively. The WF_g accounted for the main share, and the proportions of WF_b and WF_{gr} are smaller. More importantly, the WF of crop production depends on two factors: crop water utilization (CWU) and crop yield. Accordingly, a decline in rice WF_b by 5.15 m^3/t per year was identified due with the increase in yield and decline in CWU for blue water, indicating the importance of the reduction of consumptive blue water resources related to WF in rice production. In other words, the WF reflects the impact of crop production on water resources more fully. Regarding the single-double rice cropping system, single-rice, early-rice and late-rice accounted for 50.4%, 25.1% and 24.5% of the NWF related to the production of rice, respectively. However, a decline in WF was identified at 7.59 m^3/t per year for early-rice. Meanwhile, the blue water proportion of single and early rice decreased in turn as well as the green and gray water proportion of both early and

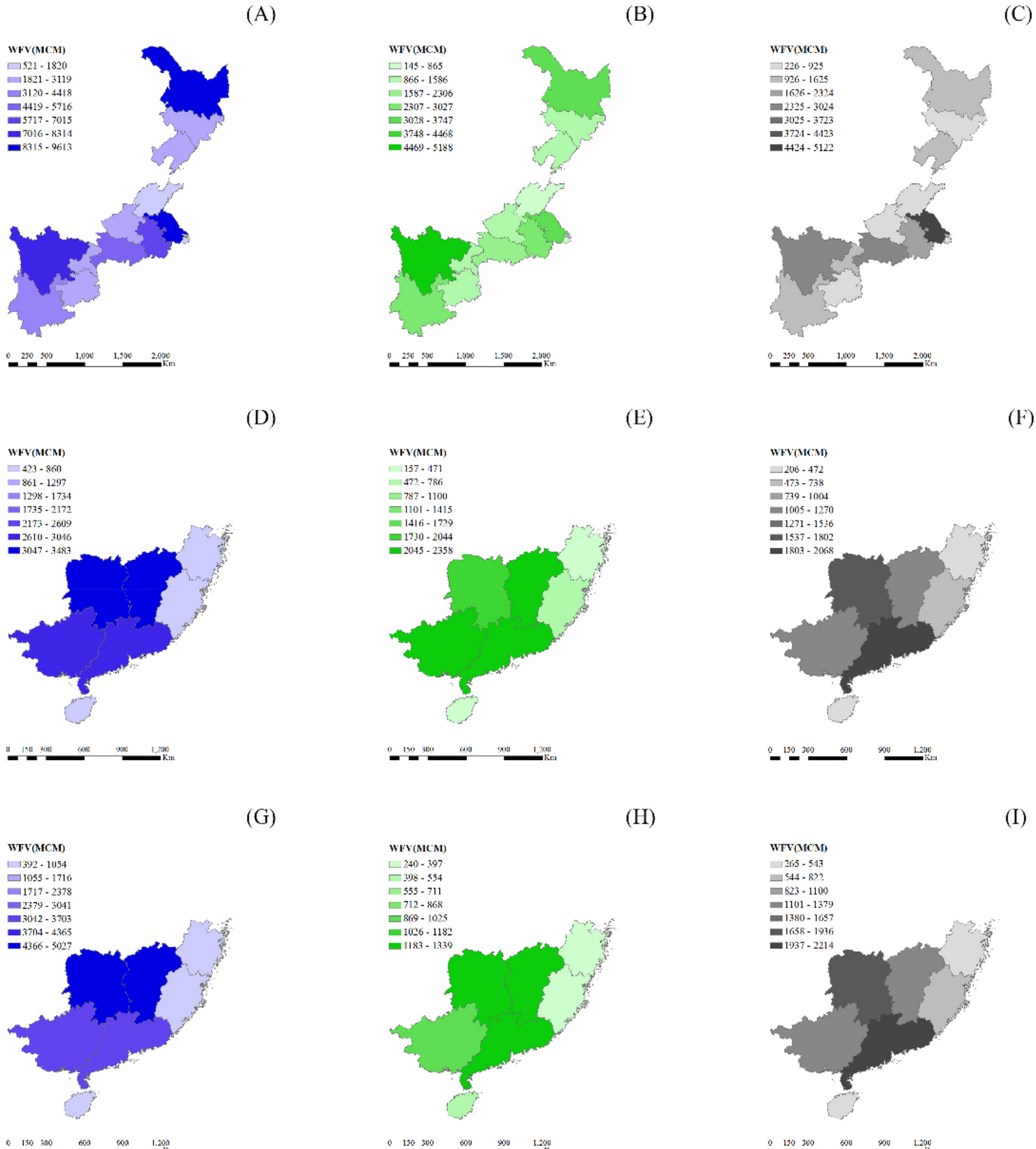


Fig. 7. Trends in WFV for single-rice (A–C), and early-rice (D–F) and late-rice (G–I) of agro-ecological zones across China during the period of 2001–2010.

late rice decreased. Moreover, the unit yield of WF of double rice was 36.1 m^3/t less than the single-rice average, which indicates double rice has more advantages than single-rice in effective use of water resources.

Although rice WF in China are included in the literature above, the dominant reason why the values of WF in He et al. (2010), Wang et al. (2014b), Xu and Zhang (2016) and Zhuo et al. (2016) are not in agreement with the current study is the difference in research period and region. Specifically, He et al. (2010), Xu and Zhang (2016) and Zhuo et al. (2016) deal with both provinces and basins rather than the entire China, while Wang et al. (2014b) did not assess the WF_{gr} and make the single-double rice distinction. Moreover, the WF of the current study was investigated for the period of 2001–2010, whereas the value of Wang et al. (2014b) was reported for 2010. The WF of rice calculated by Wang et al. (2014b) and Xu and Zhang (2016) were 1390 and 961

Table 3
Values of AWF and WAWF for each WF component of single-rice, early-rice and late-rice during the period of 2001–2010.

Rice	Year	AWF/(m^3/t)			WAWF/(m^3/t)
		Single-rice	Early-rice	Late-rice	
WF_b	2001	679.27	434.56	600.28	619.05
	2002	593.22	514.91	476.82	555.74
	2003	571.89	562.05	665.88	588.89
	2004	611.90	545.06	695.62	616.50
	2005	578.29	501.04	639.88	576.58
	2006	671.42	473.38	651.93	631.56
	2007	575.61	564.44	590.92	576.64
	2008	550.04	442.82	595.13	539.58
	2009	588.06	534.23	664.72	593.61
	2010	561.27	394.25	555.14	529.72
WF_g	2001	742.58	376.05	171.62	561.90
	2002	937.57	349.26	270.07	697.33
	2003	963.48	309.19	174.94	687.07
	2004	884.50	304.22	162.43	634.81
	2005	972.07	363.33	186.73	704.57
	2006	869.03	357.96	149.12	632.34
	2007	1035.07	281.57	190.92	729.53
	2008	1006.97	341.01	191.53	723.06
	2009	854.15	275.77	150.17	608.42
	2010	1066.56	361.26	231.14	771.51
WF_{gr}	2001	513.38	250.27	236.64	410.29
	2002	589.00	259.80	249.73	461.42
	2003	628.77	257.33	258.55	487.33
	2004	669.20	254.69	267.00	513.55
	2005	641.30	258.39	261.98	495.96
	2006	688.49	275.71	266.82	529.26
	2007	717.56	266.20	265.18	545.19
	2008	704.15	261.15	260.75	535.09
	2009	681.81	250.39	253.74	517.92
	2010	680.70	261.01	249.46	518.30

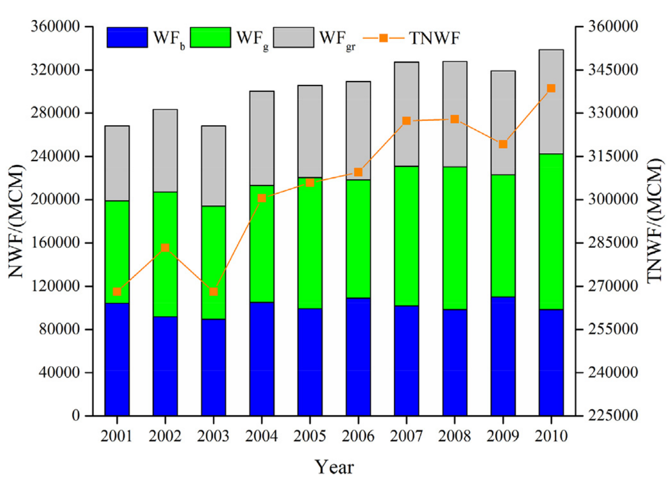


Fig. 8. Temporal change in NWF and TNWF of agro-ecological zones across China during the period of 2001–2010.

m^3/t, respectively, both of which are lower than the 1759 m^3/t found in the present study. The value from Zhuo et al. (2016) was 5803 m^3/t, which is greater than the result in the current study.

As seen from Table 4, WF in most studies ranged from 800 m^3/t to 2000 m^3/t. However, the component consequences were quite different, such as the proportion of WF_b in most research ranged from 18% to 60%; nevertheless, the share of WF_b was 3.9% in Zhuo et al. (2016), which was 6.6% of the maximum value (60.3% by Marano and Filippi, 2015). Meanwhile, the proportion of WF_g in most research ranged from 30% to 75%; nevertheless, the share of WF_g was 7.1% in Zhuo et al. (2016), which was 9.3% of the maximum value (76.2% by Gheewala et al., 2014). Moreover, the proportion of WF_{gr} in most research ranged from 6% to 25%, but the share of WF_{gr} was 89% in Zhuo et al. (2016), which was 15.6 times the minimum value (5.7% by Yoo et al., 2013). Compared with the current study, the estimate of WF_g obtained by Bulsink et al. (2010) was 2527 m^3/t. Indonesia is located in the Pacific region and across the equator where the average annual precipitation reaches 2000 mm. Hence, the WF_g for that location is significantly larger than other researchers found. In addition, the WF_{gr} estimated by Zhuo et al. (2016) was 5164 m^3/t, which is 107 times the minimum value (48 m^3/t by Yoo et al., 2013).

The large amount of fertilizer use is affecting the quality of land and water resources. For instance, the Yellow River Basin has experienced booming agriculture, while the growing application of fertilizers increased the WF_{gr} (Zhuo et al., 2016). However, the WF_{gr} related to crop production refers to the volume of water needed to assimilate the nutrients leaching from agricultural fields through runoff or soil erosion, which is a main cause of non-point source pollution, which is difficult to control. Rice is submerged with a thin layer of water during the long growing season (Peng et al., 2009), therefore, the rice is not only the largest water consumer in China, but also the most important origin of agricultural non-point source pollution (Cao et al., 2018). Furthermore, the agricultural non-point source pollution caused during flooding paddy soil or the rainy season also cannot be ignored. Crop appropriation of water resources could be comprehensively quantified when the WF_{gr} is included in WF calculation. At present, the calculation method of WF_{gr} is not uniform, mainly because of the complex processes of pollution sources. The WF_{gr} is mainly caused by the loss of chemical fertilizers and pesticides in crop production systems. As the process of pesticides utility is difficult to detect, normally, the WF_{gr} caused by loss of fertilizer (T-N and T-P) was accounted for in most studies (e.g., Cao et al., 2018; Lee et al., 2018; Miguel et al., 2016; Yoo et al., 2013). Owing to data limitations, the present study selected nitrogen as a representative element for estimating the gray WF. Moreover, one needs to account for only the most critical pollutant, which needs the highest water volume (Zheng et al., 2018a).

Usually, nitrogen leaching from fertilizers is used as the most critical pollutant to estimate gray water, which also is supported by the work of Ababaei and Etedali (2017), Li et al. (2018), Mekonnen and Hoekstra (2011) and Yang et al. (2018). Similar to present study, Ababaei and Etedali (2017) and Mekonnen and Hoekstra (2011) assumed that crops receive the same maximum allowable concentration (C_{Max}), natural nitrogen concentration (C_{Nat}) and rate of leached nitrogen (α) at world and country level. Meanwhile, the selection of the above three parameters was also the same. However, compared with this study and Mekonnen and Hoekstra (2011), Ababaei and Etedali (2017) have further assumed the values (α), i.e. 10% and 5% of the total nitrogen fertilizer applied under irrigated and rainfed conditions, respectively. This distinction is deemed necessary since the amount of fertilizer application, application strategies, soil types, crop growth statuses and field water movement processes would exert significant impacts on the rate of nitrogen leaching, although the influence mechanism of external factors on WF_{gr} was not clear (Cao et al., 2018). Utilization and transport processes of field nitrogen was related to crop growth and water status, hence, Li et al. (2018) added the volume of percolation, draining and sunning field pollution, rainwater overflow pollution and seepage pollution. For instance, 2.7% of the value (α) was assumed to represent the amount of nitrogen loss at the later tillering stage, while this value (α) was 8% at the yellow maturity stage. Due to the actual drainage and leakage with nitrogen have been taken as the cause of WF_{gr} of crop production, therefore, the values (C_{Max}) of Cao et al. (2018) and Li et al. (2018) were small than in the present study. Compared with a standard allowable concentration of 10 mg/L recommended by the USEPA, the previous two research efforts chose the highest permissible concentration for C_{Max} was 2.0 mg/L, which is based on China's environmental quality standard of surface water for "level III" water body. Meanwhile, Li et al. (2018) focused also on the impacts of seepage pollution on groundwater, grade III of the groundwater quality standard of

Table 4
Documented assessment approaches for water footprint in rice production system.

Document	Color	Method	Region	Period	Component/(m^3/t)			Classification of rice
					WF_b	WF_g	WF_{gr}	
Bulsink et al., 2010	Blue/green/gray	P-M equation/nitrogen fertilizers lost	Indonesia	2000–2004	735 (21.2%)	2527 (72.8%)	212 (6.0%)	No
Gheewala et al., 2014	Blue/green	P-M equation	Thailand	2009–2011	477 (23.8%)	1528 (76.2%)	/	No
He et al., 2010	Blue/green/gray	P-M equation/assumed 5%–15% of fertilizers lost	Hunan province in China	1960–2008	34%	42%	24%	Single/early/late
Marano and Filippi, 2015	Blue/green	P-M equation	Santa Fe and Entre Ríos in Argentina	2009–2013	552 (60.3%)	364 (39.7%)	/	No
Mekonnen and Hoekstra, 2011	Blue/green/gray	Grid-based dynamic water balance model/assumed 10% of nitrogen fertilizer lost	Global	1996–2005	341 (20.4%)	1146 (68.5%)	187 (11.1%)	No
Wang et al., 2014b	Blue/green	Irrigation quota method	China	2010	760 (54.7%)	630 (45.3%)	/	No
Xu and Zhang, 2016	Blue/green/gray	P-M equation/assumed 10% applied nitrogen fertilizer lost	Jiangsu province in China	2000–2010	177 (18.4%)	594 (61.8%)	190 (19.8%)	No
Yoo et al., 2013	Blue/green/gray	P-M equation/referencing several studies for T-N and T-P runoff	South Korea	2004–2009	502 (59.4%)	295 (34.9%)	48 (5.7%)	No
Zhuo et al., 2016	Blue/green/gray	P-M equation/assumed 10% of fertilizers lost	Yellow river basin in China	1961–2009	225 (3.9%)	414 (7.1%)	5164 (89.0%)	No
This study	Blue/green/gray	P-M equation/assumed 10% of fertilizers lost	China	2001–2010	583 (33%)	675 (38%)	501 (29%)	Single/early/late

China (GB/T14848-1993) was adopted, which states that C_{Max} was 20 mg/L. Hence, Li et al. (2018) considered growth stages in WF_{gr} estimation, which was not considered in other studies. Considering pollutants that produced WF_{gr} were solutions rather than single substance, based on field measurements, Cao et al. (2018) and Li et al. (2018) used a stricter assumption on the difference between maximum allowable N and natural N concentration (C_{Max}–C_{Nat}) of surface water, viz.2 mg/L in their studies while 10 mg/L in present work, and made their results meet the WF concept. Moreover, the reclamation of gray water could be applied in wastewater-fed agriculture, which in nutrients flow from wastewater into plants that expedite nutrient removal from wastewater coupled with the production of crop, leaf or flower. At the same time, reclamation of gray water can reduce the cost of water and decrease the application of synthetic fertilizer, which can improve sustainability for land and water resources. This concept may be adopted as a method for ecological treatment of wastewater. Overall, in future research, exploring the accurate accounting of WF_{gr} in crop production is of great significance for sustainable utilization of regional water resources, which will be generally pronounced in the world or national scale.

5. Conclusions

Estimating WF of crops at large-scales ignores changes in water resources availability and crop yields at a variety of levels. Thus, the estimation of NWF at the national scale is adopted, which is able to determine where each WF component is originally located which takes into account the spatial variability of factors impacting crop water utilization. Specifically, this paper investigates the rice NWF of China during 2001–2010 with the help of observed phenological data from 207 agro-meteorological stations. The historical change and composition characteristics of SR, ER and LR in six agro-ecological zones were assessed for the first time, and the coordinated relationship of crop water utilization with water sustainability and food security were explored. The following primary conclusions can be drawn.

The average NWF of rice in China was 304,848 MCM per year from 2001 to 2010. NWF of the three types of rice (SR, ER and LR) have different time-varying characteristics. The WF_g was as high as 38% of the total NWF, higher than 33% by WF_b and 29% by WF_{gr}. The total NWF was relatively stable in rice production over years, but the composition was not, especially for single-rice and double rice. The SR, ER and LR accounted for 50.4%, 25.1% and 24.5% of the NWF. Meanwhile, the blue water proportion of each single and early rice was decreased in turn as well as the green and gray water proportion of both early and late rice were decreased. Moreover, the unit yield of WF of double rice was 36.1 m^3/t less than the single-rice average. Based on comprehensive consideration of NWF, double rice has more advantages than single-rice in effective use of water resources. In summary, the current study not only proved the feasibility of assessing NWF at a large-scale, but also provided a new method for WF accounting, which provides helpful information for agricultural production and offers an additional degree of freedom to contribute to alleviating water stress.

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.

Acknowledgements

This work was jointly supported by the Distinguished Young Fund Project of Jiangsu Natural Science Foundation (BK20180021), the Fundamental Research Funds for the Central Universities (B200204016), the Fundamental Research Funds for the National Science Foundation of China (51779073, 51979071), the National "Ten Thousand Program" Youth Talent, the Six Talent Peaks Project in Jiangsu Province, the Qing Lan Project, the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), the Central Universities in China (2019B73114), the China Scholarship Council (CSC) during a visit of 'Jiazhong Zheng (No. 201906710163)' to Purdue University, the Postgraduate Research & Practice Innovation Program of Jiangsu Province (SJKY19_0469) and the Australian Research Council for Discovery Project Grant (DP170104138). Thanks to the National Meteorological Information Center, China Meteorological Administration (http://cdc.cma.gov.cn/) for offering the meteorological data. Cordial thanks are extended to the Editor-in-Chief, Associate Editor Professor Wei Ouyang and anonymous referee for their valuable comments which greatly improved the quality of the paper.

Author contributions

JZ, WW, GL, YD, XC, DC and BE discussed the results and contributed to the final manuscript. JZ and WW conceived of the presented idea. JZ and GL performed the computations. JZ wrote the manuscript. WW, XC and DC supervised the findings of this work. JZ, WW, GL and YD made contributions to the acquisition and analysis of data. WW and BE revised it critically for important intellectual content.

References

Ababaei, B., Etedali, H.R., 2014. Estimation of water footprint components of Iran's wheat production: comparison of global and national scale estimates. Environmental Processes 1 (3), 193–205.

Ababaei, B., Etedali, H.R., 2017. Water footprint assessment of main cereals in Iran. Agric. Water Manag. 179, 401–411.

Allen, R.G., Pereira, L., Raes, S., Smith, D., 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements, FAO Irrigation and Drainage Paper, vol. 56. FAO–Food and Agriculture Organization of the United Nations, Rome.

Blokhina, O., Virolainen, E., Fagerstedt, K.V., 2003. Anti-oxidative damage and oxygen deprivation stress. Ann. Bot. 91, 179–194.

Bocchiola, D., 2015. Impact of potential climate change on crop yield and water footprint of rice in the Po valley of Italy. Agric. Syst. 139, 223–237.

Bolat, I., Dikilitas, M., Ikinci, A., Ercisli, S., Tonkaz, T., 2015. Morphological, physiological, biochemical characteristics and bud success responses of myrobolan 29 c plum rootstock subjected to water stress. Can. J. Plant Sci. 96, 485–493.

Bulsink, F., Hoekstra, A.Y., Booij, M.J., 2010. The water footprint of Indonesian provinces related to the consumption of crop products. Hydrol. Earth Syst. Sci. 14, 119–128.

Cao, X., Wu, M., Guo, X., Zheng, Y., Gong, Y., Wu, N., Wang, W., 2017. Assessing water scarcity in agricultural production system based on the generalized water resources and water footprint framework. Sci. Total Environ. 609, 587–597.

Cao, X., Wu, M., Shu, R., Zhuo, L., Chen, D., Shao, G., Guo, X., Wang, W., Tang, S., 2018. Water footprint assessment for crop production based on field measurements: a case study of irrigated paddy rice in East China. Sci. Total Environ. 610–611, 84–93.

Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., Gautam, R., 2006. The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol. Econ. 60 (1), 186–203.

Cetinkaya, H., Kulak, M., Karaman, M., Karaman, H.S., Kocer, F., 2017. Flavonoid accumulation behavior in response to the abiotic stress: can a uniform mechanism be illustrated for all plants? Flavonoids-From Biosynthesis to Human Health. InTech

Challinor, A.J., et al., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Chang. 4 (4), 287–291.

Chapagain, A.K., Hoekstra, A.Y., 2002. Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. J. Organomet. Chem. 11, 835–855.

Chapagain, A.K., Hoekstra, A.Y., 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol. Econ. 70, 749–758.

Cong, Z., Wang, S., Ni, G., 2008. Simulations of the impact of climate change on winter wheat production. Journal of Tsinghua University (Science and Technology) 48 (9), 46–50.

Ding, Y., Wang, W., Song, R., Shao, Q., Jiao, X., Xing, W., 2017. Modeling spatial and temporal variability of the impact of climate change on rice irrigation water requirements in the middle and lower reaches of the Yangtze River, China. Agric. Water Manag. 193, 89–101.

Döll, P., 2002. Impact of climate change and variability on irrigation requirement: a global perspective. Climate Change 54, 269–293.

Döll, P., Siebert, S., 2002. Global modeling of irrigation water requirements. Water Resour. Res. 38, 8-1-8-10.

FAO, 2014. http://faostat.fao.org/default.aspx.

FAO, 2018. http://www.fao.org/faostat/en/#data/QC.

Fischer, G., Tubiello, F.N., Velthuizen, H.V., A. Wiberg, D., 2007. Climate change impacts on irrigation water requirement: effects of mitigation, 1990–2080. Technol. Forecast. Soc. Chang. 74, 1083–1107.

Gheewala, S.H., Silalertruksa, T., Nilsalab, P., Mungkung, R., Perret, S.R., Chaiyawannakarn, N., 2014. Water footprint and impact ofwater consumption for food, feed, fuel crops production in Thailand. Water 6 (6), 1698–1718.

Gleick, P.H., 2000. The changing water paradigm. A look at twenty-first century water resources development. Water Int. 25, 127–138.

Grafton, R., Williams, J., Perry, C., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S., Wang, Y., Garrick, D., Allen, R., 2018. The paradox of irrigation efficiency. Science 361, 748–750.

Gupta, S., Gupta, N.K., 2005. High temperature induced antioxidative defense mechanism in contrasting wheat seedlings. Indian J. Plant Physiol. 10, 73–75.

He, H., Huang, J., Huai, H., Tong, W., 2010. The water footprint and its temporal change characteristics of rice in Hunan. Chinese Agricultural Science Bulletin 26 (14), 294–298 (Chinese).

Hoekstra, A.Y., 2013. Sustainable, efficient and equitablewater use: the three pillars under wise freshwater allocation. WIREs Water 1 (1), 31–40.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London, UK.

Huntiugton, T.G., 2006. Evidence for intensification of the global water cycle: review and synthesis. J. Hydrol. 319, 83–95.

Jiménez, S., Dridi, J., Gutiérrez, D., Moret, D., Irigoyen, J.J., Moreno, M.A., Gogorcena, Y., 2013. Physiological, biochemical and molecular responses in four Prunus rootstocks submitted to drought stress. Tree Physiol. 33, 1061–1075.

Kalefetoglu, T., Ekmekçi, Y., 2005. The efffects of drought on plants and tolerance mechanisms (review). G.Ü. Fen Bilimleri Dergisi 18, 723–740.

Kulak, M., Ozkan, A., Bindak, R., 2019. A bibliometric analysis of the essential oil-bearing plants exposed to the water stress: how long way we have come and how much further? Sci. Hortic. 246, 418–436.

Laribi, B., Bettaieb, I., Kouki, K., Sahli, A., Mougou, A., Marzouk, B., 2009. Water deficit effects on caraway (Carum carvi L.) growth, essential oil and fatty acid composition. Ind. Crop. Prod. 30, 372–379.

Lee, S., Choi, J., Yoo, S., Mohtar, R., 2018. Water footprint for Korean rice products and virtual water trade in a water-energy-food nexus. Water Int. 43 (6), 871–886.

Li, H., Qin, L., He, H., 2018. Characteristics of the water footprint of rice production under different rainfall years in Jilin Province, China. J. Sci. Food Agric. 98, 3001–3013.

Li, M., Fu, Q., Singh, V.P., Ji, Y., Liu, D., Zhang, C., Li, T., 2019. An optimal modelling approach for managing agricultural water-energy-food nexus under uncertainty. Sci. Total Environ. 651, 1416–1434.

Lovarelli, D., Bacenetti, J., Fiala, M., 2016. Water footprint of crop productions: a review. Sci. Total Environ. 548–549, 236–251.

Luan, X., Wu, P., Sun, S., Wang, Y., Gao, X., 2018. Quantitative study of the crop production water footprint using the SWAT model. Ecol. Indic. 89, 1–10.

Luo, Y., Jiang, Y., Peng, S., Cui, Y., Khan, S., Li, Y., Wang, W., 2015. Hindcasting the effects of climate change on rice yields, irrigation requirements, and water productivity. Paddy Water Environ. 13, 81–89.

Ma, X., Ma, F., Li, C., Mi, Y., Bai, T., Shu, H., 2010. Biomass accumulation, allocation, and water-use efficiency in 10 Malus rootstocks under two watering regimes. Agrofor. Syst. 80, 283–294.

Mali, S.S., Singh, D.K., Sarangi, A., Parihar, S.S., 2017. Crop water footprints with special focus on response formulation: the case of Gomti river basin (India). Environ. Earth Sci. 76, 786.

Marano, R.P., Filippi, R.A., 2015. Water footprint in paddy rice systems. Its determination in the provinces of Santa Fe and Entre Ríos, Argentina. Ecol. Indic. 56, 229–236.

Mekonnen, M.M., Hoekstra, A.Y., 2010. A global and high-resolution assessment of the green, blue and grey water footprint of wheat. Hydrol. Earth Syst. Sci. 14 (7), 1259–1276.

Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and gray water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600.

Miguel, A., van, M., Zhang, G., Perez-Soba, M., Martorano, L.G., Lisboa, L.S., Beltrao, N.E., 2016. Impact of agricultural expansion on water footprint in the Amazon under climate change scenarios. Sci. Total Environ. 569–570, 1159–1173.

Ministry of Water Resources of P.R. China, 2002-2011. Water Resources Bulletin. China Water Power Press.

Nouri, H., Stokvis, B., Galindo, A., Blatchford, M., Hoekstra, A.Y., 2019. Water scarcity alleviation through water footprint reduction in agriculture: the effect of soil mulching and drip irrigation. Sci. Total Environ. 653, 241–252.

Peng, S.B., Tang, Q.Y., Zou, Y.B., 2009. Current status and challenges of rice production in China. Plant Production Science 12 (1), 3–8.

Radwan, A., Kleinwächter, M., Selmar, D., 2017. Impact of drought stress on specialised metabolism: biosynthesis and the expression of monoterpene synthases in sage (Salvia officinalis). Phytochemistry 141, 20–26.

Rhodes, D., Nadolska-Orczyk, A., 2001. Plant Stress Physiology. eLS. John Wiley Sons Ltd.

Rodríguez, A., Ruiz-Ramos, M., Palosuo, T., Carter, T.R., Fronzek, S., Lorite, I.J., Ferrise, R., Pirttioja, N., Bindi, M., Baranowski, P., Buis, S., Cammarano, D., Chen, Y., Dumont, B., Ewert, F., Gaiser, T., Hlavinka, P., Hoffmann, H., Höhn, J.G., Jurecka, F., Kersebaum, K.C., Krzyszczak, J., Lana, M., Mechiche-Alami, A., Minet, J., Montesino, M., Nendel, C., Porter, J.R., Ruget, F., Semenov, M.A., Steinmetz, Z., Stratonovitch, P., Supit, I., Tao, F., Trnka, M., de Wit, A., Rötter, R.P., 2019. Implications of crop model ensemble size and composition for estimates of adaptation effects and agreement of recommendations. Agric. For. Meteorol. 264, 351–362.

Sangwan, N.S., Farooqi, A.H.A., Shabih, F., Sangwan, R.S., 2001. Regulation of essential oil production in plants. Plant Growth Regul. 34, 3–21.

Silalertruksa, T., Gheewala, S., Mungkung, R., Nilsalab, P., Lecksiwilai, N., Sawaengsak, W., 2017. Implications of water use and water scarcity footprint for sustainable rice cultivation. Sustainability 9, 2283.

Sun, S., Wu, P., Wang, Y., Zhao, X., Liu, J., Zhang, X., 2013. The impacts of interannual climate variability and agricultural inputs on water footprint of crop production in an irrigation district of China. Sci. Total Environ. 444, 498–507.

Sun, S., Liu, J., Wu, P., Wang, Y., Zhao, X., Zhang, X., 2016. Comprehensive evaluation of water use in agricultural production: a case study in Hetao Irrigation District, China. J. Clean. Prod. 112, 4569–4575.

Tuninetti, M., Tamea, S., D'Odorico, P., Laio, F., Ridolfi, L., 2015. Global sensitivity of high-resolution estimates of crop water footprint. Water Resour. Res. 51, 8257–8272.

United States of Agricultural Department (USDA), 2017. Grain: World Markets and Trade.

Wang, W., Yu, Z., Zhang, W., Shao, Q., Zhang, Y., Luo, Y., Jiao, X., Xu, J., 2014a. Responses of rice yield, irrigation water requirement and water use efficiency to climate change in China: historical simulation and future projections. Agric. Water Manag. 146, 249–261.

Wang, Y., Wu, P., Engel, B., Sun, S., 2014b. Application of water footprint combinedwith a unified virtual crop pattern to evaluate cropwater productivity in grain production in China. Sci. Total Environ. 497, 1–9.

Wang, W., Zou, S., Shao, Q., Xing, W., Chen, X., Jiao, X., Luo, Y., Yong, B., Yu, Z., 2016. The analytical derivation of multiple elasticities of runoff to climate change and catchment characteristics alteration. J. Hydrol. 541, 1042–1056.

Wang, W., Ding, Y., Shao, Q., Xu, J., Jiao, X., Luo, Y., Yu, Z., 2017. Bayesian multi-model projection of irrigation requirement and water use efficiency in three typical rice plantation region of China based on CMIP5. Agric. For. Meteorol. 232, 89–105.

White, D.J., Hubacek, K., Feng, K., Sun, L.X., Meng, B., 2018. The water-energy-food nexus in East Asia: a tele-connected value chain analysis using inter-regional input-output analysis. Appl. Energy 210, 550–567.

Xiong, J., Ding, C.Q., Wei, G.B., Ding, Y.F., Wang, S.H., 2013. Characteristic of dry-matter accumulation and nitrogen-uptake of super-high-yielding early rice in China. Agron. J. 105 (4), 1142–1150.

Xu, P., Zhang, X., 2016. Study onwater footprint of main crops production in Jiangsu Province. Journal of Water Resources and Water Engineering 27 (1), 232–237 (Chinese).

Yadav, R., Arora, P., Chaudhury, A., 2012. Plant secondary metabolites: from diseases to health. Front. Plant Sci. 1, 3–23.

Yan, M., Luo, T., Bian, R., Cheng, K., Pan, G., Rees, R., 2015. A comparative study on carbon footprint of rice production between household and aggregated farms from Jiangxi, China. Environ. Monit. Assess. 187, 332.

Yang, X., Asseng, S., Wong, M.T.F., Yu, Q., Li, J., Liu, E., 2013. Quantifying the interactive impacts of global dimming and warming on wheat yield and water use in China. Agric. For. Meteorol. 182–183, 342–351.

Yang, Y.C.E., Ringler, C., Brown, C., Mondal, M.A.H., 2016. Modelling the agricultural water-energy-food nexus in the Indus River basin, Pakistan. J. Water Resour. Plan. Manag. 142 (12), 4016062.

Yang, M., Xiao, W., Zhao, Y., Li, X., Huang, Y., Lu, F., Hou, B., Li, B., 2018. Assessment of potential climate change effects on the rice yield and water footprint in the Nanliujiang catchment, China. Sustainability 10 (2), 242.

Yaşar, F., 2003. Tuz stresi altındaki patlıcan genotiplerinde bazı antioksidan enzim aktivitelerinin in vitro ve in vivo olarak incelenmesi. Doctorate Thesis. Yüzüncü Yıl Üniv. Fen Bilimleri Enstitüsü, Van.

Yoo, S.H., Choi, J.Y., Lee, S.H., Kim, T., 2013. Estimating water footprint of paddy rice in Korea. Paddy Water Environ. 12, 43–54.

Yoo, S.H., Lee, S.H., Choi, J.Y., Im, J.B., 2015. Estimation of potential water requirements using water footprint for the target of food self-sufficiency in South Korea. Paddy Water Environ. 14, 259–269.

Yunus, M., Singh, N., De Kok, L.J., 2013. Environmental Stress: Indication, Mitigation and Eco-conservation. Springer, Dordrecht.

Zhang, L.J., Yin, X.A., Zhi, Y., Yang, Z.F., 2014. Determination of virtual water content of rice and spatial characteristics analysis in China. Hydrol. Earth Syst. Sci. 18, 2103–2111.

Zhang, Y., Huang, K., Ridoutt, B.G., Yu, Y., 2018. Comparing volumetric and impact-oriented water footprint indicators: case study of agricultural production in Lake Dianchi Basin, China. Ecol. Indic. 87, 14–21.

Zheng, J., Wang, W., Cao, X., Feng, X., Xing, W., Ding, Y., Dong, Q., Shao, Q., 2018a. Responses of phosphorus use efficiency to human interference and climate change in the middle and lower reaches of the Yangtze River: historical simulation and future projections. J. Clean. Prod. 201, 403–415.

Zheng, J., Wang, W., Chen, D., Cao, X., Xing, W., Ding, Y., Dong, Q., Zhou, T., 2018b. Exploring the water–energy–food nexus from a perspective of agricultural production efficiency using a three-stage data envelopment analysis modelling evaluation method: a case study of the middle and lower reaches of the Yangtze River, China. Water Policy 21 (1), 49–72.

Zheng, J., Wang, W., Ding, Y., Liu, G., Xing, W., Cao, X., Chen, D., 2019. Assessment of climate change impact on the water footprint in rice production: historical simulation and future projections at two representative rice cropping sites of China. Sci. Total Environ. 709, 136190.

Zhuo, L., Mekonnen, M.M., Hoekstra, A.Y., 2016. The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: a study for China (1978–2008). Water Res. 94, 73–85.